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Origins of short gamma-ray bursts deduced from offsets in their host galaxies revisited *

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Abstract The spatial distribution of short Gamma-ray bursts (GRBs) in their host galaxies provides us with an opportunity to investigate their origins. Based on the currently observed distribution of short GRBs relative to their host galaxies, we obtain the fraction of the component that traces the mergers of binary compact objects and the one that traces star formation rate (such as massive stars) in early- and late-type host galaxies. From the analysis of projected offset distribution and only based on population synthesis and massive star models, we find that the fraction of massive stars is $0.37^{+0.42}_{-0.37}$ with an error at the 1σ level for a sample with 22 short GRBs in the literature. From these results, it is hard to accept that the origin of short GRBs with observed statistics is well described by current models using only the offset distribution. The uncertainties in observational localizations of short GRBs also strongly affect the resulting fraction.

Key words: gamma-rays: bursts — cosmology: galaxy — methods: statistical

1 INTRODUCTION

After the first discovery of redshift and the host galaxy associated with short Gamma-ray bursts (GRBs with duration $T_{90} < 2$s) GRB 050509B (Gehrels et al. 2005; Bloom et al. 2006), observations of the host galaxies of short GRBs (Berger et al. 2005; Hjorth et al. 2005; Fox et al. 2005; Covino et al. 2006) provide us with an opportunity to study the population of their host galaxies and the nature of their progenitors (e.g. Prochaska et al. 2006; Savaglio et al. 2009; Zhang et al. 2009).

The lower explosion energies and star formation rates, lack of an associated supernova (SN) and the locations in their host galaxies suggest that the mergers of binary compact objects are promising candidates for the progenitor of short GRBs (see Berger et al. 2005; Fox et al. 2005; Belczynski et al. 2006). Based on these observations, binary compact objects were studied as possible short GRB progenitors by the population synthesis (PS) methods (for example, Lipunov et al. 1997; Bloom et al.

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1999; Fryer et al. 1999; Belczynski et al. 2002, 2007). By this method, Belczynski et al. (2006) presented binary compact object formation rates, merger rates, locations, and afterglow properties for different initial conditions. Some predictions from the PS analysis agreed well with the existing observational constraints, such as the redshift and luminosity distributions of short GRBs (e.g., Guetta & Piran 2006; Nakar et al. 2006; O'Shaughnessy et al. 2008). By comparing the spatial offsets from their host galaxies and X-ray isotropic energies of short GRBs with extended emission, Troja et al. (2008) found that the properties of short GRBs without extended emissions are consistent with neutron star-neutron star (NS–NS) binary mergers occurring in low-density environments and different from those with extended emissions. The luminosity, star formation rates, and metallicities of short GRB host galaxies before Feb. 2008 were measured by Berger (2009). Based on their optical spectroscopy, the binary models that predict a wide range of merger timescales are favored, based on the analysis of their observed data. With analysis of Hubble Space Telescope (HST) observations for 10 short GRB host galaxies, NS–NS binaries are also proposed by Fong et al. (2010) as a progenitor population for short GRBs, based on the light distribution traced in their host galaxies.

However, unlike long GRBs (GRBs with duration $T_{90} > 2$s) that are exclusively linked with star-forming galaxies (e.g., Bloom et al. 1998; Fruchter et al. 1999; Djorgovski et al. 2003; Christensen et al. 2004; Castro Cerón et al. 2006; Savaglio et al. 2009), short GRBs reside in all types of galaxies (Berger et al. 2005, 2007; Fox et al. 2005; Gehrels et al. 2005; Berger 2009). Berger (2009) investigated properties of the host galaxy for all short GRBs identified by the Swift X-Ray Telescope and found that the majority of short GRBs appear to occur in star-forming galaxies. This fact suggests that some short GRBs may come from another origin that traces the star formation rate. In fact, Zhang et al. (2009) showed that not only long GRBs, but also a good fraction of short GRBs could originate from the deaths of massive stars (called collapsars). Moreover, Virgili et al. (2011) tried to reproduce the luminosity-redshift distribution and the peak flux distribution of short GRBs, and they concluded that a significant fraction of collapsars can be attributed as one origin of short GRBs. Based on the appearance of a plateau in the distribution of duration for prompt GRB emission, Bromberg et al. (2012) also suggested that most of the soft short GRBs observed by BATSE are likely to originate from a collapsar.

In this study, we would like to consider the origin of short GRBs from the point of view of the spatial distribution of short GRBs in their host galaxies. It is well known that the distribution of binary compact objects could be wider than that of massive stars, because binary compact objects can have kick velocities (e.g. Wang et al. 2006; Cui et al. 2007, and references therein) and it takes a long time for them to merge by emitting gravitational waves. We try to obtain the fraction of the component that traces the star formation rate (such as a single massive star collapse, which we call "Colp" in this study) and the component of binary compact objects merging (which we call "Merg" in this study) as the progenitor of short GRBs. We obtain them by reproducing the observed distribution in their host galaxies with theoretical models. We use the results of the PS calculations that give the distribution of Merg in late- and early-type host galaxies (Belczynski et al. 2006) as well as the distribution of Colp in their host galaxies that is deduced from observations of the distribution of stars (Bloom et al. 2002). Many previous studies claimed that short GRBs are consistent with a progenitor population of NS-NS binaries using very small samples, for example only 10 bursts used in Fong et al's work (2010), and only 17 cases including those with extended emissions in the work of Troja et al. (2008). In this work, we collect 22 short GRBs from previous papers and study their origins from the offsets in host galaxies. The fraction of the massive star component as the origin of short GRBs is found to be $0.37^{+0.42}_{-0.37}$ with an error at the 1σ level. Thus it is hard to identify the origin of short GRBs with observed statistics by only studying the offset distribution. The data and the method are presented in Section 2. In Section 3, we give the best fitting results for different types of host galaxies. In Sections 4 and 5, the discussion and conclusions are respectively presented. Throughout the paper, a concordance cosmology with parameters $H_0 = 71$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.30$ and $\Omega_\Lambda = 0.70$ is adopted.

2 DATA AND METHOD

We investigate the fraction of Colp components and that of late-type host galaxies in this study by fitting the observed spatial distribution of short GRBs in their host galaxies. We use the fraction of Colp components and that of late-type host galaxies as fitting parameters. Thus the most favored fractions for them can be obtained from the fitting (least-square method). The fraction of late-type host galaxies can be compared with the observed fraction.

