SHORT GAMMA-RAY BURSTS: THE MASS OF THE ACCRETION DISK AND THE INITIAL RADIUS OF THE OUTFLOW

YI-ZHONG FAN\textsuperscript{1,2} AND DA-MING WEI\textsuperscript{1,2}

\textsuperscript{1} Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China; yzf@pmo.ac.cn, dmwei@pmo.ac.cn
\textsuperscript{2} Key Laboratory of Dark Matter and Space Astronomy, Chinese Academy of Sciences, Nanjing 210008, China

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ABSTRACT

In this work, we estimate the accretion-disk mass in the specific scenario of binary–neutron-star merger with current observational data. Assuming that the outflows of short gamma-ray bursts (GRBs) are driven via neutrino–antineutrino annihilation we estimate the disk mass of about half of short bursts in the sample to be $\sim0.01–0.1\,M_\odot$, in agreement with that obtained in the numerical simulations. Massive disks ($\sim$several $0.1\,M_\odot$) found in some other short GRBs may point to the more efficient magnetic process of extracting energy or the neutron star and black hole binary progenitor. Our results suggest that some short bursts may be really due to the coalescence of double neutron stars and are promising gravitational wave radiation sources. For future short GRBs with simultaneous gravitational-wave detections, the disk mass may be reliably inferred and the validity of our approach will be tested. We also propose a method to constrain the initial radius of a baryonic outflow where it is launched ($R_0$) without the need of identifying an ideal thermal spectrum component. We then apply it to GRB 090510 and get $R_0 \lesssim 6.5 \times 10^6(G_{\text{ph}}/2000)^{-4}$ cm, suggesting that the central engine is a black hole with a mass $< 22\,M_\odot(G_{\text{ph}}/2000)^{-4}$, where $G_{\text{ph}}$ is the bulk Lorentz factor of the outflow at the photospheric radius.

Key words: accretion, accretion disks – gamma rays: general – radiation mechanisms: non-thermal

1. INTRODUCTION

Since the discovery of the afterglow and then the measurement of the redshift in 1997, our understanding of gamma-ray bursts (GRBs) has been revolutionized (for reviews see Piran 2004; Zhang & Mészáros 2004). As usual some aspects are understood better than others. For example, the late-time ($t > 10^4$ s) afterglow emission is likely dominated by the radiation of the electrons accelerated by external forward shock while the earlier afterglow emission may consist of at least two components, including that powered by the prolonged activity of the central engine and the external shock emission (e.g., Fan & Wei 2005; Mészáros 2006; Zhang et al. 2006; Zhang 2007). The origin of the prompt $\gamma$-ray emission is less clear. Widely discussed scenarios include the internal shock model, the internal magnetic energy dissipation models, and the photospheric models. The GRBs’ central engine is either a stellar black hole surrounded by a hyper-accreting disk (MacFadyen & Woosley 1999) or a quickly rotating magnetar (Usov 1992). For a magnetar-like central engine the outflow is expected to be Poynting-flux dominated. In the case of a stellar black hole surrounded by a hyper-accreting disk, the outflow could be either baryonic or Poynting-flux dominated, depending on the energy extraction process (for reviews see Piran 2004; Zhang & Mészáros 2004). Such a central engine is usually characterized by the mass and the spin of a black hole, and the rate of accretion onto a black hole. Our current knowledge of these physical parameters is mainly from numerical simulations since current electromagnetic data alone cannot break the degeneracies between the parameters (see Section 2.1). For some specific long bursts (for which the duration is longer than $\sim2$ s) the situation is better. The modeling of their associated supernovae sheds some light on the mass of the central remnant (e.g., Deng et al. 2005). However, for short GRBs (with a duration less than 2 s) no bright associated supernova has been detected. In this work, we investigate whether it is possible to make some progress with some specific assumptions. We concentrate on the binary–neutron-star merger model which has been supported by host galaxy observations and by the non-detection of accompanying bright supernova for some short bursts (e.g., Gehrels et al. 1993; Fox et al. 2005; Barthelmy et al. 2005; Berger et al. 2005; Hjorth et al. 2005). The other possibility, that some short events might have a massive star origin (e.g., Zhang et al. 2003; Fan et al. 2005; Zhang et al. 2009; Virgili et al. 2011; Panaitescu 2011), will not be addressed.

Besides the physical parameters of the central engine, the initial radius of the outflow where it is launched ($R_0$) is an important parameter revealing the physical process taking place at the center of the burster. In the collapsar scenario, the interaction of the accelerated/cooled ejecta with the envelope material may give rise to a reborn hot fireball (e.g., Lazzati et al. 2009) and then the derived $R_0$ would mark the site of the interaction, which is much larger than the initial size of the ejecta. If such an interaction is ignorable, $R_0$ imposes an independent though rough constraint on the mass of the central black hole. For a baryonic outflow the acceleration and the energy dissipation processes are well understood (Piran et al. 1993; Mészáros et al. 1993). With a reliable thermal component identified in the prompt spectrum, it is possible to constrain the bulk Lorentz factor and $R_0$ of the shells (Pe‘er et al. 2007). Such a goal was achieved for some long GRBs, in particular GRB 090902B, and a typical $R_0 \sim 10^8–10^9$ cm was inferred (e.g., Pe‘er et al. 2007; Ryder et al. 2010). For short GRBs, no reliable thermal spectrum component has been identified. A unique candidate is GRB 090510, characterized by a very soft MeV spectrum and a rather hard GeV radiation component (Gao et al. 2009). But the peculiar spectrum of this short burst, unlike the long event GRB 090902B, cannot be reasonably fitted by a thermal component superposed by a power-law component (B. Zhang & B. Zhang 2011, private communication). Therefore, one purpose of this work is to find a way to estimate $R_0$ without the need for identifying an ideal thermal component.
This work is structured as follows. In Section 2, we discuss the difficulty of estimating the physical parameters of the central engine with current observational data, and then show that some progress is achievable in the specific double neutron star merger scenario. The mass of the accretion disk of some short GRBs has been estimated. In Section 3, we present a method in which an ideal thermal signature is not needed to estimate \( R_0 \) with the assumption that the outflow is baryonic. We apply the method to GRB 090510 and then constrain \( R_0 \). Our results are summarized in Section 4 with some discussion.

