On the offset of Short Gamma-ray Bursts

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ABSTRACT

Short Gamma-Ray Bursts (SGRBs) are expected to form from the coalescence of compact binaries, either of primordial origin or from dynamical interactions in globular clusters. In this paper, we investigate the possibility that the offset and afterglow brightness of a SGRB can help revealing the origin of its progenitor binary. We find that a SGRB is likely to result from the primordial channel if it is observed within 10 kpc from the center of a massive galaxy and shows a detectable afterglow. The same conclusion holds if it is 100 kpc away from a small, isolated galaxy and shows a weak afterglow. On the other hand, a dynamical origin is suggested for those SGRBs with observable afterglow either at a large separation from a massive, isolated galaxy or with an offset of 10-100 kpc from a small, isolated galaxy. We discuss the possibility that SGRBs from the dynamical channel are hosted in intra-cluster globular clusters and find that GRB 061201 may fall within this scenario.

Key words: gamma–ray: burst – stars: formation – cosmology: observations.

1 INTRODUCTION

The afterglows of several Short Gamma Ray Bursts (SGRBs) have recently been localized on the sky with Swift (Gehrels et al. 2004), allowing for a determination of their redshift and host galaxy (see e.g. Berger 2009; Fong, Berger & Fox 2010). SGRBs are observed in all kinds of galaxies (from star-bursts to ellipticals and also associated with galaxy clusters) with a wide range of offsets.

SGRBs are currently believed to result from the coalescence of a compact binary, either a double neutron star or a neutron star (NS) and a black hole (BH) binary (Nakar 2007). Compact binaries are known to form in different environments along two main channels: (i) from the evolution of massive stars in primordial binaries rising in the galactic field (Narayan, Paczynski & Piran 1992), and (ii) through three (or a few)-body dynamical interactions among stars and compact remnants in globular clusters (GCs) (Grindlay, Portegies Zwart & McMillan 2006). Salvaterra et al. (2008) have shown that both formation channels are needed in order to reproduce the Swift redshift distribution of SGRBs, with the dynamical channel in GCs contributing mainly at $z \lesssim 0.3$.

In this paper, we investigate the nature of the observed offsets in relation to the galaxy type and burst environment in order to discriminate between the two channels and highlight the origin of SGRBs. A wide range of offsets is expected in both channels. In the primordial scenario, a large separation from the host galaxy can originate from the natal kick rising at the time of formation of the compact object (Belczynski et al. 2006). This mechanism is not present in case of dynamical origin: few body interactions that are at the origin of dynamical double neutron stars do not release binaries with large recoil velocities (Devecchi et al. in preparation). So, the offset in this latter case has to be ascribed to the underlying GC spatial distribution. For isolated galaxies this reflects the GC distribution that is known to decline more gently compared to stars (see Brodie & Strader 2006 and references therein). In galaxy clusters, GCs may have a wider spread, since there are hints (both theoretical and observational) that a population of intra-cluster GCs (ICGCs) can exist. SGRBs inside ICGCs can explain large potential offsets in galaxy groups and clusters, besides natal kicks.

We outline here three different cases for the origin of the offsets: (i) primordial SGRB kicked from a galaxy, isolated (Belczynski et al. 2006) or in a cluster (Niino & Totani 2008), by a natal kick; (ii) dynamical SGRB in a GC bound to an isolated or cluster galaxy, and (iii) dynamical SGRB in a ICGC.