2.1 Observational Data

In this study, we investigate the distribution of short GRBs in two ways. One is the offsets, i.e. the distances of short GRBs from the center of their host galaxies. Strictly speaking, the distance we can measure from observation is only the projected distance in the direction perpendicular to the line of sight. Thus in this work we apply a capital letter "R" with a subscript "projected," $R_{\rm projected}$, to denote this distance and that of the compact star deduced from the kick and binary evolution model as described in Section 2.2. The other is the same as the above offsets, but normalized by the radii of their host galaxies, which are the normalized offsets, $R_{\rm projected}/R_{\rm e}$.

Our sample includes 22 short GRBs. This sample represents all possible data for short GRBs from previous work prior to 2009 June with no other selection criteria except that of short GRBs with observed data of offsets. The selection effects in the sample (e.g., naked bursts or dust attenuation) have not been considered here. For a burst with an unknown host, like GRB 070809 whose host has not been found within a deep limit, the nearest galaxy is taken as its host galaxy. These samples include the bursts in the original classification (Kouveliotou et al. 1993) and the ones that not only have a spike of short duration but also extended emission (EE) as defined by Norris & Bonnell (2006). In our sample, nine bursts have host galaxies with a known radius (for example Fong et al. 2010). Therefore, we study 22 offsets and nine normalized offsets for short GRBs. The properties of the bursts and their host galaxies in our sample are listed in Table 1. Columns denote the GRB name, the duration (T_{90}), the redshift (z), the offset ($R_{\rm projected}$), the normalized offset ($R_{\rm projected}/R_{\rm e}$), the type of host galaxy and the references for these data. Most of the values of T_{90} are taken from the work of Berger (2009) except for GRB 051227, GRB 060505 and GRB 060614 from Troja et al. (2008) and GRB 090426 and GRB 090510 from the Swift GRB table[1]. We only include three bursts with the redshift limits of the putative host galaxies: GRB 051210 (z<1.4), GRB 060121 (z>1.7) and GRB 060313 (z<1.1) from the work of Troja et al. (2008) and one burst with the offset limit (<0.6″) for GRB 070429B (Cenko et al. 2008). Since the host galaxy of GRB 070809 has not been found to a deep limit, the nearest galaxy is taken as its host galaxy (Fong et al. 2010). The normalized offset of GRB 060502B is deduced from the outer component with a best fit Sérsic profile since Bloom et al. (2007) found that a significantly better fit was obtained with a model of the sum of two general Sérsic profiles. For the morphology of the host, elliptical (E) or spiral (S) types were reported by O'Shaughnessy et al. (2008) and star formation (SF) or low star formation (LSF) were given by Zhang et al. (2009) and references therein. Others are the host galaxies without observation reports ("0") or too faint ("Faint") to determine their morphology.

From Table 1, we can see that the short GRB host galaxies include not only early-type but also late-type cases. The observed number ratio of late- to early-type host galaxies is 5:1 (Berger 2009; Fong et al. 2010).

2.2 Method of Analysis

Belczynski et al. (2006) developed an updated PS code to calculate the merger locations of binary compact objects in early- and late-type host galaxies: elliptical (simply defined as "Ellip" in this

[1] *http://heasarc.gsfc.nasa.gov/docs/swift/archive/*

Table 1 Properties of the Short GRB Samples

GRB	T_{90} (s)	z	$R_{\rm projected}$ (kpc)	$R_{\rm projected}/R_{\rm e}$	Type	Ref
050509B	0.04	0.225	54.3 (12.1)	2.59 ± 0.58	E	[1, 2, 9]
050709*	0.07	0.161	3.70 (0.03)	2.04 ± 0.02	S	[1, 2, 9]
050724*	3	0.258	2.69 (0.07)	1.28 ± 0.05	E	[1, 2, 9]
051210	1.27	<1.4	30.3 (19.5)	5.66 ± 3.65	0	[1, 2]
051221A	1.4	0.546	2.05 (0.19)	0.88 ± 0.08	S	[1, 2, 9]
060121	1.97	>1.7	0.96 (0.37)	0.18 ± 0.07	Faint	[1, 2]
060313	0.7	<1.1	2.57 (0.53)	1.66 ± 0.32	Faint	[1, 2]
060502B	0.09	0.287	70.0 (16.0)	6.66 ± 1.52	E	[2, 8, 9]
060505	4	0.089	7.45 (0.53)	...	S	[2, 9]
060614*	103	0.125	$\sim$1.10	...	LSF	[2, 10]
060801	0.5	1.131	19.7 (19.8)	...	0	[2]
061006*	0.42	0.438	1.37 (0.27)	0.41 ± 0.09	LSF	[1, 2, 10]
061201	0.8	0.111	33.9 (0.40)	...	SF	[2, 10]
061210*	0.19	0.41	10.7 (9.70)	...	SF	[2, 10]
061217	0.21	0.827	55.0 (28.0)	...	SF	[2, 10]
070429B	0.5	0.9023	$\sim$16.99	...	Faint	[3, 10]
070714B*	3	0.9225	$\sim$11.64	...	S	[4, 10]
070724A	0.4	0.457	4.80 (0.10)	...	SF	[2, 10]
070809	1.3	0.2187	$\sim$20.0	...	S	[1, 10]
071227	1.8	0.381	15.0 (2.20)	...	S	[5, 10]
090426	1.2	2.609	$\sim$0.80	...	SF	[6, 10]
090510	0.3	0.903	$\sim$5.50	...	SF	[7, 10]

* Burst with extended emission. References: [1] Fong et al. (2010); [2] Troja et al. (2008); [3] Cenko et al. (2008); [4] Graham et al. (2009); [5] D'Avanzo et al. (2009); [6] Levesque et al. (2010); [7] Rau et al. (2009); [8] Bloom et al. (2007); [9] O'Shaughnessy et al. (2008); [10] Zhang et al. (2009).

work), spiral (defined as "Sp"), and starburst (defined as "SB") galaxies. When they calculated the motions of binary objects, they took into account the gravitational potential of their host galaxies. In their study, the mass density of each host galaxy is assumed to be constant, and they modeled gravitational potentials for each type of galaxy with a large and a small mass. The bulge mass and radius for a large elliptical galaxy are taken as $5 \times 10^{11}\ M_\odot$ and 5 kpc, respectively. The total mass of the bulge and disk M and the disk radius for a large spiral and a starburst galaxy $R_{\rm e}$ are assumed to be $M = 10^{11}\ M_\odot$ and $R_{\rm e} = 12$kpc respectively. The small galaxies are downscaled by a factor of 10^3 in mass and of 10 in size (constant density). The offsets of NS-NS (defined as "NN" hereafter) and NS-BH (neutron star-black hole, "NB") merger locations were given by Belczynski et al. (2006) for different types of host galaxies. Although Belczynski et al. (2002) presented all types of binaries, in this work we only consider two types: NN and NB in three kinds of host galaxies: Ellip, Sp, and SB as mentioned by Belczynski et al. (2006). The offset distributions for the bursts from NN or NB here are deduced from the PS method developed in the work of Belczynski et al. (2006). The mass of the host galaxy we consider is between the large and small galaxies in their work. The number ratio of the NN to NB merger components has been calculated by Belczynski et al. (2002). They evolved $N_{\rm tot} = 3 \times 10^7$ initial binaries in a spiral galaxy and found that 52 599 NNs and 8 105 NBs were formed, which implies that the ratio of NN to NB is 6.49. They also found that the evolutionary time (the time required for the initial progenitor binary on ZAMS to form two stellar remnants) is typically on the order of a few to several tens of Myr, and their distributions are similar among different types of galaxies. Thus it is reasonable to assume this ratio to be the same for every galaxy since the structure of the star cluster and the evolution of a binary in them are similar in every type of galaxy. Therefore, we fix this parameter to be 6.49 for each type of galaxy.