2. THE MASS OF THE ACCRETION DISK OF SOME SHORT GRBs

2.1. The Difficulty of Estimating Physical Parameters of the Central Engine with Current Limited Data

A nascent stellar black hole surrounded by a hyper-accreting disk, the widely adopted central engine of GRBs, is characterized by some important parameters, including the mass and spin of a central black hole \( (M_{BH} \text{ and } a) \), where \( a \equiv J/|GM_{BH}^2c|, J \) is the angular momentum of the black hole and \( c \) is the speed of light), the mass of accretion disk \( M_{\text{disk}} \), or, alternatively, the accretion rate \( \dot{M} \).

The accretion disk is so hot that the energy loss may be mainly through neutrino and anti-neutrino radiation. The later neutrino and anti-neutrino annihilation may launch a baryonic fireball (Eichler et al. 1989). The annihilation luminosity has been extensively investigated in the literature (e.g., MacFadyen & Woosley 1999; Popham et al. 1999; Liu et al. 2007; Zalamea & Beloborodov 2011). In general, the luminosity is a function of \( M_{\text{acc}} \), \( a \), and \( M \), and possibly also the vertical structure of the disk.\(^3\) In this work we adopt an empirical relation proposed by Zalamea & Beloborodov (2011), which reads

\[
L_{\nu} \approx 10^{52} \text{erg s}^{-1} x_{\text{ms}}^{-4.8} \left( \frac{M_{\text{BH}}}{3 M_{\odot}} \right)^{-3/2} \times \begin{cases} 0, & \text{for } M < M_{\text{ign}}; \\ m_{9/4}, & \text{for } M_{\text{ign}} < M < M_{\text{trap}}; \\ m_{9/4}^{9/4}, & \text{for } M \geq M_{\text{trap}}, \end{cases}
\]

(1)

where the accretion rate \( \dot{M} = \dot{M}/M_{\odot} \), \( x_{\text{ms}} = r_{\text{ms}}(a)/r_{g} \), \( M_{\text{ign}} = K_{\text{ign}}(a/0.1)^{5/3}, M_{\text{trap}} = K_{\text{trap}}(a/0.1)^{1/3} \), and \( \alpha \) is the viscosity. The coefficients \( K_{\text{ign}} \) and \( K_{\text{trap}} \) are functions of the black hole spin \( a \).

The radius of last stable orbit \( r_{\text{ms}} \) is Bardeen et al. (1972)

\[
r_{\text{ms}} = r_g[3 + Z_2] \left[ (3 - Z_1)(3 + Z_1 + 2Z_2) \right]^{1/2}/2,
\]

(2)

where

\[
Z_1 = 1 + (1 - a^2)^{1/3}[(1 + a)^{1/3} + (1 - a)^{1/3}]
\]

\( Z_2 = (3a^2 + Z_1^2)^{1/2} \).

For \( a = 0 \) we have \( r_{\text{ms}} = 3r_g \) while for \( a = 1 \) we have \( r_{\text{ms}} = r_g/2 \) or \( r_{\text{ms}} = 9r_g/2 \) (retrograde). The retrograde case is irrelevant to the case of the accretion disk and will not be discussed further.

With the observational data the energy output of the central engine \( E_{\text{rad}} \) and hence \( L_{\nu} \) can be reasonably inferred, which, however, is not enough to break the degeneracies among parameters \( M_{\text{acc}}, a, \) and \( m \). As shown in footnote 3, the same applies to the magnetic process of energy extraction. That is why it is rather hard to constrain the physical parameters of the central engine with current electromagnetic data and our knowledge of the central engine is mainly from numerical simulations. Fortunately, the specific scenario of binary–neutron-star merger could be an exception for which a preliminary probe is plausible.

2.2. An Exception: The Double Neutron Star Merger Scenario

In the specific binary–neutron-star merger model, also the leading one, for short GRBs (Eichler et al. 1989; Nakar 2007; Lee & Ramirez-Ruiz 2007), the mass of the formed black hole and its spin parameter can be relatively reasonably evaluated.

The mass of the central engine is expected to be close to the total mass of the progenitors since the mass ejection during the merger is expected to be tiny (Rosswog et al. 1999) and the mass range of neutron stars is relatively narrow. For the 10 neutron-star binaries well studied so far, the total mass of the binaries ranges from 2.57 \( M_\odot \) to 2.83 \( M_\odot \) (Kiziltan et al. 2011). Therefore, the mass of the nascent black hole formed in the merger is expected to be close to \( M_{\odot} \sim 2.7 M_\odot \).

The spin parameter of the formed black hole can be semi-quantitatively estimated. Following Lee et al. (2000) and for simplicity, we assume that the double neutron stars have a similar mass \( M_{\odot} \sim 1.4 M_{\odot} \), and that the orbital angular momentum of the binary system is \( J_{\text{binary}} = \sqrt{GM_{\odot}^2r_t/2} \), where \( r_t \) is the tidal radius. The spin parameter of the formed black hole can be expressed by \( a \equiv x y J_{\text{binary}}/[2yM_{\odot}^2G/c] = (x/y)r_t/r_{\text{E}_{\odot}} \), assuming that a fraction \((x/y)\) of the orbital angular momentum of the neutron star binary goes into a nascent black hole keeping a fraction \( y \) of the total mass. For the binary–neutron-star merger scenario, the tidal radius is \( r_t \approx 6r_{E_{\odot}} \) (Haensel et al. 1991) and we have \( a = 0.61x/y, \) about 10% smaller than that suggested by Lee et al. (2000). As already mentioned, \( y \) is close to 1. Let us estimate \( x \). The gravitational radiation changes the energy of the binary system at a rate \( dE/dt \approx 1.9 \times 10^{35}(r_t/6r_{E_{\odot}})^{-5} \text{erg s}^{-1} \) and the merger takes a time \( \Delta t \sim 1.4 \text{ms} (r_t/6r_{E_{\odot}})^{4} \) (Haensel et al. 1991). The corresponding change of the angular momentum \( \Delta J_{\text{binary}} \sim (dE/dt)\Delta t/\sqrt{2G M_{\odot} r_t/2} \). We then have \( x = 1 - \Delta J_{\text{binary}}/J_{\text{binary}} \approx 0.9 \). Therefore, we have \( a \sim 0.55, \) i.e., the formed black hole rotates rapidly. As found in Lee et al. (2000), for the double neutron stars having different masses \( M_{\odot} \approx M_{\odot} \), \( M_{\odot}/2 \), roughly one has \( a \propto \mathcal{R} \equiv (M_{\odot}^2+M_{\odot}/2)^{6/7} \) \( (M_{\odot}^4+M_{\odot}^2/2)^{1/6} \). For the 10 neutron-star binaries discussed in Kiziltan et al. (2011), one finds that \( \mathcal{R} \) ranges from 0.275 to 0.282, i.e., \( a \) is insensitive to the mass ratio of the binaries.