2 QUANTIFYING THE OFFSET

2.1 Primordial SGRBs

The theoretical spatial distribution of primordial SGRBs has been computed for isolated galaxies of different types.
and sizes\(^1\) using population synthesis models by Belczynski et al. (2006). The offset results from the combination of the natal kick velocity with the time that elapses from the formation of the compact binary and its gravitational wave driven coalescence time. We select two windows for the offset: the first between 0–10 kpc and the second between 10–100 kpc. We note that with our definition of the offset we include also SGRBs located well inside the host galaxy. From figure 3 of Belczynski et al. (2006), we infer that the bulk of SGRB events happens within the 10 kpc scale for star-bursts and spirals, whereas for ellipticals this is true only for large hosts. For small ellipticals only \(\sim 15\%\) shows this kind of offsets. The relative fraction of SGRBs with small offset increases from early to late host galaxies, and from small to large hosts. Instead, we find that the 10–100 kpc window is always poorly populated by primordial SGRBs regardless the type and size of the host galaxy, being the fraction of merging double neutron stars (DNS) around \(~ 10 – 20\%\). Finally, only for small ellipticals, we have a good probability \((\sim 75\%)\) to find SGRBs with very large offset \((\text{i.e. } \geq 100 \text{ kpc})\), whereas in other host types this fraction is only \(< 5 – 20\%\). This finding may not hold true if the host is member of a galaxy cluster. As shown by Niino & Totani (2008), the fraction of SGRB events occurring at very large offset may be as large as \(~ 80\%\) if the potential well of each member galaxy is determined by stars instead of dark matter due to dilution in the clustering process. If, instead, the dark matter sub-halos are associated to member galaxies as for field galaxies, the escape fraction is only \(20\%\).

2.2 Dynamical SGRBs: GCs bound to galaxy

We consider a model for the GCs spatial distribution based on current observations of extra-galactic GC spatial profiles.

The number density surface of the GC system has been fitted in the literature either via a power-law \((\Sigma \propto r^{-\alpha})\) or as a modified Hubble law \((\Sigma \propto (r^2 + r_c^2)^{-1})\). Trends between the V-magnitude \((M_V)\) of the host galaxy and both \(\alpha\) and \(r_c\) have been found, suggesting for a link between the evolution of the GC systems and its host galaxy (Forbes et al. 1996; Ashman & Zepf 1998): \(\alpha = 0.28M_V + 7.5\) and \(r_c = -0.62M_V - 11\) kpc. In order to take into account both for the presence of a core and the change in the slope of the outer profile, we here consider a "mixed" model. The number density of the GCs has been modeled as:

\[
\Sigma(r) = \frac{\Sigma_0 r_c^{-\alpha - 2}}{(r + r_c)^{\alpha}}.
\]

The corresponding cumulative distribution is:

\[
C(r) = \frac{2\pi \Sigma_0}{2 - \alpha} \left[ \left( \frac{r}{r_c} + 1 \right)^{(1 - \alpha)} \left( \frac{r}{r_c} \frac{1}{1 - \alpha} \right) + \frac{1}{1 - \alpha} \right].
\]

For each galaxy we relate \(M_V\) to the stellar mass by \(M_V = -2.5 \log M_* + 4.83\) and assume a ratio \(M_*/M_{vir} = 0.1\) between the stellar and the dark matter mass. For an isolated galaxy, the truncation radius for the GC distribution is taken to be the virial radius. For a cluster galaxy the maximum radius at which the GCs can still be bound to their host is the tidal radius \(r_t\) computed assuming that each galaxy as well as the underlying cluster follows the singular isothermal profile. For a galaxy at distance \(R\) from the cluster center, the tidal radius \(r_t = R\sigma_g/\sigma_c\), where \(\sigma_g\) and \(\sigma_c\) correspond to the galaxy and cluster velocity dispersion, respectively. We stress here that our models for the GC spatial profile are based on the extrapolation of the observed one up to the truncation radius.

The GC spatial distributions in large isolated host galaxies (i.e. \(M_{vir} \sim 10^{12} M_\odot\)) are flatter that in smaller galaxies. GCs can be as far as several hundred kpc, leading to offset of comparable extend. In Fig. 1 we plot the cumulative GC spatial distributions for two different galaxy masses. Solid lines correspond to isolated systems. Dotted, dashed and dot-dashed lines refer to galaxies located at 500 kpc, 1 Mpc and 2 Mpc from the center of a Virgo-like cluster, respectively.\(^2\) For galaxies harbored in clusters, tidal truncation produces smaller offsets as shown in Fig. 1. For the same offset windows of Section 2.1, we find that the bulk of the GC population residing in a large isolated host galaxy is expected to be outside the 100 kpc scale\(^3\). The 10–100 kpc interval is also well populated \((\sim 30\%)\), contrary to the

\(^1\) Belczynski et al. (2006) considered three different galaxy types, i.e. starburst, spiral and elliptical. They investigated both small and large hosts with viral masses of \(\sim 10^9 M_\odot\) and \(\sim 10^{12} M_\odot\), respectively.