As mentioned by Smith et al. (2005) and Belczynski et al. (2006), most elliptical galaxies are formed before $z \sim 2$ and there are no star-forming regions, but late-type galaxies have ongoing and active star-forming regions. This suggests that in the spirals and starburst galaxies, short GRBs may not only originate from Merg but also from Colp. Thus we consider Colp in this study. As for the model of Colp, Bloom et al. (2002) proposed a model of the number density of massive-star forming regions in a disk galaxy to be

$$N(r)dr \propto r\exp(-1.67r)dr, \tag{1}$$

where $r = R/R_{\rm half}$ and the half-light radius of galaxy $R_{\rm half} = 1.67 \times R_{\rm e}$ ($R_{\rm e}$ is the disk scale length). Although the distribution of massive star forming regions in a galaxy has large uncertainty as mentioned in their work, this distribution function is frequently used in the analysis of offset/normalized offset of GRBs. Thus we use this distribution as a template in this study.

In summary, in our study, we only consider the distributions of NN and NB (that is, Merg) for early-type host galaxies, but we consider distributions of Merg and Colp for late-type host galaxies. The procedure for analysis includes the following steps:

(1) The theoretical offset/normalized offset curves for each type of host galaxy are derived with the help of the PS model and the model of number density for massive-star forming regions. The curves of the Merg component have been calculated for the cases of large and small mass galaxies by the PS model (Belczynski et al. 2006). We linearly interpolate[2] one hundred curves in a horizontal direction according to the mass of the host galaxy between two curves of large and small galaxies when we derive the distribution of the Merg component. We use the number density of massive-star forming regions as the distribution of the Colp component (see Eq. (1)). The radius and mass for the large galaxies are $R_{\rm e} = 12$ kpc and $M = 10^{11}\,M_\odot$ and those for the small galaxies are $R_{\rm e} = 1.2$ kpc and $M = 10^{8}\,M_\odot$, respectively. We note that the interpolation scale with M is equal to that with $R_{\rm e}$ since the mass of the host galaxies for each progenitor component (Colp or Merg) can be represented by one typical of a host galaxy.

(2) A Matlab curve fitting code developed by the MathWorks company[3] is used to fit the observed distribution by three kinds of independent parameters: the fraction of the Colp component, the fraction of late-type host galaxies, and the mass of host galaxies, which is degenerate with the cumulative probability distribution function of offset originating from the Colp or Merg component in different types of host galaxies. The range of fractions is in [0, 1] and the cycle step size is selected as 0.01 in our fitting process. Since the host galaxies for short GRBs include all types, we combine two/three distributions of offset/normalized offset for different types of host galaxy with proper weight. When we consider the contribution from the late-type galaxies, we add the Colp component with proper weight. The proper weights are determined by the least-square method to reproduce the observed offset/normalized offset.

(3) The statistical method is applied to test all the fittings and gives the test results.

We give an example as follows. In the Ellip-SB-Sp[4] model, there are five components: two Colp and two Merg in late-type host galaxies (Sp-SB), and one Merg in early-type host galaxy (Ellip). We introduce the parameters f_1 and f_2 as the fractions of Colp in SB and Sp galaxies respectively, and g_1 and g_2 as the fractions of SB and Sp galaxies in all types of galaxies. Then the model of offset/normalized offset distributions is

$$\begin{aligned} P_{\rm fit} \;=\; & [P_{\rm Colp,1} \times f_1 + P_{\rm Merg,1} \times (1 - f_1)] \times g_1 \\ & + [P_{\rm Colp,2} \times f_2 + P_{\rm Merg,2} \times (1 - f_2)] \times g_2 \\ & + P_{\rm Merg,3} \times (1 - g_1 - g_2), \end{aligned} \tag{2}$$

[2] The first and tenth interpolations in the spiral galaxy model agree well with the models of Belczynski et al. (2002) with masses 1.5×10^9 and $1.5\times10^{10}\ M_\odot$, respectively. Thus the interpolated models in our work are an acceptable approximation.

[3] *http://www.mathworks.com/*

[4] The model name in our work is defined by the type of the host galaxy, i.e. Ellip-SB-Sp, Ellip-SB, and Ellip-Sp denoting which type of host galaxy is considered in the model.

where $P_{\rm Colp,1}$ and $P_{\rm Merg,1}$ are the cumulative probability distribution function of the offsets for Colp and Merg in an SB galaxy. $P_{\rm Colp,2}$ and $P_{\rm Merg,2}$ are those in an Sp galaxy, and $P_{\rm Merg,3}$ is that of Merg in an Ellip galaxy. The fractions of Colp and of the late-type host galaxy are $f_{\rm Colp} = f_1 \times g_1 + f_2 \times g_2$ and $f_{\rm late-type} = g_1 + g_2$, respectively. That is to say, $f_{\rm Colp}$ and $f_{\rm late-type}$ can be taken as functions of f_1, f_2, g_1, and g_2, i.e. $f_{\rm Colp}(f_1, f_2, g_1, g_2)$ and $f_{\rm late-type}(g_1, g_2)$. For the Ellip-Sp model, $g_1 = f_1 = 0$ while for the Ellip-SB model, $g_2 = f_2 = 0$. The most favored offset/normalized offset curves are obtained by the least-square method. In addition, the proper weights f_1, f_2, g_1 and g_2 and the proper theoretical curves $P_{\rm Colp,1}$, $P_{\rm Merg,1}$, $P_{\rm Colp,2}$, $P_{\rm Merg,2}$ and $P_{\rm Merg,3}$ are obtained as well by the best fitting of the observed offset/normalized offset.

