Possible Correlations between the Emission Properties of SGRBs and Their Offsets from the Host Galaxies

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Abstract

Short gamma-ray bursts (SGRBs) are widely believed to be from mergers of binary compact objects involving at least one neutron star and hence have a broad range of spatial offsets from their host galaxies. In this work, we search for possible correlations between the emission properties of 18 SGRBs and their offsets from the host galaxies. The SGRBs with and without extended emission do not show significant differences between their offset distributions, in agreement with some previous works. There are, however, possible correlations between the optical and X-ray afterglow emission and the offsets. The underlying physical origins are examined.

Key words: gamma-ray burst: general – gamma rays: general

1. Introduction

Gamma-ray bursts (GRBs), the most violent explosion after the Big Bang, are usually divided into two basic categories: the short GRBs (SGRBs) with a duration shorter than 2 s and the long GRBs (LGRBs) that last longer (Kouveliotou et al. 1993). The LGRBs are most likely powered by the collapse of (rapidly rotating) massive stars (macFadyen & Woosley 1999), while the SGRBs likely arise from the coalescence of compact object binaries involving at least one neutron star (Eichler et al. 1989; Paczynski 1991; Narayan et al. 1992), though the mergers may also produce some LGRBs (Della Valle et al. 2006; Gal-Yam et al. 2006; Gehrels et al. 2006; Fynbo et al. 2006; Zhang et al. 2007; Jin et al. 2015; Yang et al. 2015). The smoking-gun signature of the collapsar origin of most LGRBs is the luminous supernovae in the late afterglow emission. The mergers of compact object binaries are known to be the promising gravitational-wave (GW) sources in the aLIGO/AdVirgo era. Direct observational evidence for the compact object merger origin of SGRBs is still unavailable, since no GW emission associated with SGRBs has been detected yet. Before the establishment of SGRB/GW association, which likely will happen in 2020s (Li et al. 2016a) when the detection rate will reach about 1 yr−1, the most important evidence for the merger origin of some GRBs is the identification of Li–Paczyński macronovae in GRB 130603B, GRB 060614, and GRB 050709 (Berger et al. 2013; Tanvir et al. 2013; Yang et al. 2015; Jin et al. 2016). If these macronovae were powered by the NS–BH (neutron star; black hole) mergers, the detection prospect by the aLIGO/AdVirgo network is quite promising (Li et al. 2017).

The study of the properties of host galaxies of GRBs became feasible after the launch of the BeppoSAX satellite (Boella et al. 1997), which localized the burst accurately. Wainwright et al. (2007) studied the morphological properties of GRB host galaxies and showed that most have approximately exponential profiles and some are merging and interacting systems. Bloom et al. (2002) studied the locations of LGRBs relative to their host galaxies and found a strong connection between the LGRB location and the star formation region. They also found that the observed offset distribution of LGRBs is consistent with the expected distribution of massive stars in exponential disks (see also Blanchard et al. 2016). All of these findings are in agreement with the collapsar model for LGRBs. For SGRBs, it is more complicated to associate them with their host galaxies due to the faintness of the afterglows and the fact that the binary systems could have traveled far away from their birth sites before the coalescences (Fryer & Kalogera 1997; Lipunov et al. 1997; Bloom et al. 1999; Belczynski et al. 2006; Wang et al. 2006). Research on the host galaxies of SGRBs was not available until 2005, when the SGRB afterglows were finally discovered (Fox et al. 2005; Hjorth et al. 2005; Covino et al. 2006). In a study of the spatial offsets of SGRBs from their host galaxies, Troja et al. (2008) showed that, among SGRBs, those with extended hard X-ray emission components have smaller projected physical offsets than those without extended emission (EE), possibly due to a systematic difference in the progenitors (i.e., the BH–NS and NS–NS mergers give rise to different “types” of events). If correct, such a finding has far-reaching implications for the GW detection (Li et al. 2016a). Later, the detailed investigation of Hubble Space Telescope (HST) observations of SGRB host galaxies (Fong et al. 2010; Fong & Berger 2013) determined the host morphological properties and measured precise physical and host-normalized offsets of SGRBs relative to the galaxy centers. They found that most SGRB hosts are late-type galaxies that have exponential disk profiles and a median size that is twice as large as that of LGRB hosts. Analysis of the distribution of SGRB offsets relative to their host galaxy centers indicated that SGRB progenitors are compact object binaries (NS–NS/NS–BH). Berger (2011) also got the same conclusion and ruled out a dominant population of SGRBs from magnetar giant flares. Recently, Li et al. (2016b) made a detailed comparative study of LGRBs and SGRBs, particularly the properties of the host galaxies and the offsets.

