Short gamma ray bursts: formation and offsets

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ABSTRACT
Short gamma ray bursts have been observed a variety of galaxies types with varying angular offsets from the centre of their host galaxies. To investigate the properties of short gamma ray burst offsets, a sample of short gamma ray bursts with host galaxies has been gathered. Two formation channels proposed to explain the observed offsets of short gamma ray bursts from their host galaxies are discussed. The classification of short gamma ray bursts into these formation channels is demonstrated for short gamma ray bursts with host galaxies. The possibility of faint dwarf galaxies as host environments for the observed short gamma ray bursts is also investigated. However, by extrapolating the distribution of dwarf galaxies around the Milky Way to redshifts corresponding to the short gamma ray bursts, we show that it is unlikely that dwarf galaxies are the hosts of short gamma ray bursts.

Key words: Gamma-ray burst: offset, formation - Galaxy: dwarf galaxy

1 INTRODUCTION
Gamma Ray Bursts (GRBs) are non-repeating, highly energetic events that emit mainly gamma rays over a short timeframe. First detected by the Vela satellites in 1969 (Klebesadel et al. 1973), hundreds of theoretical models were emerged to explain these bursts while little data was gained to verify these assumptions. However, in 1997, the first optical and X-ray afterglows were detected with direct measurements of their redshifts through optical spectroscopy which leads to an intense investigation of GRBs progenitor channels, energy source and origin systems.

GRBs can be classified into two categories, mainly based on duration and spectral hardness: the short-hard and long-soft bursts with a separation at about 2 sec (Kouveliotou et al. 1993). The longer GRBs (LGRBs) can extend to hundreds of seconds. They originate from the brightest regions of galaxies and closely track stellar mass (Wainwright et al. 2007). For LGRBs that originate from distances close enough for supernova detection to be possible it has been observed that the events can usually be associated with a Type Ib or Type Ic supernova. The almost unanimous consensus among the astrophysics community is that the collapse of rapidly-rotating massive stars or collapsars are LGRB progenitors (MacFadyen & Woosley 1999; Fruchter et al. 2006). Short gamma ray bursts (SGRBs), on the other hand, can last as short as milliseconds and have harder spectra and lower fluences than their longer duration counterparts. SGRB progenitors are thought to be the coalescence of compact object binaries (with neutron star and/or black hole constituents DNS/NS-BH) in the case of SGRBs (Paczynski 1991).

SGRBs are significantly fainter than their long duration counterparts, and were, hence, observed at a relatively low event rate with large and uncertainties in source sky location (Hurley et al. 2002). The launch of NASAs Swift satellite in late 2004, which provided the first chance for detecting accurate positions rapidly for SGRBs, indeed led to the detection of the first X-ray, optical and radio afterglows in the following years (Berger et al. 2005). As an increasing number of SGRBs are localized with measurements of redshift and host galaxy data, they have been in both star-forming and elliptical (old stellar population) galaxies and not just in the galactic centre but sometimes in the outer regions of the galaxy and in some cases even in the galactic halo (Belczynski et al. 2006; Berger 2011; Fong et al. 2013). Up to now, only one SGRB (GRB130603B) has been observed to be associated with a ‘kilonova’ (Tanvir et al. 2013). The observation that would furthermore confirm that the coalescence of compact binaries is the correct progenitor system would be the coincident detection of gravitational waves from the event. However, this confirmation is not expected to be made in the next few years so at present the best method for deducing the most likely progenitor system is through statistical analysis of the locations of the SGRBs.

In this paper, we discuss the SGRB formation scenarios proposed to explain the observed locations with respect to their host galaxies. In particular, two scenarios, primodial and dynamical, for explaining the observed SGRB offsets are explored and applied to a subset of SGRBs with host galaxies. We then investigated the possibility that SGRBs
are hosted by faint dwarf galaxies around its brighter host galaxy before discussing our observations.

2 DATA SET

To investigate the formation of SGRBs by their offset properties based on Table 1 and reduce the uncertainty, we select the GRBs from the data set shown in Fong et al. (2013). The sample of 7 SGRBs, which do not have extended emissions, are located by more than one camera and their host’s redshift and morphology are available, are shown in Table 2.

As discussed in the previous section, short gamma ray bursts are not often observed to lie within the centre of their host galaxy but rather towards the outer regions or outside of the galaxy entirely. One aim of this research was to determine whether the short GRB progenitors could be located in satellite galaxies in orbits around their host galaxies. In order to carry out this investigation, data from several papers were amalgamated to construct a dataset which comprised of short GRB observations which were accurately associated with a host galaxy. Each event was observed with an angular offset from the host galactic centre. The events and their data are shown in Table 2 (Fong et al. 2010; Fong & Berger 2013). It can be seen that most of the events that have been successfully associated with a host galaxy are located by more than one camera and their hosts' redshift and morphology are available, are shown in Table 2.