3 RESULTS

The results for the best fitting offset distribution are shown in Figure 1. The types of host galaxies are shown at the top of the panels. The horizontal axis represents the projected distance from the center of the host galaxy, while the vertical axis represents the cumulative fraction of offsets with $R_{\rm projected} < R$. Red step lines represent the offset distribution of the observed sample including 22 bursts. The blue dashed curves are the best fitting curves. Green and blue solid curves are respectively $P_{\rm Colp}$ and $P_{\rm Merg}$ with the best fitting parameters. The deep/bright gray regions in the left panels represent 1σ/3σ error ranges. In the right panels, all of the possible ranges are shown for the Colp and Merg components. The Colp components are the same for the late-type host galaxies with the same assumed mass. From Figure 1, we can find that the observed data are all in the 3σ error ranges of best fitting results.

Table 2 presents the following values: $\chi^2_{\rm min}$, "reduced" masses of early- and late-type galaxies, the fraction of the Colp component in the late-type galaxy and its error, the fraction of the late-type host galaxy and its error, and the statistical results for the Kolmogorov-Smirnov test (K-S test) for the best fitting curve. Here, the "reduced" masses of host galaxies are expressed as $M_{\rm Merg,3}$, $M_{\rm Colp,1} \times f_1 + M_{\rm Merg,1} \times (1 - f_1)$ and $M_{\rm Colp,2} \times f_2 + M_{\rm Merg,2} \times (1 - f_2)$ for elliptical, starburst and spiral galaxies, respectively. Also, the "reduced" mass expressions of the early- and late-type galaxies are defined as $M_{\rm early} = M_{\rm Merg,3}$ and $M_{\rm late} = [M_{\rm Colp,1} \times f_1 + M_{\rm Merg,1} \times (1 - f_1)] \times g_1 + [M_{\rm Colp,2} \times f_2 + M_{\rm Merg,2} \times (1 - f_2)] \times g_2$. Here $M_{\rm Colp,1,2}$ are the most favored mass of SB and Sp galaxies as a host galaxy of Colp respectively, while $M_{\rm Merg,1,2,3}$ are that of SB, Sp, and Ellip as a host galaxy of Merg. In the analysis of deciding the best-fit, we choose one distribution of $P_{\rm Merg,\it i}$ (i=1, 2, 3) and $P_{\rm Colp,\it j}$ (j=1, 2) for each type of galaxy, which gives $M_{\rm Merg,\it i}$ and $M_{\rm Colp,\it j}$

Table 2 Values of $\chi^2_{\rm min}$, the "reduced" mass of the host galaxies, the fraction of the late-type host galaxies with 1σ error, the fraction of Colp with 1σ error in parentheses, and the test results for the best fit of offset and normalized offset distributions.

Sample		Offset Analysis			Normalized Offset Analysis		
Early-type galaxy		Ellip			Ellip		
Late-type galaxy		SB	Sp	SB-SP	SB	Sp	SB-SP
$\chi^2_{\rm min}$		0.20	0.24	0.19	0.28	0.37	0.28
$M_{\rm early}(10^{10} M_\odot)$		6.97	42.0	12.4	50	50	50
$M_{\rm late}(10^{10} M_\odot)$		6.04	4.86	5.55	10	0.21	10
Fraction	Late-type	$0.83^{+0.17}_{-0.83}$	$0.74^{+0.26}_{-0.65}$	$0.82^{+0.18}_{-0.82}$	$0.31^{+0.42}_{-0.31}$	0.24 ± 0.21	$0.30^{+0.32}_{-0.30}$
	Colp component	$0.32^{+0.37}_{-0.32}$	0.48±0.39	$0.37^{+0.42}_{-0.37}$	$0.17^{+0.29}_{-0.17}$	$0.24^{+0.32}_{-0.24}$	$0.19^{+0.26}_{-0.19}$
K-S statistic		0.10	0.11	0.12	0.20	0.20	0.21