Motivated by this previous remarkable progress, in this work we search for possible correlations between the emission
We should note that GRB 060614 has a longer duration than 2 s. However, some of the properties make it more like an SGRB (Gal-Yam et al. 2006; Gehrels et al. 2006; Zhang et al. 2007).

In this paper, all EE refers to the soft gamma/hard X-ray emission following the initial spike. Sometimes the EE is not evident in the gamma-ray band but can be distinguished in the X-ray band.

properties of SGRBs and their offsets from the host galaxies. In Section 2, we describe our data sample. In Section 3, we present the statistical results, discuss the uncertainties, and present some preliminary explanation. Finally, in Section 4, we summarize our discussions.

2. Data

Fong et al. (2010) published the offsets of nine SGRBs (including angular offset $R_{\theta}$, physical offset $R_{\text{phy}}$, and host-normalized offset $R_{\text{nor}}$) from their host galaxy centers. Later, Fong & Berger (2013) provided another sample including 16 SGRBs. Among these 25 SGRBs, there are just 16 with measured redshifts. In addition to these, Fong & Berger (2010) published the offsets of nine SGRBs. Among these SGRBs, some have both gamma-ray and X-ray afterglow light curves were fitted by power-law or broken power-law models. The optical afterglow data are adopted from Fong et al. (2016) and GRB 150101B from Fong et al. (2016), we have a sample consisting of 18 SGRBs. For these bursts, we collect the total isotropic energy of prompt gamma-ray emission ($E_{\text{iso}}$) and calculate the X-ray (0.3–10 keV) afterglow fluence ($F_{X,11}$) at $11 \times (1 + z)$ hr post-burst and the optical flux density ($F_{\text{opt},6}$) at $6 \times (1 + z)$ hr post-burst, during which the X-ray and optical afterglow light curves were fitted by power-law or broken power-law models. The optical afterglow data are adopted from Fong et al. (2015), and the X-ray data are taken from Fox et al. (2005), Berger (2014), and the Swift official website (http://www.swift.ac.uk/xrt_curves/). Due to the absence of enough afterglow data in a few events, in total we have just 13 sets of $F_{X,11}$ and 14 of $F_{\text{opt},6}$. Among these SGRBs, some have $F_{X,11}$ but no $F_{\text{opt},6}$, and some have $F_{\text{opt},6}$ but no $F_{X,11}$. Finally, we also collect 13 $E_{\text{iso}}$ (Zhang et al. 2012, 2015) out of the 18 SGRBs. With the $T_{90}$ and redshifts, we convert $E_{\text{iso}}$, $F_{X,11}$, and $F_{\text{opt},6}$ into time-averaged gamma-ray luminosity ($L_\gamma$), X-ray luminosity ($L_{X,11}$), and optical luminosity ($L_{\text{opt},6}$). In principle, it is easier to measure the redshifts of the bursts with brighter afterglow emission, and this could be a source of the selection effect. However, for a good fraction of SGRBs, the redshifts are not determined with the afterglow spectrum measurements. Instead, they are given by the association probability evaluation, since most SGRBs are found to be outside of their host galaxies. We therefore suggest that the redshift-selected sample may not be seriously biased.

In addition, in order to examine whether there is indeed a difference of host galaxies between SGRBs with and without EE (see Norris & Bonnell 2006), we also compare the properties of these two subgroups.

For comparison, we select a sample of LGRBs as well. In our LGRB sample, there are two ultra-long GRBs (GRB 060218 and GRB 130925). The durations ($T_{90}$) of GRB 060218 and GRB 130925 are $\sim$2100 s (Campana et al. 2006) and $\sim$7000 s (Greiner et al. 2014), respectively. It should be noted that GRB 060218 is also a low-luminosity GRB.