The above semi-quantitative analysis is in agreement with the numerical simulation, in which a typical \( a \sim 0.78 \) was found, depending weakly on the total mass and the mass ratio of the binary neutron stars (Kiuchi et al. 2009).
For a = 0.78, we have $r_{\text{ms}} \approx 1.45 r_g$, $x_{\text{ms}} = 1.45$, and (for $M_{\text{ign}} < M < M_{\text{trap}}$)

$$L_{\nu,\bar{\nu}} \approx 2 \times 10^{51} \text{erg s}^{-1} m^{9/4} \left(\frac{x_{\text{ms}}}{1.45}\right)^{-4.8} \left(\frac{M_{\text{BH}}}{2.7 M_\odot}\right)^{-3/2}.$$  \hspace{1cm} (3)

A typical $M_{\text{disk}} \sim 10^{-3} - 10^{-1} M_\odot$ is found in the numerical simulation of the binary–neutron–star coalescence (see Kiuchi et al. 2009 and references therein). The binary–neutron–star merger hypothesis is supported if our $M_{\text{disk}}$ estimated with the observational data is within such a mass range. In the foreseeable future the binary–neutron–star merger model for short GRBs could be directly tested by the gravitational wave data and the mass of the binaries as well as the formed disk could be inferred (Kiuchi et al. 2010). Therefore, the validity of our following approach will be directly tested.

2.3. A Simple Approach and Case Studies

A simple approach. Below we take the simplest approach to estimate $L_{\nu,\bar{\nu}}$. The isotropic-equivalent kinetic energy of the outflow powering long-lasting afterglow ($E_{\text{k,iso}}$) and the opening angle of the ejecta $\theta_1$ can be derived from the modeling of the multi-wavelength afterglow data (Panaitescu 2006). However, in a good fraction of short GRBs, such a goal is not achievable due to the lack of prompt observations. Fortunately, for the X-ray emission above both the typical synchrotron radiation and the cooling frequency, the flux is independent of the poorly constrained number density of the medium $n$ and the X-ray luminosity is a good probe of $E_{\text{k,iso}}$ (Kumar 2000). Following Fan & Piran (2006) we take

$$E_{\text{k,iso}} \sim 10^{53} \text{erg} \mathcal{L}_X^{4/(p+2)} \left(\frac{1 + z}{2}\right) \epsilon_n^{-(p-2)/(p+2)} \epsilon_B^{(1-p)/(p+2)} (1 + Y)^{4/(p+2)},$$  \hspace{1cm} (4)

where $\mathcal{L}_X$ is the X-ray afterglow luminosity at $t = 10$ hr after the trigger of the burst, $\epsilon_n$ and $\epsilon_B$ are the fractions of shock energy given to the electrons and magnetic field, respectively, $Y$ is the Compton parameter, and $p \sim 2$ is the energy distribution index of the shock-accelerated electrons and is constrained by the X-ray spectrum. The convention $Q_a = Q/10^9$ has been adopted here and throughout this work except for some specific notations.

The jet opening angle is estimated to be (Frail et al. 2001)

$$\theta_j \approx 0.076 \left(\frac{t_f}{1 \text{ day}}\right)^{3/8}[(1 + z)/2]^{-3/8} E_{\text{k,iso,51}}^{-1/8} n_{-2}^{1/8},$$  \hspace{1cm} (5)

where $t_f$ is the jet break time. We then estimate the “intrinsc” power released by the GRB central engine as

$$\dot{E}_{\text{out}} \approx (1 + z)(E_{\gamma,\text{iso}} + E_{\text{k,iso}})^{2/7} / (2T_{\text{act}}),$$  \hspace{1cm} (6)

where $T_{\text{act}}$ is the duration of the activity of the central engine. In reality, $\dot{E}_{\text{out}}$ is just a fraction ($F \lesssim 0.3$) of the total neutrino–antineutrino annihilation luminosity outside the horizon of the rotating black hole, i.e., $\dot{E}_{\text{out}} = \mathcal{F}L_{\nu,\bar{\nu}}$ (e.g., Aloy et al. 2005). The real duration of the main activity of the central engine might be shorter than the duration of the prompt emission $T_{90}$ by a factor $R \gtrsim 1$, i.e., $T_{\text{act}} = T_{90}/R$, because different propagation velocities of the front and rear ends will lead to a radial stretching of the ultrarelativistic ejecta (see Section 4.1 of Aloy et al. 2005 for more details). Hence we have (for $M_{\text{ign}} < M < M_{\text{trap}}$)

$$\dot{m} \approx 0.53 M_\odot \left[\frac{R(1 + z)(E_{\gamma,\text{iso,51}} + E_{\text{k,iso,51}})^{2/7}}{\mathcal{F} T_{90}}\right]^{4/9} \left(\frac{x_{\text{ms}}}{1.45}\right)^{2.1} \left(\frac{M_{\text{BH}}}{2.7 M_\odot}\right)^{2/3}$$  \hspace{1cm} (7)

and

$$M_{\text{disk}} \approx 0.53 M_\odot \left[\frac{(E_{\gamma,\text{iso,51}} + E_{\text{k,iso,51}})^{2/7}}{\mathcal{F}^2} \left(\frac{x_{\text{ms}}}{1.45}\right)^{2.1} \left(\frac{M_{\text{BH}}}{2.7 M_\odot}\right)^{2/3}\right]^{4/9}$$  \hspace{1cm} (8)

Since $R \gtrsim 1$ and $\mathcal{F} < 1$, their impacts on estimating $M_{\text{disk}}$ are partly canceled. For $a = 0.6$, we have $x_{\text{ms}} \approx 1.9; M_{\text{disk}}$ given in Equation (8) will be enhanced by a factor of $\sim 1.8$.

Case studies. So far we have 10 short GRBs, as listed in Table 1, having relatively abundant afterglow data, with which we can estimate $\dot{E}_{\text{out}}$ and then $M_{\text{disk}}$. For simplicity, instead of discussing all bursts one by one, below we focus on a few special events.