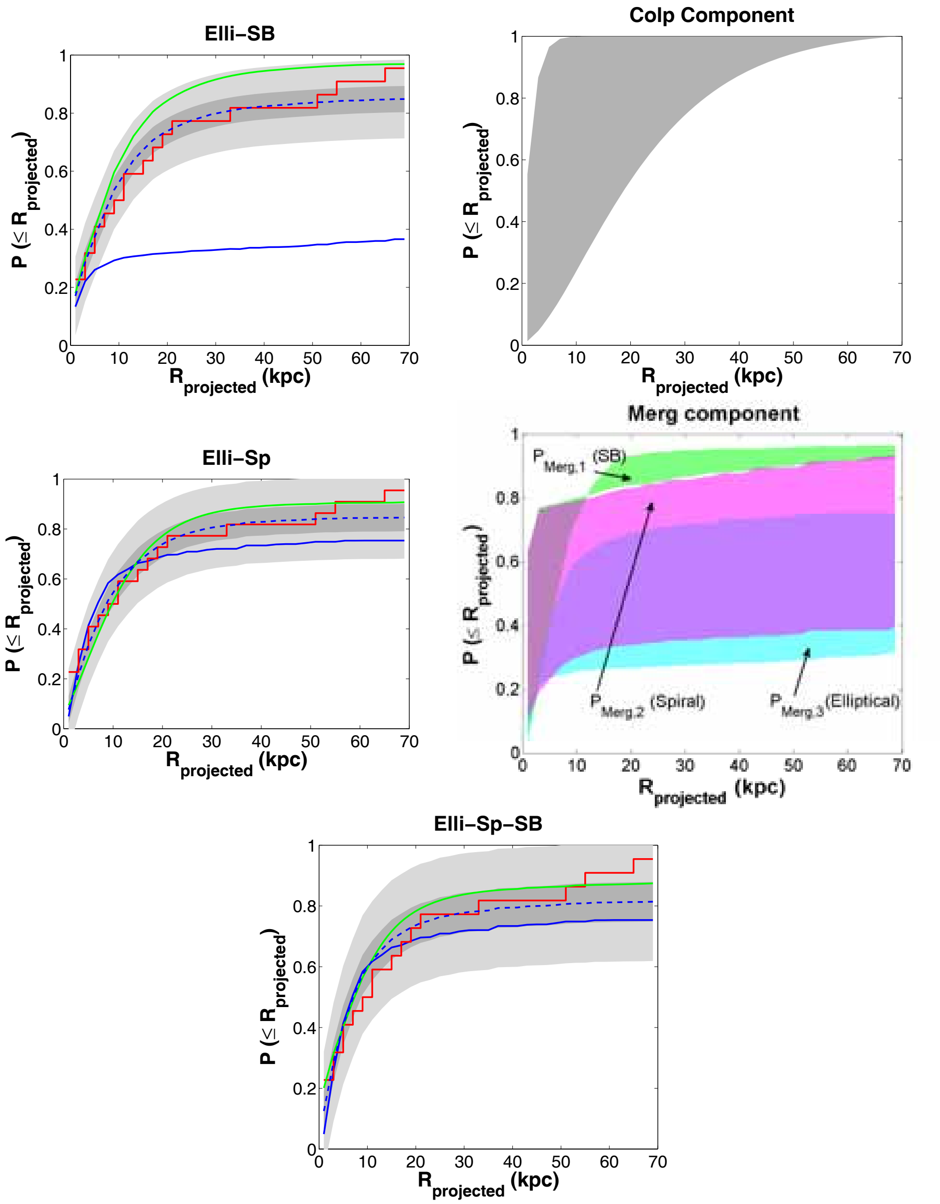

Fig. 1 Results for the cumulative offset distribution. The horizontal axis represents the projected distance from the center of the host galaxy, while the vertical axis represents the cumulative fraction of offsets with $R < R_{\rm projected}$. *Left panels*: the top labels represent what kind of host galaxies are considered. Red step lines represent the 22 observed samples. The blue dashed curve is the best fitting curve. Green and blue solid curves are $P_{\rm Colp}$ and $P_{\rm Merg}$ with the best fitting parameters respectively. The deep/bright gray regions in the left panels represent $1\sigma/3\sigma$ error ranges for the best fit. *Right panels*: The regions in which we linearly interpolate 100 curves in the horizontal direction between the results of the PS model and the model of the number density of massive-star forming regions (see Sect. 2.2). The Colp components are the same for the late-type host galaxies with the same assumed mass. The Merg components predicted in starburst, spiral and elliptical host galaxies are presented by $P_{\rm Merg,1}$, $P_{\rm Merg,2}$, and $P_{\rm Merg,3}$ respectively.

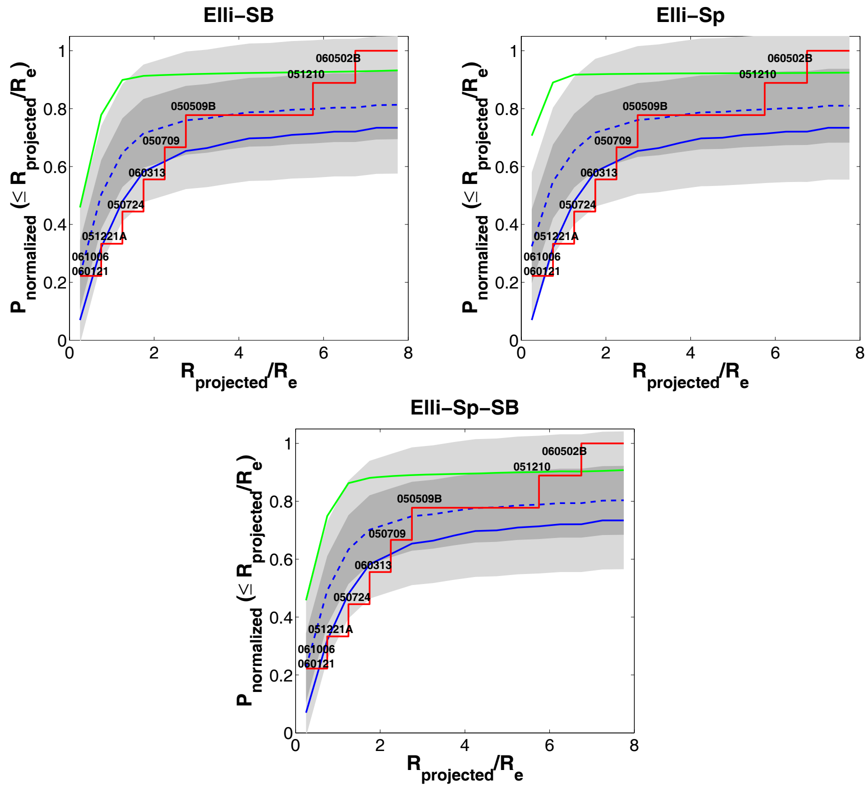

Fig. 2 Same as left panel of Fig. 1, but for results of the normalized offset. The red line is the observed data. The GRB identifications are noted along the red line. The deep/bright gray regions represent $1\sigma/2\sigma$ error ranges for the best fitting.

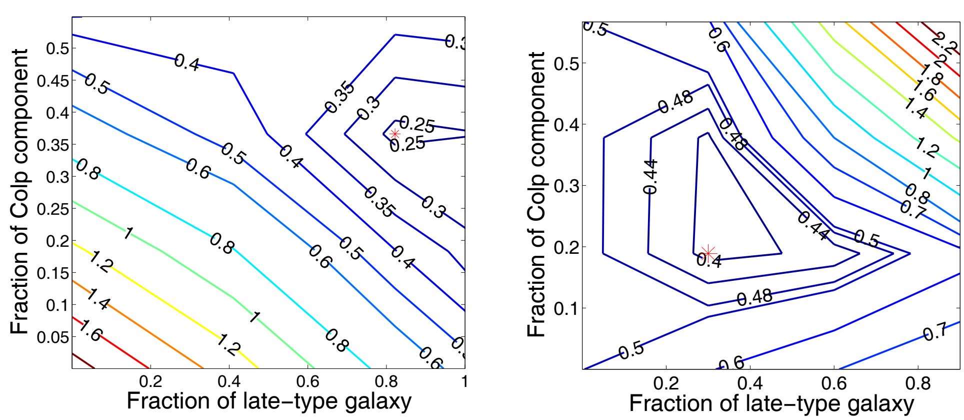

Fig. 3 Contour plot of χ^2 in the plane of the fractions of Colp and late-type galaxies in the Ellip-SB-Sp model. The minimum, $\chi^2_{\rm min}$, is denoted by the red star. *Left panel*: the offset analysis. *Right panel*: the normalized offset analysis.

that correspond to the mass of galaxies that have the most favored offset distributions $P_{\rm Merg,\it i}$ and $P_{\rm Colp,\it j}$ respectively.

For example, the best fitting parameters for the Ellip-SB-Sp model are

$$f_1 = 0.34^{+0.49}_{-0.34}, \qquad f_2 = 0.61^{+0.79}_{-0.61},$$
$$g_1 = 0.49^{+0.41}_{-0.21}, \qquad g_2 = 0.33^{+0.29}_{-0.30},$$
$$M_{\rm Colp,1} = 0.51 \times 10^{10} M_\odot, \qquad M_{\rm Merg,1} = 1.20 \times 10^{10} M_\odot,$$
$$M_{\rm Colp,2} = 0.13 \times 10^{10} M_\odot, \qquad M_{\rm Merg,2} = 39.26 \times 10^{10} M_\odot,$$

and

$$M_{\rm Merg,3} = 12.40 \times 10^{10} M_\odot.$$

Then we can obtain the parameters of this model as shown in Table 2. Please note that Ellip-SB and Ellip-Sp are sub-groups of Ellip-SB-Sp, rather than different models of Ellip-SB-Sp. Hence similarly good agreements in the three models just mean that Ellip-SB-Sp agrees with observations in a wide range of g_1 and g_2. We present the results for the three models in the following discussion. We mainly discuss the Elli-SB-Sp model in our work for the purpose of demonstration. We will analyze the difference between these models in future work.