3. Statistical Results

3.1. Offset Distribution of SGRBs with and without EE

In this subsection, following Troja et al. (2008), we check whether there is a difference between offset distributions of SGRBs with and without EE. We also consider X-ray EE, while Troja et al. (2008) only considered gamma-ray EE. Among the 18 SGRBs, five have both gamma-ray and X-ray EE, and another three have just X-ray EE. For SGRBs with and without EE, the distributions of their offsets from the host galaxies are shown in Figure 1. The offsets of SGRBs with and without EE seem to have similar distributions. In order to verify this, we take a Kolmogorov-Smirnov (K-S) test to examine the relationship of the two distributions and find that the $p$-values are 0.30, 0.24, and 0.83 for $R_{\theta}$, $R_{\text{phy}}$, and $R_{\text{nor}}$, respectively. This indicates that there is no significant difference between the two subsample distributions, consistent with Fong et al. (2010), Salvaterra et al. (2010), and Fong & Berger (2013).
3.2. Correlation between Luminosities and Their Offsets from the Host Galaxy Centers

Now we turn to searching for possible correlations between the GRB/afterglow luminosities (i.e., $L_{\gamma}$, $L_{X,11}$, and $L_{opt,6}$) and the offsets ($R_{\text{phys}}$ and $R_{\text{norm}}$). In Figure 2, we show the data for all SGRBs. The blue diamonds and green circles represent SGRBs with and without macronova signals. There is a clear trend that the farther the SGRB is from the center of the host galaxy, the lower the afterglow (in both the X-ray and optical bands) luminosity. But the average isotropic prompt (gamma-ray band) luminosity does not follow this trend. To obtain the quantitative relationship, we use a power-law model to fit the data of all sample SGRBs. The green lines are the best-fit results, and their expressions and correlation coefficients are summarized in Table 1. The most significant correlations are $L_{X,11} \propto R_{\text{norm}}^{-1.16\pm0.57}$ and $L_{opt,6} \propto R_{\text{norm}}^{-1.23\pm0.51}$, and their correlation coefficients are 0.66 and 0.70, respectively.

For comparison, we also show LGRBs and ultra-long GRBs in each panel of Figure 2. The LGRBs are generally located to the upper left of the SGRBs in the two-dimensional map, and their luminosities are independent of offsets. All absolute values of correlation coefficients are smaller than 0.33. Due to the limited number of ultra-long GRBs, no general conclusion on their distribution can be drawn (note that GRB 060218 is distinguished for its very low luminosity and small offset).

There are several observational biases that might impact the observed correlations. For instance, it is easier to detect bright optical afterglows close to the center of galaxies than faint ones, which may soften the luminosity–offset correlation. However, we think the effect is not significant for the following reasons. First, it should be easy to detect bright afterglows with large offsets, but there is no burst on the upper right side of each panel in Figure 2. Second, if there was an SGRB close to the center of the host and its afterglow was faint (it lay to the lower left of the correlations), it might be detected in the X-ray band because the X-ray afterglows are less affected by the host galaxies (Le Floc’h et al. 2003) and have a much higher luminosity.
The offset distribution of NS–NS binaries in Milky Way–type galaxies has been widely examined (Lipunov et al. 1997; Bloom et al. 1999; Fryer et al. 1999; Belczynski et al. 2006). It is found to be consistent with the observed offset distribution of SGRBs (Fong et al. 2010; Berger 2011; Fong & Berger 2013), though the possibility of the existence of other progenitor systems cannot be ruled out. Such a result has been taken as one piece of compelling evidence for the compact object merger origin model. As shown in Figure 2, more than 60\% of LGRBs have been found inside their host galaxies (Blanchard et al. 2016; Lyman et al. 2017), while about 70\% of SGRBs are located outside their host galaxies.

The prompt gamma-ray emission of GRBs has been widely attributed to the internal energy dissipation of the unsteady outflow material launched by the central engines (Kumar & Zhang 2015). Hence, the prompt emission luminosities are mainly governed by the central engines and should not display significant dependence on the offsets from the host galaxies. One exception is that the SGRB progenitors might mainly consist of two subgroups: one includes the NS–BH binaries, which may obtain smaller kick velocities for their larger mass system, and the other includes the NS–NS binaries. The former may be more concentrated around the host galaxy center, while the latter may have a larger typical offset. If the NS–BH merger-driven GRBs are more typical than the NS–NS merger origin GRBs, one may expect some dependence of the prompt emission luminosities on the offset, as argued in Troja et al. (2008). The current prompt emission data presented in Figure 2 are still insufficient to draw a reliable conclusion.