\(^2\) We have assumed a mass for the Virgo cluster of \(1.4 \times 10^{15} M_\odot\) according to Fourqué et al. (2001). This for an isothermal sphere corresponds to a \(\sigma_c \sim 1300\) km s\(^{-1}\).

\(^3\) The existence of a possible break in the GC spatial distribution may reduce their fraction at very large distance.

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central ten kpc ($\sim 5\%$). In a small isolated host galaxy, GCs are evenly distributed in the two windows.

For host galaxies in clusters the tidal truncation cuts the GC distribution so that the 10–100 kpc is an ill defined window. In small galaxies, we find the bulk of GCs inside 10 kpc. For the massive ones, less than 10–20% of GC is in this offset window. Bound GCs in large (small) galaxies can extend out to 50-100 (18-75) kpc.

2.3 Dynamical SGRBs: Intra-cluster GCs

Different observations (Bassino et al. 2002, 2003; Jordán et al. 2003) indicate the existence of a population of ICGCs. Theoretical investigations on the spatial distribution of GCs in galaxy clusters predict an ICGC fraction of $\sim 30\%$ regardless of the cluster total mass (Bekki & Yahagi 2006). ICGCs are spread over the cluster volume and can be found far from the cluster center. Using the projected radial density profile of figure 2 by Yahagi & Bekki (2005), we obtain the cumulative distribution of ICGCs as function of the projected distance that is shown in Fig. 2. The plot illustrates that ICGCs can be found up to very large distances from the cluster center with $\sim 20\%$ at $R > 1$ Mpc.

3 AFTERGLOW DETECTABILITY

The intensity of the afterglow of GRBs is expected to be related to the local environment around the burst (Sari, Piran & Natarajan 1998). Given the wide range of SGRB progenitors, of their offsets and therefore of the diverse habitat of the explosion, we try here to discuss possible constraints on the nature of the SGRB formation channels from afterglow observations. For the range of parameters and observation times we are interested in, the afterglow can be modeled as (slow cooling regime; Sari et al. 1998; Perna & Belczynski 2002):

$$F_\nu \sim 1.1n_{\text{ei}}^{1/2}\xi_B^{1/2}E_{50}d_{28}^{-2}(1+z)(\nu/\nu_0)^{-2/3}\text{mJy}$$

(3)

where $\nu_0 = 5.7 \times 10^{13}\xi_B^{1/2}E_{50}^{1/2}t_4^{-3/2}(1+z)^{1/2}$ Hz, $E_{50}$ is the kinetic energy in units of $10^{50}$ erg s$^{-1}$, $d_{28}$ is the luminosity distance in units of $10^{28}$ cm, and $t_4$ is the time from the explosion in days. We assume here an adiabatic shock and isotropic emission. The $\gamma$-ray isotropic equivalent energy output, $E_{\text{iso}}$ is a reasonable estimator of $E$ and usually is taken to be $10^{49–51}$ erg s$^{-1}$ (Nakar 2007). $\xi_B$ is the fraction of the magnetic field energy density of the equipartition value and $\xi_B$ is the fraction of the internal density that is carried by the electrons. $p$ is the power index of the electron distribution. Typical values are $\xi_B \sim 10^{-2.4}$, $\xi_B \sim 10^{-1.2}$ (derived for long GRBs; Panaitescu & Kumar 2001).

A SGRB originated from the primordial channel exploding at a very large offset (i.e. $\gtrsim 100$ kpc) from an isolated host galaxy is embedded in the intergalactic medium. Given the very low gas density ($n \sim 10^{-7}$ cm$^{-3}$), the afterglow, if present at all, should be probably too faint to be detected both in the X-rays and in the optical.