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3 GRB FORMATION AND OFFSETS

These are the two main channels for compact binaries formations in different scenarios: through the evolution of massive stars in primordial binaries rising in the galactic field (Narayan et al. 1992), and from three (or even more)-body dynamical interactions among stars and compact remnants in globular clusters (GCs) (Grindlay et al. 2006). To reproduce the redshift distribution data of SGRBs from Swift, both formation channels are important (Salvaterra et al. 2008).

3.1 Kicked or born?

A binary star systems behaviour and evolution are determined by the initial masses of the stars, their semi-major axis distance and the eccentricity of the binary at the time when the system is formed. In the first stage of the binary’s lifetime there is a small amount of mass transfer between the two stars which acts to circularize the orbit of the binary and also cause the stars to spiral towards each other (Fong et al. 2010). Then, when one of the stars in the system reaches supernova the resulting NS often receives an asymmetric impulse as a result of the event. The kick velocity which a NS receives can vary significantly and it has been shown that a Maxwellian velocity distribution fits well with observations (Bloom et al. 1999). Complex modelling has shown that the semi-major axis of the orbit is altered and that the binary system as a whole obtains a kick velocity in a random direction with a median velocity of around 300 km s⁻¹. These models consider the birth-rate of binary systems, initial system velocity, initial position in the galaxy, lifetime of the stars and the merger rate of the neutron stars which is an average of one hundred million years. The results predict that the median radial distance from the galactic centre for a NS-NS merger is 10 kpc and that ninety percent of the mergers should occur within 30 kpc of the host (this corresponds to 4 arc seconds at z = 1). These results match well with the sample of GRBs used in this research and act to confirm the conclusion that the short gamma ray bursts are not situated in dwarf galaxies. The typical dwarf galaxy distribution has ninety five percent of the satellites at a distance greater than 20 kpc from the galactic centre.

Population synthesis models has been made to computed for theoretical spatial distribution of primordial SGRBs generated from isolated galaxies of different types and sizes (Belczynski et al. 2006). Considering three different galaxy types (elliptical, spiral and starburst) and two kinds of sizes (small hosts with masses of \( \sim 10^7 \msun \) and large ones of \( \sim 10^{12} \msun \), respectively), two windows for offsets (first from 0 to 10 kpc, and the second between 10 and 100 kpc) are selected thus SGRBs can be located well inside their host galaxies. However, the “kick velocity” explanation for offset of GRBs is inconsistent with observations of double neutron star systems in the Milky Way. The Hulse-Taylor binary pulsar, together with other known double neutron star systems in the Milky Way appear to be low kick-velocity (\( \lesssim 50 \, \text{km s}^{-1} \)) system. Thus, double neutron star systems are expected to remain within the central region of their parent (spiral or star-forming) galaxies (Grindlay et al. 2006).

Regarding of dynamical origin of SGRBs: they came from double neutron stars and went through dynamical channels (usually as a result of few body interactions). While binaries to be released with large recoil velocities are almost impossible, underlying globular clusters (GCs) spatial distribution should be taken into consideration. In the case of host galaxies in clusters, GC distribution is cut by tidal truncation within the galaxies, leaves the offset in 10-100 kpc an unclear window. On the one hand, only 10-20% of massive ones are in this offset window; on the other hand, the bulk of GCs from small galaxies are less than 10 kpc. Bound GCs mostly extend up to 50-100 kpc both in large and small galaxies (Salvaterra et al. 2010). Speaking of the SGRBs from isolated galaxies, as both theoretical and observational support the existence of numerous intra-cluster GCs (ICGCs), GCs are believed to have a wider distribution so as to explain large potential offsets beyond the theory of natal kicks (Salvaterra et al. 2010). From theoretical estimation ICGCs occupy \( \sim 30\% \) despite of the cluster total mass of the GCs spatial distribution. Since observations have provided an indication of ICGCs existence, they should be found far from center of host cluster and spread throughout the cluster volume as expected. The main results of all above studies by far are listed in Table 3 (Salvaterra et al. 2010). We will compare the samples shown in Table 1 with results of Salvaterra et al. (2010).