**GRB 051221A**, a burst with a duration $z = 1.4$ s, was at redshift $z = 0.5465$ and is distinguished by a long-lasting X-ray flat segment in the afterglow. Such a flat segment could be due to either the energy injection from the central engine (Soderberg et al. 2006; Burrows et al. 2006) or the forward shock emission of the emerging wide-component of the two component jet (Jin et al. 2007). The afterglow parameters reported in the literature are different. In the analysis we take the parameters obtained in the two-component jet modeling, in which the long activity of the central engine is not needed. If we take the somewhat more conservative estimate $E_{\nu,\bar{\nu}} \approx 3 \times 10^{59}$ erg (Soderberg et al. 2006; Burrows et al. 2006), the mass of the accretion disk will be reduced by a factor of 0.6.

**GRB 090510**, a burst at redshift $z = 0.903$, is the most energetic short event ever recorded and is also remarkable for its long-lasting GeV emission that is likely powered by an external forward shock (Gao et al. 2009; De Pasquale et al. 2010; Corsi et al. 2010). The self-consistent interpretation of the GeV/X-ray/optical data is not an easy task and the parameters are found to be somewhat unusual. At $t \approx 1200$ s after the trigger of the burst, the X-ray and the optical afterglow emission change the decline behaviors achromatically (De Pasquale et al. 2010). Such changes are most likely due to the jet effect, that is, the edge of the outflow enters our line of sight and the visible emitting region cannot be approximated as a spherical surface anymore. The jet opening angle is small as $\sim 0.006$ (Gao et al. 2009; Corsi et al. 2010; He et al. 2011), which is about one order of magnitude smaller than that of other bursts (see Table 1) or that found in numerical simulation (Aloy et al. 2005). It is unclear how such a narrow collimation is reached. Nevertheless a similar narrow collimation was identified in the afterglow modeling of the naked-eye burst GRB 080319B (Racusin et al. 2008).

**GRB 100816A**, has a burst at $z = 0.8035$, a local duration of $2.8 / (1 + z) = 1.55$ s, consistent with being a short burst. The result of the Swift Burst Alert Telescope (BAT) spectral lag analysis is also consistent with being a short hard burst, but the error bars are too large to be definitive (Oates et al. 2010). With the X-ray light curve we take a jet break time
The preliminary white band flux decline of the afterglow data of this burst is likely the density profile of the circumburst medium. The following approach is partly motivated by Pe’er et al. (2007). In their work, photospheric radiation taking place in the radiation-dominated phase and the matter-dominated phase has been investigated separately, whereas we solve the problems jointly. Furthermore, we focus on constraining $R_{	ext{BH}}$ in the absence of an ideal thermal signature, different from what has been done in the literature.

As shown in Table 1, for about half of short bursts in the sample, the accretion disk has a mass $\sim 0.01-0.1 M_{\odot}$, clearly consistent with that found in the numerical simulations of a double neutron star merger (e.g., Rosswog et al. 2003; Kiuchi et al. 2009). For some other events, such as GRB 051221A and GRB 050724, the inferred $M_{\text{disk}} \sim$ several $0.1 M_{\odot}$ may be a bit massive to form. This puzzle can be solved in either of the following scenarios. One is that the outflows of these short GRBs were launched via some more efficient magnetic processes rather than the neutrino mechanism, as speculated in the literature (e.g., Rosswog et al. 2003; Lee & Ramirez-Ruiz 2007). With footnote 3, for $a \approx 0.78$, $M_{\text{BH}} = 2.7 M_{\odot}$, and $M = (0.1, 1.0) M_{\odot}$ s$^{-1}$ we have $L_{\text{iso}} \sim (100, 10) L_{\odot}$. Consequently, the disks with $M_{\text{disk}}$ about 10 or more times smaller than those presented in Table 1 may be enough to power these short events. The outflow launched in this way is Poynting-flux dominated and the prompt emission due to the magnetic energy dissipation should have a high linear polarization degree. The other is that some short GRBs are from the neutron-star–black-hole merger for which a massive disk is possible. Another possibility that cannot be ruled out is that some short events might have a massive star origin. Since our estimated $M_{\text{disk}}$ is close to that found in numerical simulations, the compact object merger scenario is likely viable, implying that some (possibly a considerable fraction of) short GRBs may really be driven by the coalescence of double neutron stars and are promising gravitational wave radiation sources.

### 3. ESTIMATING THE INITIAL RADIUS OF THE OUTFLOW

#### 3.1. The Method

The following approach is partly motivated by Pe’er et al. (2007). In their work, photospheric radiation taking place in the radiation-dominated phase and the matter-dominated phase has been investigated separately, whereas we solve the problems jointly. Furthermore, we focus on constraining $R_{\text{BH}}$ in the absence of an ideal thermal signature, different from what has been done in the literature.

For a baryonic outflow, most of the initial thermal energy may have been converted into the kinetic energy of the baryons at the end of the acceleration (Shemi & Piran 1990), but a (quasi-)thermal emission component is likely inevitable (Paczynski 1990). The (quasi-)thermal emission is mainly from the photosphere at a radius $R_{\text{ph}}$, which satisfies the following relations.

### Table 1

| GRB   | $T_{90}$ (s) | $z$       | $E_{\gamma,\text{iso}}$ (erg) | $E_{k,\text{iso}}$ (erg) | $\dot{\gamma}$ (rad) | $M_{\text{disk}}$ ($M_{\odot}$) | References |
|-------|-------------|-----------|-------------------------------|--------------------------|----------------------|---------------------------------|------------|
| 050509B | 0.05       | 0.2248    | $4.5 \times 10^{58}$          | $\ldots$                 | $0.02$               | 1                               |            |
| 050709 | 0.07       | 0.216     | $6.9 \times 10^{59}$          | $3.7 \times 10^{50}$ b   | 0.21                 | 0.03                            | 1.2        |
| 050724 | 3.0        | 0.257     | $4 \times 10^{50}$            | $6.0 \times 10^{50}$ b   | 0.2                  | 0.37                            | 1.2        |
| 051221A | 1.40      | 0.5465    | $2.4 \times 10^{51}$          | $1.0 \times 10^{52}$ c   | 0.10                 | 0.46                            | 3.4        |
| 061006 | 0.4        | 0.4377    | $2.1 \times 10^{51}$          | $1.8 \times 10^{51}$ d   | $\sim 0.11$          | 0.10                            | 5.6        |
| 070714B | 3.0        | 0.9224    | $1.2 \times 10^{51}$          | $3.6 \times 10^{51}$ d   | $\geq 0.08^a$        | $\geq 0.24$                      | 7          |
| 071227 | 1.8        | 0.381     | $5.8 \times 10^{50}$          | $5 \times 10^{50}$ d     | $\geq 0.09^b$        | $\geq 0.13$                      | 8          |
| 090426 | 1.25       | 2.699     | $3 \times 10^{51}$            | $8.7 \times 10^{52}$     | 0.06                 | 0.30                            | 9          |
| 090510 | 0.30       | 0.903     | $1.2 \times 10^{53}$          | $5 \times 10^{53}$       | 0.00                 | 0.06                            | 10–12      |
| 100816A | 2.8        | 0.8035    | $5.8 \times 10^{53}$          | $1.1 \times 10^{52}$ d   | $\geq 0.01^e$        | $\geq 0.07$                      | 13         |

Notes.