SGRBs from the primordial channel that blow well inside the host, produce relative bright afterglows given the high density of the interstellar medium. Assuming a mean redshift for the primordial population of $z \sim 0.5$ as suggested by Salvaterra et al. (2008), a density $n \sim 1$ cm$^{-3}$ and $E_{50} = 10$, the X-ray afterglow flux is $\sim 2.7 \times 10^{-10}$ erg s$^{-1}$ cm$^{-2}$ and detectable with Swift/XRT. Optical observation by Swift/UVOT at 100 sec from the bursts can reveal the afterglow for the same parameters, while 8-meter telescopes would detect it even one day after the explosion with magnitude $R \sim 23.3$. Weaker explosion energies may not provide enough signal to detect the optical afterglow.

For dynamically formed SGRBs, the burst originates inside the GC. The gas density inside a GC has been measured only for 47 Tuc (Freire et al. 2001, 2003) and is of the order of $\sim 0.1$ cm$^{-3}$. For a SGRBs at an average $z \sim 0.2$ (Salvaterra et al. 2008), one expect to detect the X-ray afterglow for bursts with $E_{50} > 0.5$. Also optical detection with 8-m telescopes is possible for $E_{50} > 1$. For $E_{50} = 10$, the X-ray flux is $5 \times 10^{-10}$ erg s$^{-1}$ cm$^{-2}$ and magnitude $R \sim 22.6$ at 1 day from the burst. In this case, a detection by the UV-optical telescope (UVOT) on aboard to Swift may be possible.

The detectability of afterglows from primordial SGRBs ejected in the intra cluster medium have been studied by Niino & Totani (2008), that predicted an observable X-ray afterglow as the burst is blowing in a medium of $\sim 10^{-3}$ cm$^{-3}$ for $z = 0.2$ (Niino & Totani 2008). The optical afterglow is in this case quite faint (magnitude $R \sim 26$ for a burst exploding at $z = 0.2$ and observed at $t \sim 10^4$ s) requiring 8-m telescope follow-up observations. We note that SGRBs in ICGCs should be brighter as they blow inside the denser medium of the GC, so that a possible discriminant could be the detection of a relative bright optical afterglow.

4 DISCUSSION

In this paper, we showed how the combination of the observed spatial offset, host type/mass and afterglow bright-
ness can shed light on the pathway of formation of SGRB binary progenitors, resulting either from primordial binaries, or from dynamical interactions in GCs. The main results of our study are summarized in Fig. 3. Key results of our analysis are:

- If a SGRB is observed with a large separation from a massive, isolated galaxy we expect that it belongs to the dynamical channel and, residing in a globular cluster, it may show an observable X-ray and optical afterglow;
- A SGRB exploding with a large offset from a small, isolated host galaxy is likely to ensue from the primordial channel. In this case the progenitor binary is ejected in the intergalactic medium following a large natal kick. Nor or weak afterglow is expected given the very low density of the medium;
- A SGRB observed within 10 kpc from the center of a massive galaxy (either isolated or in a cluster) should arise from the primordial channel with a detectable afterglow;
- A SGRB associated to a galaxy cluster but not to any of its specific members may result from both formation scenarios. A possible discriminant could be the detection of an optical afterglow that is expected to be brighter in the case of the denser intra-cluster globular cluster natal environment;
- A SGRB with an offset of 10-100 kpc from a small, isolated galaxy is more probably originated from the dynamical channel and this may be confirmed from the identification of the afterglow.