From Table 2, we find that the fraction of the Colp component is $0.37^{+0.42}_{-0.37}$ with an error at the 1σ level for the offset analysis. The ratio of SB to Sp for the Elli-SB-Sp model is found to be 3/2. We also find that the fraction (~ 0.82) of the late-type host galaxy in the Ellip-SB-Sp model is consistent with the observed number ratio (5:1) from Table 2 (Fong et al. 2010).

The results of the best fitting normalized offset distribution are shown in Figure 2 and Table 2. The fractions of the late-type host galaxies and those of Colp are also presented there. The GRB identifications are noted along the solid step lines in Figure 2. We can see that the observed data are all in the 2σ error ranges of the best fitting results. We also find that the fractions of Colp for all types of host galaxies (Ellip-Sp-SB) and late-type host galaxies are $0.19^{+0.26}_{-0.19}$ and $0.30^{+0.32}_{-0.30}$, respectively. The $\chi^2_{\rm min}$ and the errors of the fractions for the normalized offset are larger than those of the offset analysis. This is likely to be because the size of the normalized offset sample is smaller. Thus, the results for the offset analysis would be more reliable than those for the normalized offset in this work.

Figure 3 shows the contour plots of χ^2 in the plane of the fractions of Colp and late-type galaxies deduced in the fitting process for the offset (left panel) and normalized offset (right panel) analysis. The Ellip-SB-Sp model is adopted and the minimum, $\chi^2_{\rm min}$, is denoted by the red star. For this figure, we would like to explain the procedure using the example of $f_{\rm late-type} = g_1 + g_2$ and $f_{\rm Colp} = f_1 \times g_1 + f_2 \times g_2$ as follows.

(A) $f_{\rm late-type}$ and $f_{\rm Colp}$ can be obtained as a function of f_1, f_2, g_1 and g_2 once f_1, f_2, g_1 and g_2 are fixed, i.e., $f_{\rm late-type}(g_1, g_2)$ and $f_{\rm Colp}(f_1, f_2, g_1, g_2)$ are determined.
(B) Using $f_{\rm late-type}(g_1, g_2)$ and $f_{\rm Colp}(f_1, f_2, g_1, g_2)$, χ^2 is regarded as a function of $f_{\rm late-type}$ and $f_{\rm Colp}$, such as $\chi^2(f_{\rm Colp}, f_{\rm late-type}, f_1, f_2, g_1, g_2)$.
(C) When degenerate parameter sets are found, where different parameter sets of (f_1, f_2, g_1, g_2) give the same values of ($f_{\rm late-type}$, $f_{\rm Colp}$), the minimum χ^2 among them is chosen: $\chi^2(f_{\rm Colp}, f_{\rm late-type})$ = min($\chi^2(f_{\rm Colp}, f_{\rm late-type}, f_1, f_2, g_1, g_2)$).
(D) A contour of χ^2 in ($f_{\rm Colp}$, $f_{\rm late-type}$) space can be drawn, like Figure 3.

4 DISCUSSION

Troja et al. (2008) analyzed the different properties of short GRBs with extended emission (EE) and those without EE and found that the bursts with large offsets have no observed EE components. Here we also investigate the offset for these two sub-samples in our observed offset sample: one includes

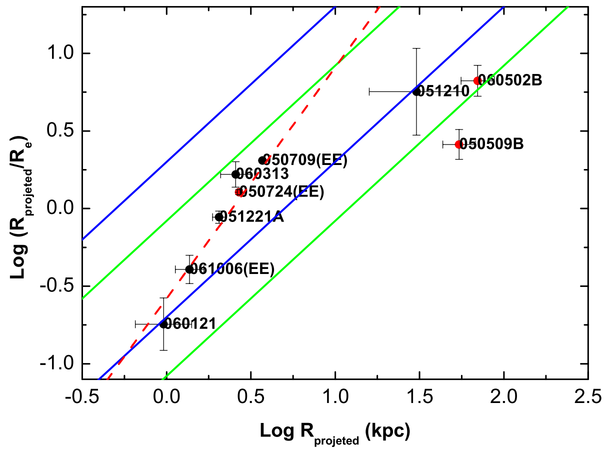

Fig. 4 Correlation of the offset $R_{\rm projected}$ and the normalized offset $R_{\rm projected}/R_{\rm e}$. The region between the blue lines is the expected range for early-type host galaxies in our calculation. The one between the green lines is for late-type galaxies. The red dashed line is the linear fitting to the bursts excluding GRB 050509B, GRB 060502 and GRB 051210. The bursts with EE are denoted behind the GRB name with "EE." The red dots are the bursts with observed elliptical host galaxies.

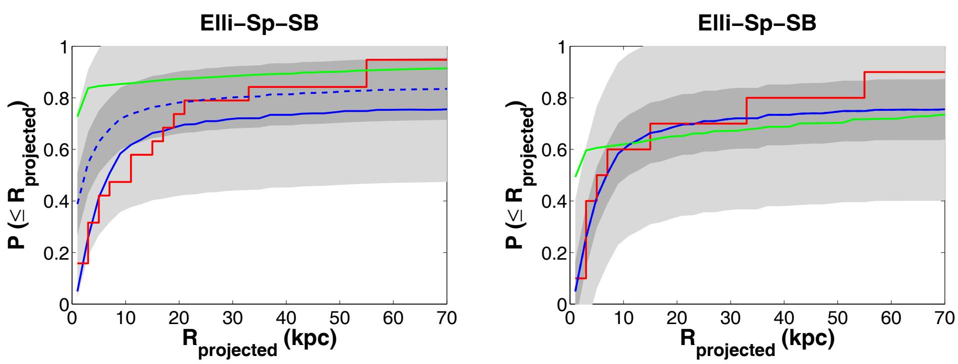

Fig. 5 Same as left panel of Fig. 1, but for the sample without redshift uncertainty (19 GRBs, *left panel*) and that without redshift and position uncertainties (10 GRBs, *right panel*).

six bursts with EE and the other is composed of 16 bursts without EE. The results are summarized in Table 3. The fitting results show that the average fractions of the late-type galaxies are about 0.58 for the bursts without EE and 0.63 for those with EE. The average Colp component fractions for the two samples are also very close: $\sim$0.48 and $\sim$0.52. Taking into account the error bars, it seems that there is no significant difference between the bursts with or without EE in this analysis. However, there is a weak tendency that a larger fraction of GRBs with EE may have the collapsar origin, which seems to be consistent with the predictions of Bromberg et al. (2012).