* We estimate $M_{\text{disk}}$ with Equation (8), adopting $M_{\text{BH}} = 2.7 M_{\odot}$, $a = 0.78$, $\mathcal{F} = 0.3$, and $R = 1$.

* We take the lower value obtained in Panaitescu (2006).

* There was a flat segment in the X-ray afterglow and its origin is still unclear. Here, we take an $E_{k,\text{iso}} \sim 10^{52}$ erg required in the two-component jet model (Jin et al. 2007).

* This parameter is estimated by Equation (4) by taking $\epsilon_e \sim 0.1$, $\epsilon_B \sim 0.01$, and $Y \sim \mathcal{O}(1)$.

* The jet opening angle is estimated by Equation (5). For GRB 090426, a jet break time $t = 0.4$ day (Nicuesa Guelbenzu et al. 2011) and $n \sim 10$ cm$^{-3}$ (Xin et al. 2011) have been adopted. For other events, we take the time of the last Swift/XRT detection, reported at http://www.swift.ac.uk/xrt_curves/, as $\dot{\gamma}$ and $n \sim 0.01$ cm$^{-3}$ to set a lower limit on the half-opening angle.

References. (1) Fox et al. 2005; (2) Panaitescu 2006; (3) Soderberg et al. 2006; (4) Jin et al. 2007; (5) Berger et al. 2007; (6) Golenetskii et al. 2006; (7) Kenko et al. 2008; (8) Cai et al. 2010; (9) Xin et al. 2011; (10) Abdo et al. 2009; (11) He et al. 2011; (12) Gao et al. 2009; (13) Oates et al. 2010.

$t \gtrsim 2 \times 10^5$ s. The most valuable information inferred from the afterglow data of this burst is likely the density profile of the circumburst medium. The preliminary white band flux decline is $\sim t^{-1.15}$ for $100 \, s < t < 10^4 \, s$, steeper than the simultaneous $r^{-1}$-like X-ray decline (Oates et al. 2010). The spectral index of the X-ray afterglow photons is $\approx 1.03 \pm 0.12$, suggesting that the X-ray emission is above the cooling frequency of the forward shock electrons for $p \sim 2$. If the slow-cooling fireball was expanding into the interstellar medium and the typical synchrotron radiation frequency is below the observer’s band, the optical afterglow emission should decline with the time as $t^{-0.75}$, shallower than the X-ray decline, which is at odds with the data. For a free-wind medium, the optical decline should be $t^{-1.25}$ steeper than the X-ray decline (Zhang & Mészáros 2004). Therefore, the current data favor the free-wind medium model, in which the progenitor should be a massive star rather than a pair of compact objects. If our speculation could be confirmed by careful analysis of available afterglow data reported in GCNs, the collapsar origin of GRB 100816A with an intrinsic duration $\sim 1.4$ s would be established. In turn, such a result would support the hypothesis that collapsars can produce short events (Zhang et al. 2003) and the progenitors of short GRBs are diverse (Fan et al. 2005; Zhang et al. 2009). If so, the calculation made in Table 1 on these kind of bursts is likely invalid.
Based on its definition, $R_{ph}$ can be expressed as (e.g., Paczyński 1990; Daigne & Mochkovitch 2002; Jin et al. 2010)

$$R_{ph} \approx 4.5 \times 10^{11} \text{ cm } L_{b} \Gamma_{0}^{2} \eta_{3}^{-1}$$

$$\approx 3.7 \times 10^{11} L_{b} f^{-2} \eta_{3}^{-3}, \quad (9)$$

where $f \equiv 3 \Gamma_{ph}/4 \eta_{3}$ is the initial dimensionless entropy, and $\Gamma_{ph}$ is the bulk Lorentz factor of the outflow at the photospheric radius.

The photospheric radius is also related to $R_{0}$. Following Piran et al. (1993) and Mészáros et al. (1993), we introduce an $R_{ph}$, at which the bulk Lorentz factor of the outflow is $\Gamma_{0} \sim 1$. With the parameter

$$\frac{1}{D} = \frac{\Gamma_{0}}{\Gamma_{ph}} + \frac{3 \Gamma_{0}}{4 \eta_{3} \Gamma_{ph}} - \frac{3}{4 \eta_{3}}, \quad (10)$$

the acceleration calculation yields (Piran et al. 1993)

$$R_{ph} = R_{0} (\Gamma_{0}/\Gamma_{ph})^{1/2} D^{3/2}, \quad (11)$$

where $\eta_{3} = e_{ph}/n_{0} m_{p} c^{2} \approx \eta_{0}/\Gamma_{0}$. Then we have $1/D = \Gamma_{0}/\Gamma_{ph} + 3 \Gamma_{0}/4 \eta_{3} - 3 (1 - f) \Gamma_{0}/4 f \eta_{3} + 9 \Gamma_{0}^{2}/16 \eta_{3}^{2} f$, the first term will be dominant as long as $1 - f \gg \Gamma_{0}/4 \eta_{3}$, which is usually satisfied. So we have

$$1/D \approx 3 (1 - f) \Gamma_{0}/4 f \eta_{3}, \quad D \eta_{3}/\eta_{0} \approx 4 f /[3 (1 - f)], \quad (12)$$

with which we get

$$R_{ph} \approx \frac{4}{3} R_{0} \frac{f}{(1 - f)^{3/2}} \approx 1.3 \times 10^{10} \text{ cm } \eta_{3} R_{0,7} \frac{f}{(1 - f)^{3/2}}, \quad (13)$$

where the relation $R_{0} \approx R_{0}/\Gamma_{0}$ has been used.