We now apply our results to a few observed SGRBs. Troja et al. (2008) suggested that SGRBs showing an extended-duration soft emission component in their prompt emission preferentially have small projected physical offsets. Recent HST observations of a sample of SGRB host galaxies show that the distribution of offsets has a median of ∼5 kpc, about 5 times larger than for long GRBs, with no evidence of differences between SGRBs with and without extended emission (Fong et al. 2010). In the case of a host galaxy at low redshift, deep optical/NIR imaging can allow to resolve the galaxy surface brightness profile; the detection of an optical afterglow can then clearly pinpoint the SGRB position with respect to the host galaxy. This is the case of GRB 071227 (z = 0.38) and GRB 060505 (z = 0.09). GRB 071227 was firmly classified as a SGRB (Sato et al. 2007, Golenetskii et al. 2007; Onda et al. 2008) and occurred on the plane of a large (r ∼ 15 kpc) spiral galaxy at a relatively large offset (∼15 kpc; D’Avanzo et al 2009; Fong et al 2010). This could equally favor both the primordial or dynamical formation channel for its progenitor (Fig. 3). We note however that its location on the galactic plane and within the light of the host likely favors a primordial origin. The case of GRB 060505 is even more interesting, given that the classification of this GRB is still debated. The duration (T90 ∼ 4 s) and the spectral lag point towards a long GRB classification (McBreen et al. 2008; Xu et al 2009), the non-detection of an associated supernova down to deep limits favors for a SGRB (Ofek et al. 2007), while detailed study of its host galaxy led to different interpretations of its progenitor (Levesque & Kewley 2007; Thoene et al. 2008). Nevertheless, we note that GRB 060505 is an outlier of the $E_{p,i} - E_{iso}$ correlation like all SGRBs of known redshift and peak energy $E_{p,i}$ (Amati et al. 2007). In the scenario of a double compact object merger progenitor for GRB 060505, the position of the afterglow at an offset of 6.5 kpc from a large spiral galaxy (Levesque & Kewley 2007; Thoene et al. 2008), makes a primordial origin highly probable (Fig. 3). A primordial origin is also a valuable hypothesis for the progenitor of the farthest short-duration (T90 ∼ 1.3 s) GRB, occurred at z ∼ 2.6 (GRB 090426; Levesque et al. 2010; Antonelli et al. 2009). The position of the optical afterglow inside the host galaxy, the intrinsic absorption measured in the X-ray spectrum, and the redshift could be indicative of a “primordial” binary system that merged in a relatively short time (107–108 yr). On the other hand, a core-collapse origin for this burst cannot be excluded in light of its consistency with the $E_{p,i} - E_{iso}$ correlation that holds for long GRBs (Antonelli et al. 2009), making the classification of GRB 090426 not straightforward.

As discussed above, the measure of the redshift of a SGRB is a key issue to accurately evaluate its offset and to relate it with the size of its host galaxy. However, some conclusions can also be drawn for those SGRBs with no measured redshift. The detection of an optical afterglow with sub-arcsec precision coincident with the profile of a galaxy (see, e.g. GRB 070707 and GRB 051227; Piranomonte et al.

\[ \begin{array}{|c|c|c|c|}
\hline
\text{offset} & \text{isolated} & \text{cluster} \\
\hline
\text{prim.} & \text{S} & \text{S} & \text{G} \\
\text{dyn.} & \text{L} & \text{L} & \text{no-G} \\
\hline
0-10 kpc & 0.15 & 0.60 & 0.20 \\
10-100 kpc & 0.10 & 0.20 & 0.75 \\
>100 kpc & 0.75 & 0.20 & 0.20 \\
\hline
\end{array} \]

Figure 3. Percentages of SGRB events with offset in the three domains for the two formation channels and the two galaxy models. The gray scale indicates the afterglow visibility: darker colors refer to brighter afterglows, white is associated to a non detectable afterglow. The percentages are computed for SGRBs resulting from primordial binaries and from the dynamical channel. Left panel is for isolated galaxies where (S/L) refers to the small (large) galaxy model. Right panel is for SGRBs occurring in cluster of galaxies where G(no-G) refers to events bound (un-bound) to a cluster galaxy member. In the case of primordial galaxies there exist a large uncertainty ranging between 20-80% for ejected SGRBs depending on dominance of dark matter in shaping the potential well of the member galaxies (see Niino & Totani 2008). Note that the table does not provide the relative contribution from the two channels but only the distribution in the three offset intervals.