We check the correlation between the offset and normalized offset. In Figure 4, we show the observed correlation and the theoretically calculated one. The region between the two blue lines is the expected range for early-type host galaxies from our calculation. The one between the two green lines is that for late-type galaxies. The boundaries of these regions correspond to the maximum and

Table 3 Same as Table 2, but the offset analysis for the bursts without/with EE.

Sample		Offset analysis for the bursts without EE			Offset analysis for the bursts with EE		
Early-type galaxy		Ellip			Ellip		
Late-type galaxy		SB	Sp	SB-Sp	SB	Sp	SB-Sp
$\chi^2_{\rm min}$		0.30	0.35	0.31	0.20	0.19	0.19
$M_{\rm early}(10^{10}M_\odot)$		49.0	50	50	37.6	22.8	7.96
$M_{\rm late}(10^{10}M_\odot)$		10	7.43	10	0.21	0.31	0.41
Fraction	Late-type	$0.61^{+0.39}_{-0.61}$	0.54±0.45	$0.60^{+0.40}_{-0.60}$	$0.67^{+0.33}_{-0.67}$	0.58±0.47	$0.65^{+0.35}_{-0.65}$
	Colp component	$0.48^{+0.52}_{-0.48}$	0.53±0.34	$0.43^{+0.51}_{-0.43}$	$0.45^{+0.53}_{-0.45}$	$0.54^{+0.46}_{-0.54}$	$0.57^{+0.43}_{-0.57}$
K-S statistic		0.10	0.11	0.10	0.10	0.11	0.10

minimum mass of the host galaxies in our analysis. Red points denote the early-type host galaxies, while black points denote the late-type ones. Except for GRB 050509B with a large host galaxy radius, all the observed data are in the expected range using our models, in particular the late-type host galaxies. There seem to be two different groups: one is GRB 050509B, GRB 060502B and GRB 051210 with larger offsets and normalized offsets. Two of their host galaxies are elliptical, but the one for GRB 051210 is too faint to determine its type. It will be interesting to see if more bursts in this group will be found in the future with their host galaxies that are exclusively elliptical. The other group, including bursts with EE, seems to trace a linear distribution. The linear correlation coefficient is $R \simeq 0.99$. There seems to be no significant difference for the bursts with or without EE. We also find $R \simeq 0.74$ for all the observed data. These discussions are consistent with the results of Troja et al. (2008).

We analyzed the offset distribution in case that there was only one component (NN or NB) in the Merg component. The results do not change much because the distributions of NN and NB are very similar. We also analyzed the offset distribution in case that there was only a Merg component. In this case, we find that the possibility of the Ellip-Sp model is excluded from the test result of the statistical method. While we cannot exclude the possibility that short GRBs originate only from Merg cases in the Ellip-SB and Ellip-SB-Sp models, the fractions of the Colp component obtained in this work show that it is difficult to constrain the origin of short GRBs only based on the PS and massive star models for the present offset distributions. Many more effects, e.g. star-forming history, light distribution or morphology of the host galaxy, must be considered to study the origin of short GRBs.

We obtained the fraction of Colp in this study, but what the Colp may be is a different discussion. It may be the collapsars (for example MacFadyen & Woosley 1999; Proga et al. 2003; Nagataki et al. 2007; Nagataki 2009, 2011), or young neutron stars with strong magnetic fields (young magnetars, see Takiwaki et al. 2004; Komissarov & Barkov 2007; Bucciantini et al. 2009), or something else. The Colp means the component that traces star-forming regions. This discussion is outside the scope of this study.

Many factors could induce uncertainties in our work, e.g. the small size of our GRB sample, assumptions in the calculations and in the stellar evolution model, the selection effect for the GRBs and their host galaxies, etc. Our sample only includes 22 short GRBs with observed data of offsets. The short time duration of this type of GRB limits the observation of this event. The identification of their host galaxies needs high spatial resolution and high photometric ability. This is not easy for presently available instruments. In our calculations, the parameters for the GRB host galaxies, such as the mass, radius and the components within them, are assumed to be empirical values. There must be large divergence between the model predictions and the intrinsic properties of the host galaxies for the GRBs being studied. However, without a clear picture of the evolution of the host galaxies, empirical models for the host galaxies may also be adopted for the first step in the studies of the origins of short GRBs.

To test the effect of sample uncertainties of the redshift and burst position on our results, we fit the offset distribution for two sub-samples. One is for 19 bursts without redshift uncertainties (i.e. without GRB 051210, GRB 060121 and GRB060313). The other is for 10 short GRBs without redshift and position uncertainties (e.g. GRB 060801, GRB 061210, GRB 061217, GRB 070429B, GRB 060614 and GRB 070714B, etc. as shown in Table 1). The fitted results are shown in Figure 5. The fraction of the Colp component for the sub-samples of 19 and 10 bursts are 1.2 ± 0.8 and almost zero, respectively. This implies that the uncertainties in the redshift and burst position are important for determining the fraction of the Colp component that acts as one of the origins for short GRBs.

Our work is based on the star formation disk model (Bloom et al. 2002) and the PS model (Belczynski et al. 2006), whose uncertainties will introduce uncertainties in our analysis, although it is claimed that the most uncertain aspects are all parameterized to allow for systematic error analysis (Belczynski et al. 2008). The selection effects, such as naked bursts, dust attenuation and short GRBs with unknown hosts, also introduce uncertainties in our analysis. However, we would like to note that our analysis is the first step in discussing the origin of short GRBs from the point of view of the offsets/normalized offsets, including Colp in the analysis. This step is very important in shedding light on the origin(s) of short GRBs. Moreover, the "reduced" mass for early and late-type host galaxies in different models was obtained from our calculation. We hope that this could give possible predictions for future observations about the mean/middle mass of short GRB host galaxies. The improvement of these models and more observed samples are expected, so that we can discuss the origin of short GRBs with less uncertainties.

5 CONCLUSIONS

We have investigated the fractions of Colp and Merg as the origins of short GRBs from the offset/normalized offset analysis with 22 short GRBs with known offset distributions in their host galaxies. We have found that the fraction of Colp is $0.37^{+0.42}_{-0.37}$ with an error at the 1σ level for the offset analysis. With a larger error for this fraction, the origin of short GRBs is thus hard to understand using only statistics from studying the offset distribution.