The presence of possible correlations between the X-ray and optical afterglow emission and the offsets is somewhat expected. This is because the number density of the circumburst medium ($n_c$) is expected to decrease with the distance to the host galaxy center (Fong et al. 2015), and the afterglow emission flux $F$ depends on $n_c$ as long as the observer’s frequency $\nu_{\text{obs}}$ is $<\max\{\nu_c, \nu_m\}$, where $\nu_m$ and $\nu_c$ refer to typical synchrotron frequency and cooling frequency (Sari et al. 1998), respectively. Note that in the standard afterglow model, for $\nu_{\text{obs}} > \max\{\nu_c, \nu_m\}$ we have the afterglow flux independent of $n_c$. For example, in the most likely scenario of $\nu_m < \nu_{\text{obs}} < \nu_c$, we have $F \propto n_c^{-1/2}$. Supposing that beyond a distance from the center there is a relation $n_c \propto R^{-\alpha}$, we have $F \propto R^{-\alpha/2}$. If the observed dependence of $F$ on the offset is solely due to such an effect, we can constrain $\alpha \sim 2.2$. So far it is unclear whether this is the case. The kinetic energy ($E_k$) also has an impact on $F$, but it seems to be independent of the offset from the host galaxy center.

As a comparison, LGRBs from massive star collapse occurred in star-forming regions of galaxies, and their progenitors are almost static to their birthplace (Bloom et al. 2002). This model is supported by the noncorrelation between LGRB/afterglow luminosities and their offsets from host galaxies.

4. Summary

In this work, we carry out some statistical analysis focusing on the possible dependence of the emission properties on the offsets of SGRBs. We find possible correlations between SGRB afterglow luminosities and their offsets from host galaxies that can be expressed as $L_{X,11} \propto R^{-1.16 \pm 0.57}$ and $L_{opt,6} \propto R^{-1.23 \pm 0.51}$ (see Table 1 for the correlation coefficients). These correlations are somewhat expected, since the number density of the circumburst medium ($n_c$) should decrease with the distance to the host galaxy center (i.e., $R$), and the afterglow emission flux $F$ depends on $n_c$ as long as the observer’s frequency $\nu_{\text{obs}} < \max\{\nu_c, \nu_m\}$ (for example, in the scenario of $\nu_m < \nu_{\text{obs}} < \nu_c$, we have $F \propto n_c^{-1/2}$). Hence, our result may have shed some light on the dependence of $n_c$ on $R$.

In addition, there are some other uncertainties related to the correlation. For instance, the angle between the line of sight and the host galaxy disk may affect the measured offset, although the effect may be weakened in the statistical study. Another uncertainty may be SGRBs that occurred in globular clusters. The natal kick velocities and merger rate of binaries in a globular cluster may be affected by the total globular cluster system. Grindlay et al. (2006) presented numerical results that SGRBs from binary neutron star mergers in globular clusters account for $\sim10\%$–$30\%$ of the total. The influence exerted by SGRBs occurring in globular clusters still needs further discussion.

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References

Belczynski, K., Perna, R., Bulik, T., et al. 2006, ApJ, 648, 1110
Berger, E. 2011, NewAR, 55, 1
Berger, E. 2014, ARA&A, 52, 43
Berger, E., Fong, W., & Chernock, R. 2013, ApJL, 774, L23
Blanchard, P. K., Berger, E., & Fong, W.-F. 2016, ApJ, 817, 144
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., Sigurdsson, S., & Pols, O. R. 1999, MNRAS, 305, 763
Boella, G., Butler, R. C., Perola, G. C., et al. 1997, A&AS, 122, 299
Campana, S., Mangano, V., Blustin, A. J., et al. 2006, Natur, 442, 1008
Covino, S., Malesani, D., Israel, G. L., et al. 2006, A&A, 447, L5
Della Valle, M., Chincarini, G., Panagia, N., et al. 2006, Natur, 444, 1050
Eichler, D., Livio, M., Piran, T., & Schramm, D. N. 1989, Natur, 340, 126
Fong, W., & Berger, E. 2013, ApJ, 776, 18
Fong, W., Berger, E., & Fox, D. B. 2010, ApJ, 708, 9

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