\[ \begin{align*}
E_{p,i} - E_{iso} & \text{ correlation like all SGRBs of known redshift and peak energy } E_{p,i} \text{ (Amati et al. 2007). In the scenario of a } \text{double compact object merger progenitor for GRB 060505, the position of the afterglow at an offset of 6.5 kpc from a large spiral galaxy (Levesque & Kewley 2007; Thoene et al. 2008), makes a primordial origin highly probable (Fig. 3). A primordial origin is also a valuable hypothesis for the progenitor of the farthest short-duration (T90 ∼ 1.3 s) GRB, occurred at } z \sim 2.6 \text{ (GRB 090426; Levesque et al. 2010; Antonelli et al. 2009). The position of the optical afterglow inside the host galaxy, the intrinsic absorption measured in the X-ray spectrum, and the redshift could be indicative of a “primordial” binary system that merged in a relatively short time (10^7–10^8 yr). On the other hand, a core-collapse origin for this burst cannot be excluded in light of its consistency with the } E_{p,i} - E_{iso} \text{ correlation that holds for long GRBs (Antonelli et al. 2009), making the classification of GRB 090426 not straightforward. As discussed above, the measure of the redshift of a SGRB is a key issue to accurately evaluate its offset and to relate it with the size of its host galaxy. However, some conclusions can also be drawn for those SGRBs with no measured redshift. The detection of an optical afterglow with sub-arcsec precision coincident with the profile of a galaxy (see, e.g. GRB 070707 and GRB 051227; Piranomonte et al.}\end{align*} \]
2008, D’Avanzo et al. 2009) strongly hints for an association between the two objects. For these bursts, offsets are consistent with zero, and the SGRB positions follow the host light. From a statistical point of view the majority of these systems probably originate from the primordial channel as a population of SGRBs exploding inside GCs should result in larger offsets.

A few interesting counter examples do exist. GRB 061201 and GRB 070809 are two SGRBs for which the detection of an optical afterglow has allowed to determine their position with high accuracy. Deep, follow-up observations fail to find a host galaxy coincident with the optical afterglow. The field of GRB 061201 has been studied by Stratta et al. (2007) with VLT and Fong et al. (2010) with HST. No host is revealed down to R(AB)= 26.1 (Stratta et al. 2007). Two galaxies are in the field of GRB 061201: a spiral galaxy at z = 0.111 (Stratta et al. 2007) at a projected distance of ∼ 32.5 kpc and a fainter object with undetermined redshift at 1.8′′ (Fong et al. 2010). Although the ejection hypothesis from one of these host candidates can not be excluded, we note that the burst should have likely exploded in a gas poor environment far away from the host. This is in contrast with the relative bright afterglow observed. GRB 061201 is also known to be 0.9 Mpc away from the galaxy cluster ACO S 995 at z = 0.0865. While the ejection hypothesis from the cluster center appears unlikely due to the high kick velocity required, we note that a sizable fraction (∼ 30%, see Fig. 2) of the ICGC population is still present at R > 0.9 Mpc. We suggest that GRB 061201 originates from the dynamical channel inside a ICGC of ACO S 995. The denser environment inside the host GC may be responsible for the brightness of its optical afterglow.

A second interesting case is GRB 070809 that is likely a SGRB (see Barthelmy et al. 2007). Similar to GRB 061201, this burst shows an optical afterglow but no underlying host galaxy to g(AB)=26.3 (Perley et al. 2008). A possible host candidate has been identified in a small spiral galaxy (z = 0.2187 (Perley et al. 2008) at a redshift, the projected distance is ∼ 20 kpc. Accordingly to Fig. 3 the probability of detecting a SGRB with this offset from a small galaxy is rather low (∼ 10%) for the primordial channel. A dynamical origin is preferred in this case. As for GRB 061201, the optical detection of the afterglow supports this interpretation. We also notice that the dynamical channel is expected to contribute most to the SGRB population at the redshift of the putative host of GRB 070809 (Salvaterra et al. 2008).

These two examples show how the results presented in this paper can provide a powerful tool to discriminate the origin of SGRBs.

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Note the existence of another, very faint host candidate with undetermined redshift ∼ 2.3′′ away from the optical afterglow position (Perley et al. 2008).