For the normalized offset analysis, the fractions of Colp and late-type host galaxies are $0.19^{+0.26}_{-0.19}$ and $0.30^{+0.32}_{-0.30}$, respectively. We believe that the offset analysis is more reliable than the normalized offset analysis since the number of samples is more limited for the normalized offset analysis. However, the normalized offsets, which are the offsets normalized by the radii of the host galaxies, allow us to consider all the offsets in a uniform manner. In fact, the normalized offsets may perform a crude deprojection (Bloom et al. 2002) and have potential to shed light on the origins of short GRBs when the number of samples becomes larger.

The effects of the uncertainty in the redshift and burst position are checked by sub-samples without those uncertainties. The fractions for both sub-samples are less than those for our sample. Therefore, the uncertainties induced by redshift and burst position must be considered in order to understand the offset distribution. We hope the future observations with less uncertainty will give more accurate results about the origin of short GRBs through studying the offset distribution.

The fractions of Colp are very similar for the bursts with EE and those without EE, which suggest that their origins may be the same. In the plane of the offset and normalized offset, almost all of the short GRBs in this study are in the expected ranges according to our models. There seem to be two groups in the plane, which may be related to the type of host galaxy.

Due to the kick velocity in the evolution of binary compact objects and the long time taken for them to merge by emitting gravitational waves, the distribution of binary compact objects could be wider than that of massive stars. Considering all the effects during the evolution of the short GRB progenitors, their origins still play an important role for the offset distribution. Conversely, offsets of

GRBs are one of the indicators for the evolution of their progenitor stars and thus become a powerful tool to study the origin of short GRBs.

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References

Belczynski, K., Bulik, T., & Rudak, B. 2002, ApJ, 571, 394
Belczynski, K., Perna, R., Bulik, T., et al. 2006, ApJ, 648, 1110
Belczynski, K., Taam, R. E., Kalogera, V., Rasio, F. A., & Bulik, T. 2007, ApJ, 662, 504
Belczynski, K., Kalogera, V., Rasio, F. A., et al. 2008, ApJS, 174, 223
Berger, E. 2009, ApJ, 690, 231
Berger, E., Price, P. A., Cenko, S. B., et al. 2005, Nature, 438, 988
Berger, E., Fox, D. B., Price, P. A., et al. 2007, ApJ, 664, 1000
Bloom, J. S., Djorgovski, S. G., Kulkarni, S. R., & Frail, D. A. 1998, ApJ, 507, L25
Bloom, J. S., Sigurdsson, S., & Pols, O. R. 1999, MNRAS, 305, 763
Bloom, J. S., Kulkarni, S. R., & Djorgovski, S. G. 2002, AJ, 123, 1111
Bloom, J. S., Prochaska, J. X., Pooley, D., et al. 2006, ApJ, 638, 354
Bloom, J. S., Perley, D. A., Chen, H.-W., et al. 2007, ApJ, 654, 878
Bromberg, O., Nakar, E., Piran, T., & Sari, R. 2012, ApJ, 749, 110
Bucciantini, N., Quataert, E., Metzger, B. D., et al. 2009, MNRAS, 396, 2038
Castro Cerón, J. M., Michałowski, M. J., Hjorth, J., et al. 2006, ApJ, 653, L85
Cenko, S. B., Berger, E., Nakar, E., et al. 2008, arXiv:0802.0874
Christensen, L., Hjorth, J., & Gorosabel, J. 2004, A&A, 425, 913
Covino, S., Malesani, D., Israel, G. L., et al. 2006, A&A, 447, L5
Cui, X. H., Wang, H. G., Xu, R. X., & Qiao, G. J. 2007, A&A, 472, 1
D'Avanzo, P., Malesani, D., Covino, S., et al. 2009, A&A, 498, 711
Djorgovski, S. G., Bloom, J. S., & Kulkarni, S. R. 2003, ApJ, 591, L13
Fong, W., Berger, E., & Fox, D. B. 2010, ApJ, 708, 9
Fox, D. B., Frail, D. A., Price, P. A., et al. 2005, Nature, 437, 845
Fruchter, A. S., Thorsett, S. E., Metzger, M. R., et al. 1999, ApJ, 519, L13
Fryer, C. L., Woosley, S. E., & Hartmann, D. H. 1999, ApJ, 526, 152
Gehrels, N., Sarazin, C. L., O'Brien, P. T., et al. 2005, Nature, 437, 851
Graham, J. F., Fruchter, A. S., Levan, A. J., et al. 2009, ApJ, 698, 1620
Guetta, D., & Piran, T. 2006, A&A, 453, 823
Hjorth, J., Watson, D., Fynbo, J. P. U., et al. 2005, Nature, 437, 859
Komissarov, S. S., & Barkov, M. V. 2007, MNRAS, 382, 1029
Kouveliotou, C., Meegan, C. A., Fishman, G. J., et al. 1993, ApJ, 413, L101
Levesque, E. M., Bloom, J. S., Butler, N. R., et al. 2010, MNRAS, 401, 963

Lipunov, V. M., Postnov, K. A., & Prokhorov, M. E. 1997, MNRAS, 288, 245
MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262
Nagataki, S. 2009, ApJ, 704, 937
Nagataki, S. 2011, PASJ, 63, 1243
Nagataki, S., Takahashi, R., Mizuta, A., & Takiwaki, T. 2007, ApJ, 659, 512
Nakar, E., Gal-Yam, A., & Fox, D. B. 2006, ApJ, 650, 281
Norris, J. P., & Bonnell, J. T. 2006, ApJ, 643, 266
O'Shaughnessy, R., Belczynski, K., & Kalogera, V. 2008, ApJ, 675, 566
Prochaska, J. X., Bloom, J. S., Chen, H.-W., et al. 2006, ApJ, 642, 989
Proga, D., MacFadyen, A. I., Armitage, P. J., & Begelman, M. C. 2003, ApJ, 599, L5
Rau, A., McBreen, S., & Kruehler, T. 2009, GRB Coordinates Network, 9353, 1
Savaglio, S., Glazebrook, K., & Le Borgne, D. 2009, ApJ, 691, 182
Smith, G. P., Treu, T., Ellis, R. S., Moran, S. M., & Dressler, A. 2005, ApJ, 620, 78
Takiwaki, T., Kotake, K., Nagataki, S., & Sato, K. 2004, ApJ, 616, 1086
Troja, E., King, A. R., O'Brien, P. T., Lyons, N., & Cusumano, G. 2008, MNRAS, 385, L10
Virgili, F. J., Zhang, B., O'Brien, P., & Troja, E. 2011, ApJ, 727, 109
Wang, C., Lai, D., & Han, J. L. 2006, ApJ, 639, 1007
Zhang, B., Zhang, B.-B., Virgili, F. J., et al. 2009, ApJ, 703, 1696