Finally, the photospheric radius is constrained by the observational data. Suppose the (quasi-)thermal emission has a temperature $T_{obs}$ and a flux $F_{bb}$, we have $4 \pi \Gamma_{ph}^{2} \sigma T_{ph}^{4} = L_{bb} = 4 \pi D_{L}^{2} F_{bb}$, which can be simplified as

$$R_{ph} \approx \left[F_{bb}/\sigma T_{obs}^{4}\right]^{1/2} (1 + z)^{-2} \Gamma_{0} D_{L}$$

$$\approx 1.3 \times 10^{11} \text{ cm } F_{bb, \nu=4}^{1/2} \left[\frac{(1 + z) T_{obs}}{1 \text{ MeV}}\right]^{-2} \eta_{3} D_{L, 28}, \quad (14)$$

where $T_{obs} \approx \Gamma_{ph} T_{bb}^{4} / \left(1 + z\right)$ has been taken into account and $\sigma$ is the Stefan–Boltzmann constant.

Denoting the comoving thermal energy density and the number density of the outflow at $R_{ph}$ as $e_{ph}'$ and $n_{ph}'$, respectively, we have the (quasi-)thermal luminosity

$$L_{bb} \approx \frac{e_{ph}^{'2}}{4 \pi^{3} / \phi + 3 + n_{ph}' m_{p} c^{2} L}.$$  

Since $e_{ph}' = e_{ph}/D^{4}$ and $n_{ph}' = n_{0}'/D^{3}$ (Piran et al. 1993), we have

$$L_{bb} \approx \frac{e_{0}^{'} 4 \pi^{3} / \phi + D n_{0}' m_{p} c^{2}}{3 + D \eta_{3} \phi} L \approx \frac{3 (1 - f)}{4} L.$$  

With $Y_{bb} \equiv L_{bb}/L < 3/4$, the above relations $f = 1 - 4 Y_{bb}/3$ and $\eta_{3} = \Gamma_{ph} / [4 (1 - 4 Y_{bb}/3)]$. Combing Equations (9), (13), and (14), we have

$$R_{0} \approx 1.5 \times 10^{8} \text{ cm } F_{bb, \nu=4}^{1/2} Y_{bb}^{3/2} \left[\frac{(1 + z) T_{obs}}{1 \text{ MeV}}\right]^{-2} D_{L, 28},$$  

$$\Gamma_{ph} \approx 10^{3} \left(1 - Y_{bb}^{4/3} - 4/3\right)^{1/3} F_{bb, \nu=4}^{1/8} \left[\frac{(1 + z) T_{obs}}{1 \text{ MeV}}\right]^{-1/2} D_{L, 28}^{1/4}.$$  

(17)

If the baryon loading is so low that at $R_{ph}$ the outflow is still radiation dominated, most of the initial energy of the outflow will be lost via the thermal radiation and $Y_{bb} \sim 3/4$, for which $\Gamma_{ph}$ cannot be reliably inferred, reflecting the well-established fact that both the observed temperature and the thermal radiation luminosity are constant until most of the initial energy of the outflow has been transferred into the kinetic energy of the particles (Piran et al. 1993; Mészáros et al. 1993). For $Y_{bb} \ll 1$ (i.e., $R_{ph}$ is far above the photosphere radius $\sim R_{0}$), Equation (17) suggests $\Gamma_{ph} \propto Y_{bb}^{-1/4}$, in agreement with Pe’er et al. (2007).

The two equations above finally give

$$R_{0} \approx 1.5 \times 10^{8} \text{ cm } \Gamma_{ph,3}^{1/2} (Y_{bb}^{4/3} - 4/3) F_{bb, \nu=4}^{1/2} D_{L, 28}^{1/4}. \quad (18)$$

Therefore, if $\Gamma_{ph}$ and $Y_{bb}$ are obtainable with the observational data, Equation (18) provides an independent estimate of $R_{0}$ without the need to identify a thermal component in the prompt spectrum. This is helpful since the physical processes taking place at $R \ll R_{ph}$ may be able to shape the thermal spectrum so significantly that the identification of an ideal thermal component would be very difficult (e.g., Beloborodov 2010). In fact, for short GRBs, no reliable thermal component has been identified so far. The disadvantage of our approach is that one can only get the time-averaged constraint.

3.2. Application to GRB 090510

GRB 090510 was detected by the Fermi $\gamma$-ray telescope and Swift satellite simultaneously. Though the physical origin of the prompt GeV emission is not clear yet, the long lasting GeV afterglow emission is most likely the synchrotron radiation of the external shock (e.g., Gao et al. 2009; Ghirlanda et al. 2010; Corsi et al. 2010; De Pasquale et al. 2010; Kumar & Barniol Duran 2010). Supposing the prompt GeV and MeV emission are from the same region, the observation of GeV photons sets an upper limit on the optical depth for pair production and then suggests a bulk Lorentz factor of the emitting region $>1200$ (De Pasquale et al. 2010; Abdo et al. 2009). To interpret the GeV emission at $t > 2$ s as the forward shock emission, a higher initial bulk Lorentz factor of the outflow $\Gamma_{0} \gtrsim 1900$ is required (He et al. 2011; Ghirlanda et al. 2010; Corsi et al. 2010). Obviously $\Gamma_{ph}$ should be larger than $\Gamma_{in}$ (it is straightforward to show that the outflow shells with higher bulk Lorentz factor contribute more to the thermal emission). In the following estimate we take $\Gamma_{ph} \sim \Gamma_{in} \sim 2000$. The time-averaged spectrum of GRB 090510 in the time interval 0.5–1.0 s can be nicely fitted by a Band function plus a power-law component. The Band function component has an isotropic-equivalent energy $E_{\text{Band, iso}} \approx 7 \times 10^{52}$ erg while the very hard power-law component (with a spectrum $F_{\nu} \propto \nu^{-0.62}$ in the energy range 10 keV–10 GeV) has an isotropic-equivalent energy $E_{\text{PL, iso}} \approx 5 \times 10^{52}$ erg (Abdo et al. 2009). The afterglow modeling gives $E_{\text{iso}} \gtrsim 5 \times 10^{53}$ erg (Gao et al. 2009; He et al. 2011). Clearly, only the Band function component may be relevant to the quasi-thermal radiation of the outflow. Hence we have a (quasi)-thermal radiation efficiency $Y_{bb} \lesssim E_{\text{Band, iso}}/E_{\text{PL, iso}} + E_{\text{Band, iso}} + E_{\text{Band, iso}} \approx 0.1$ and the thermal radiation flux $L_{bb} \lesssim 6 \times 10^{-8}$ erg s$^{-1}$ cm$^{-2}$. Substituting these values into Equation (18), we have

$$R_{0} \lesssim 6.5 \times 10^{6} \text{ cm } \Gamma_{ph, 3.3}^{-4} Y_{bb, -1}^{1/2},$$  