As shown in Table 1, In the cases of GRB 051221A, GRB 070429B, GRB 070724A and GRB 090426A, which are all discovered within large-model host galaxies and their offsets from each hosts fall in the scope of 0-10 kpc, these
Table 1. Complete SGRB Host Galaxy Sample

| GRB     | $T_{90}$ [s] | Host Type  | $z$  | Offset (kpc) |
|---------|--------------|------------|------|--------------|
| 051221A | 1.4          | L          | 0.546| 0.76         |
| 070429B | 0.5          | L          | 0.902| 4.7          |
| 070724A | 0.4          | L          | 0.457| 4.76         |
| 071227  | 1.8          | L          | 0.381| 15.0         |
| 090426A | 1.3          | L          | 2.609| 0.8          |
| 100117A | 0.3          | S          | 0.915| 0.5          |
| 111117A | 0.5          | L          | 1.3  | 10.5         |

* S(L) refers to the small (large) galaxy model (Belczynski et al. 2006). Data are selected from Fong et al. (2013) (see text for detail).

Table 2. SGRB offset and redshift

| GRB     | Offset (arcsec) | Redshift  |
|---------|-----------------|-----------|
| 061201  | 16.25           | 0.111     |
| 070429B | 1.46            | 0.902     |
| 070714B | 1.55            | 0.923     |
| 070724A | 0.94            | 0.4571    |
| 070809  | 5.63            | 0.473     |
| 071227  | 2.98            | 0.381     |
| 080905A | 8.29            | 0.1218    |
| 090510  | 1.33            | 0.903     |
| 090515  | 13.98           | 0.403     |
| 100117A | 0.17            | 0.915     |
| 130603B | 1.05            | 0.3564    |
| 070707  | 0.4             | 3.6       |
| 090305A | 0.43            | 4.1       |
| 090426  | 0.06            | 2.609     |

Each event was observed with an angular offset from the host galactic centre. Data are from Fong et al. (2010); Fong & Berger (2013).

SGRBs are likely to result from the primordial channel. The indications of this kind of SGRBs are relatively typical, since the intrinsic absorption in gamma-ray spectrum measurements, the redshift data from observation and their positions of optical afterglow (usually inside their host galaxies) are all symbolization of a primordial binary system. For GRB 100117A, the relatively small offset (≈0.5 kpc) away from its small host galaxy (which identified as elliptical type) only suggests the possibility of a dynamical origin can be 2.5 times than that from the primordial channel. GRB 071227 and GRB 111117A are even more interesting, given that the classification of such kind of SGRBs is still controversial. Consider GRB 071227 which was already firmly classified as an SGRB (Levan et al. 2008), both the formation channels of primordial or dynamical conform to the situation: 15 kpc offset from a relatively large spiral galaxy, making the classification of GRB 071227 and GRB 111117A not so straightforward. However, our best speculation for GRB 071227 based on its relative position from the host, together with the position of afterglow was observed within the hosts galactic plane, provides a possible explanation of a primordial origin. From the samples above we have seen the analysis results a powerful tool to identify different cases of their origins of the offsets.

3.2 Faint Dwarf galaxies as the physical hosts of offset SGRBs

Why the progenitor kicks would possess such a broad distribution remains unclear. It is likely that the distribution is a function of the binary system and host galaxy size, rather than the progenitor model. SGRBs that have not been robustly associated to a host galaxy, due to their apparently large offsets, are attributed to the nearest galaxy of lowest probability of chance coincidence (Bloom et al. 2002). However these SGRBs may, instead, have be very faint galaxies currently hidden from observation by an active interstellar foreground.

Dwarf galaxies are gravitationally bound systems (typically ∼1 billion stars) orbiting larger host galaxies. The satellite galaxy population of our own galaxy and that of M31, Andromeda are well known and the distances to each of the dwarf galaxies may be taken from many sources and are generally accurate to within around 5%. Fig 1 shows the distribution of dwarf galaxies around the two galaxies (Metz et al. 2007).

The limitation of current observation < 25.5 AB mag (Fong et al. 2010) shows another channel of the nature of GRB offsets: their physical hosts are faint dwarf galaxies. In particular, the apparent magnitude of Andromeda itself is 3.44 and the average apparent magnitude of its dwarf galaxies is 12.45 Table 4. For an approximate analysis then it can be taken that an average dwarf galaxy should be nine orders of magnitude dimmer than its host as shown in column four of Table 5. This suggests that the brightest host galaxy from this sample should have dwarf galaxies with an AB Mag of around twenty-five but the average host galaxy is expected to have dwarf galaxies with magnitudes on the order of thirty.

From Fig 1 (Bloom et al. 2002) it can be seen from the distribution that of the 40 well documented dwarf galaxies of the two galaxies only two lie within 20kpc of the galactic centre (95% ≥ 20kpc) and that the most probable location for a dwarf galaxy is within the radial distance of 30-60kpc from the galactic centre. Fig 1 also tentatively reveals a cut-off distance somewhere between 200kpc and 300kpc at which point...
the number of dwarf galaxies drops. This feature is due to the virial radii of the two galaxies, the Milky Way and Andromeda, which have virial radii of around 200kpc and 260kpc respectively. The virial radius is the orbital radius at which an object is in a stable orbit and therefore we would expect to see a sharp reduction in satellites beyond this distance. As the Milky Way and Andromeda are fairly typical galaxies and their satellite distributions are fairly similar it is reasonable to assume that this distribution is representative of a typical satellite galaxy distribution. This assumption allows a dwarf galaxy window to be defined. For any observed galaxy it is likely that its satellite galaxies will lie between 20kpc and 200kpc from the galactic.

By using the angular size - redshift relation, the “dwarf galaxy window” can be converted from a radial distance window to an angular offset window as a function of redshift. By superimposing the observed short gamma ray bursts onto the angular offset window it is possible to see whether or not the GRBs are observed at separations coincident with where dwarf galaxies would be expected.

Fig 2 shows that only three of the fourteen observations have offsets greater than the lower boundary of the dwarf galaxy window. Given that ninety five percent of dwarf galaxies lie beyond this lower limit, it seems that it is unlikely that these short GRBs are indeed originating from satellite galaxies. However, there is one more aspect of the observations to be considered. The geometry of the observer, galactic centre and observed event will determine what fraction of the actual separation is observed. A telescope will only observe the projection of the angular offset which is perpendicular to the line of sight. If the GRBs occur at a radius, \( R \) from the galactic centre and at an angle, \( \theta \), from the plane perpendicular to the line of sight (the angle, \( \phi \), around the plane does not affect the magnitude of the offset measured) then the observed angular offset will only correspond to \( R \cos(\phi) \). Although it is impossible to determine \( \theta \) for any single observation, if one considers the average projection for all values of \( \theta \) and then uses this to scale up each of the observed angular offsets then a more physical distribution can be obtained. On each side of the plane perpendicular to the line of sight, \( \theta \) can be any value between 0 and \( \pi \). Thus, the average fraction of the separation that is observed is given by:

\[
\frac{1}{\pi} \int_0^\pi | \cos(\theta) | \ d\theta = \frac{2}{\pi}
\]

(1)

Therefore if the GRB angular separations plotted in Fig 2 are multiplied by a factor of \( \frac{2}{\pi} \) then a better comparison can be made. Fig 3 shows that now five of the fourteen short GRB observations lie within the dwarf galaxy window. This figure is still substantially different from what would be expected if the progenitors of these short GRBs were originating from dwarf galaxies. Even from this small statistical analysis it is clear that the observations have a tendency to lie nearer to their host galaxies than the typical satellite galaxy population. Although more data is needed to confirm this conclusion, this research may tentatively conclude that the observed angular offset distributions of short gamma ray bursts suggest that the events are not occurring in dwarf galaxies orbiting the associated host galaxy.

4 CONCLUSION AND DISCUSSION

By comparison with a typical satellite galaxy population this statistical analysis of the angular offsets of fourteen SGRBs has revealed that the observed separations between the events and the galactic centre are not explained by the fact that the SGRBs are occurring in dwarf galaxies. This study has shown that less than half of the SGRBs lie beyond the offset that we would expect ninety-five percent of dwarf galaxies to lie beyond. Although this study appears to have answered the question of whether or not short gamma
Table 5. AB Magnitude data for host galaxies of observed short GRBs.

| GRB     | Redshift | Host AB Mag | Host AB Mag+9 |
|---------|----------|-------------|---------------|
| 050509b | 0.226    | 16.32       | 25.32         |
| 050709  | 0.1606   | 21.09       | 30.09         |
| 050724  | 0.257    | 19.98       | 28.98         |
| 051210  | >1.4     | 21.14       | 30.14         |
| 051221a | 0.5465   | 21.86       | 30.86         |
| 060121  | ?        | 26.22       | 35.22         |
| 061201  | 0.111    | 18.17       | 27.17         |
| 060502b | ?        | 17.88       | 26.88         |
| 061006  | 0.4377   | 21.67       | 30.67         |
| 061201  | 0.111    | 18.17       | 27.17         |

Figure 1. Histogram showing the distribution of dwarf galaxies around the Milky Way and Andromeda galaxies in kiloparsecs.

By applying the limit samples of seven SGRB offsets and their hosts to the compact binaries formation channels, four and one samples are prefer the primordial channel and dynamical channel of compact binaries formation scenario, respectively. Two sample can not distinguish the formation channel. We hope more data in the future will give more constraints.

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Figure 2. The star markers represent the observed GRB angular offsets and the two lines represent the expected minimum and maximum range of dwarf galaxy offsets.

Figure 3. The star markers represent the observed GRB angular offsets with the 3D correction applied and the two lines represent the expected minimum and maximum range of dwarf galaxy offsets.

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