(19)
which is about two or more orders of magnitude smaller than that reported in the literature (Pe'er et al. 2007; Ryde et al. 2010), suggesting that most energy has been deposited in a small cavity surrounding the nascent black hole. Since the collimation of the outflow in the double neutron star merger scenario should be mainly contributed by the interaction with accretion torus (Aloy et al. 2005), a small $R_0$ may be necessary to be consistent with the very small opening angle of the ejecta $\theta_j$ found in the afterglow modeling.

The GRB ejecta is mainly launched through the pole region of the rotating black hole. Clearly the outflow should be from a site above the horizon surface. Along the pole that means $R_0 > r_a \equiv 2G M_{\text{BH}}c^2/3 \approx 3 \text{ km} (M_{\text{BH}}/1 M_{\odot})$, regardless of the unknown spin of the black hole, where $r_a$ is the Schwarzschild radius and $G$ is the gravitational constant. In reality $R_0$ is larger than $r_a$ by a factor of a few, as found in numerical simulations (e.g., Popham et al. 1999; Liu et al. 2007; Zalamea & Beloborodov 2011). With Equation (19), for GRB 090510 we then have $M_{\text{BH}} < 22 M_\odot \Gamma_{\text{ph}}^{-1} \Gamma_{\text{bb}}^{-3} y_{1/2}$, i.e., it is likely a stellar black hole at the center, in agreement with the compact-object merger model.

For other short bursts, due to the lack of a robust estimate of $\Gamma_{\text{in}}$ and then $\Gamma_{\text{ph}}$, a reliable constraint on $R_0$ is not possible.

4. DISCUSSION AND CONCLUSION

The central engine of GRBs is widely believed to be a nascent stellar black hole surrounded by a hyper-accreting disk. With the current observational data it is, however, not easy to pin down the physical parameters, for example, the mass and the spin of a central black hole, the accretion rate (or alternatively the accretion-disk mass), and the initial radius of the outflow where it is launched ($R_0$). The main reason is that the central engine hides deeply behind the electromagnetic-radiation surface and it is hard to break the degeneracies between the parameters with very limited observational constraints. For some long bursts, in particular GRB 090902B, a reliable estimate of $R_0$ with the identified thermal spectrum component in the prompt spectrum is found. However, for short events the lack of a reliable identification of such a component renders a reasonable estimate difficult. In this work, we discuss whether we can estimate the disk mass in the specific scenario of a binary–neutron-star merger (see Section 2 for details). We also outline how to constrain $R_0$ without the identification of an ideal thermal spectrum component and then apply it to GRB 090510 (see Section 3 for details). Our main conclusions are the following.

1. Our semi-analytical estimate suggests that the nascent black hole formed in the binary–neutron-star merger scenario rotates very quickly and the spin parameter is insensitive to the initial mass ratio of the double neutron stars (see Section 2.2), in agreement with the results of recent numerical simulations (e.g., Kiuchi et al. 2009). Together with the finding that there is no significant mass ejection in the merger process (e.g., Rosswog et al. 1999), the mass of the formed black hole $M_{\text{BH}}$ as well as the spin parameter $a$ may be reasonably deduced. Consequently, a rough estimate of the accretion-disk mass is possible.

As found in Section 2.3, for about half of short GRBs in our sample, the disk mass is estimated to be $\sim 0.1 M_{\odot}$, in agreement with that found in the numerical simulation of the merger of binary–neutron-star. For some other bursts, such as GRB 051221A and GRB 050724, a massive disk ($\sim 30 M_{\odot}$) is needed. This puzzle can be solved if the outflows of these short GRBs were launched via the more efficient magnetic processes rather than the neutrino mechanism or, alternatively, if these short GRBs were from a neutron-star–black-hole merger (for which a massive disk is plausible). Since no significant divergence between the disk mass inferred from the observational data and that obtained in the numerical simulation has been found, we suggest that the compact object merger scenario for a good fraction of short bursts is viable and these events are promising gravitational wave radiation sources.

2. For GRB 090510, the initial radius of the outflow is estimated to be $R_0 \leq 6.5 \times 10^7 (\Gamma_{\text{ph}}/2000)^{-3}$ cm. Such a small $R_0$ suggests that the neutrino–antineutrino annihilation products were mainly deposited in a small cavity surrounding the nascent black hole, as expected. Moreover, the small $R_0$ imposes a constraint on the mass of the central engine $M_{\text{BH}} < 22 \Gamma_{\text{ph}}^{-1} (2000)^{-3} M_{\odot}$, consistent with the compact-object merger model.

With the future short-burst-associated gravitational wave data, the binary–neutron-star merger model will be directly tested. Moreover, the formation process of the disk, total mass, and the mass ratio of double neutron stars involved in the merger and the mass of the formed disk can be well constrained (Kiuchi et al. 2010; Kobayashi & Mészáros 2003). Consequently, the validity of our simple approach outlined in Section 2 will be unambiguously tested. Considering that the magnetic process is usually much more efficient than the neutron–antineutrino annihilation in extracting the energy, combining the derived $a$, $M_{\text{BH}}$, and $M_{\text{disk}}$ with $E_{\text{out}}$, the nature of the outflow-launching process (magnetic or neutrino–antineutrino annihilation) will be reliably probed, too. For example, if the $M_{\text{disk}}$ inferred from gravitational wave data is so small that it cannot produce the observed burst via a neutrino mechanism, the magnetic outflow-launching process will be favored.

Finally, we point out that for the possible short event GRB 100816A, the preliminary afterglow data reported in Oates et al. (2010) tentatively favor the free-wind medium model, in which the progenitor should be a massive star rather than a pair of compact objects. Careful analysis of available optical/ infrared afterglow data is thus encouraged. If our speculation is confirmed, the collapsar origin of GRB 100816A with an intrinsic duration $\sim 1.4$ s would be firmly established, in support of the hypothesis that collapsars can produce short events and the progenitors of short GRBs are diverse.

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REFERENCES

Abdo, A., Ackermann, M., Ajello, M., et al. 2009, Nature, 462, 331
Aloy, M. A., Janka, H. T., & Muller, E. 2005, A&A, 436, 273
Bardeen, J. M., Press, W. H., & Teukolsky, S. A. 1972, ApJ, 178, 347
Barthelmy, S. D., Chincarini, G., Burrows, D. N., et al. 2005, Nature, 438, 994
Beloborodov, A. M. 2010, MNRAS, 407, 1033
Berger, E., Fox, D. B., Price, P. A., et al. 2007, ApJ, 664, 1000
Berger, E., Price, P. A., Cenko, S. B., et al. 2005, Nature, 438, 988
Blandford, R. D., & Znajek, R. L. 1977, MNRAS, 179, 433
Burrows, D. N., Grupe, D., Capalbi, M., et al. 2006, ApJ, 653, 468
Caito, L., Amati, L., Bernardini, M. G., et al. 2010, A&A, 521, 80
Cenko, S. B., Berger, E., Nakar, E., et al. 2008, arXiv:0802.0874
Chen, W. X., & Beloborodov, A. M. 2007, ApJ, 657, 383
Corsi, A., Guetta, D., & Piro, L. 2010, ApJ, 720, 1008
Daigne, F., & Mochkovitch, R. 2002, MNRAS, 336, 1271
Deng, J. S., Tominaga, N., Mazzali, P. A., Maeda, K., Nomoto, K., et al. 2005, ApJ, 624, 898
De Pasquale, M., Schady, P., Kuin, N. P. M., et al. 2010, ApJ, 724, 861
Eichler, D., Livio, M., & Schramm, D. N. 1989, Nature, 340, 126
Fan, Y. Z., & Piran, T. 2006, MNRAS, 369, 197
Fan, Y. Z., & Wei, D. M. 2005, MNRAS, 364, L42
Fan, Y. Z., Zhang, B., Kobayashi, S., & Mészáros, P. 2005, ApJ, 628, 867
Fox, D. B., Frail, D. A., Price, P. A., et al. 2005, Nature, 437, 845
Gao, W. H., Mao, J. R., Xu, D., & Fan, Y. Z. 2009, ApJ, 706, L33
Ghirlanda, G., Ghisellini, G., & Nava, L. 2007, MNRAS, 382, L72
Haensel, P., Paczyński, B., & Amderstdamski, P. 1991, ApJ, 375, 209
He, H. N., Wu, X. F., Toma, K., Wang, X. Y., & Mészáros, P. 2011, ApJ, 733, 22
Hjorth, J., Watson, D., Fynbo, J. P. U., et al. 2005, ApJ, 637, 851
Kiziltan, B., Kottas, A., & Thorsett, S. E. 2011, ApJ, submitted (arXiv:1011.2491)
Kobayashi, S., & Mészáros, P. 2003, ApJ, 589, 861
Kumar, P. 2000, ApJ, 538, L125
Kumar, P., & Barniol Duran, R. 2010, MNRAS, 409, 226
Lazzati, D., Morsony, B. J., & Begelman, M. C. 2009, ApJ, 700, L47
Lee, W. H., & Ramirez-Ruiz, E. 2007, New J. Phys., 9, 17
Lee, W. H., Wijers, R. A. M. J., & Brown, G. E. 2000, Phys. Rep., 325, 83
Liu, T., Gu, W. M., Xue, L., & Lu, J. F. 2007, ApJ, 661, 1025
Macfadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262
Mészáros, P. 2006, Rep. Prog. Phys., 69, 2259
Mészáros, P., Laguna, P., & Rees, M. J. 1999, ApJ, 415, 181
Nakar, E. 2007, Phys. Rep., 442, 166
Narayan, R., Piran, T., & Kumar, P. 2001, ApJ, 557, 949
Nicuesa Guelbenzu, A., Klose, S., Rossi, A., et al. 2011, A&A, 531, L6
Oates, S. R., Markwardt, C. B., Norris, J., Evans, P. A., & Littlejohns, O. 2010, GCN Rep., 300
Paczynski, B. 1990, ApJ, 363, 218
Panaitescu, A. 2006, MNRAS, 367, L42
Panaitescu, A. 2011, MNRAS, 414, 1379
Pe'er, A., Ryde, F., Wijers, R. A. M. J., Mészáros, P., & Rees, M. J. 2007, ApJ, 664, L1
Piran, T. 2004, Rev. Mod. Phys., 76, 1143
Piran, T., Shemi, A., & Narayan, R. 1993, MNRAS, 263, 861
Popham, R., Woosley, S. E., & Fryer, C. 1999, ApJ, 518, 356
Racusin, J. L., Karpov, S. V., Sokolowski, M., et al. 2008, Nature, 455, 183
Rosswog, S., Liebendörfer, M., Thielemann, F.-K., et al. 1999, A&A, 341, 499
Rosswog, S., Ramirez-ruiz, E., & Davies, M. B. 2003, MNRAS, 345, 1077
Ryde, F., Axelsson, M., Zhang, B. B., et al. 2010, ApJ, 709, L172
Shemi, A., & Piran, T. 1990, ApJ, 365, L55
Soderberg, A., Berger, E., Kasliwal, M., et al. 2006, ApJ, 650, 261
Thompson, C., Mészáros, P., & Rees, M. J. 2007, ApJ, 666, 1012
Usos, V. V. 1992, Nature, 357, 472
Virgili, F. J., Zhang, B., O'Brien, P., & Troja, E. 2011, ApJ, 727, 109
Xin, L. P., Liang, E.-W., Wei, J.-Y., et al. 2011, MNRAS, 410, 27
Zalamea, L., & Beloborodov, A. M. 2011, MNRAS, 412, 2302
Zhang, B. 2007, Chin. J. Astron. Astrophys., 7, 1
Zhang, B., Fan, Y. Z., Dyks, J., et al. 2006, ApJ, 642, 354
Zhang, B., & Mészáros, P. 2004, Int. J. Mod. Phys. A, 19, 2385
Zhang, B., Zhang, B.-B., Virgili, F. J., et al. 2009, ApJ, 703, 1696
Zhang, B. B., Zhang, B., Liang, E.-W., et al. 2011, ApJ, 730, 141
Zhang, W., Woosley, S. E., & MacFadyen, A. I. 2003, ApJ, 586, 365