Journal of High Energy Astrophysics 7 (2015) 73–80

Contents lists available at ScienceDirect

Journal of High Energy Astrophysics

www.elsevier.com/locate/jheap

Review

Short gamma-ray bursts: A review

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ARTICLE INFO

Article history:
Received 24 April 2015
Accepted 24 July 2015

ABSTRACT

Gamma-Ray Bursts (GRBs) are rapid, bright flashes of radiation peaking in the gamma-ray band occurring at an average rate of one event per day at cosmological distances. They are characterized by a collimated relativistic outflow pushing through the interstellar medium shining in gamma-rays powered by a central engine. This prompt phase is followed by a fading afterglow emission at longer wavelength, powered in part by the expanding outflow, and in part by continuous energy injection by the central engine. The observed evidences of supernovae associated to long GRBs (those with a duration of the gamma-ray emission > 2 s) brought to a general consensus on indicating the core collapse of massive stars as the progenitor of these events. Following the most accredited model, short GRBs (the events with a duration of the gamma-ray emission ≤ 2 s) originate from the coalescence of compact binary systems (two neutron stars or neutron star-black hole systems). This paper presents a review of the observational properties of short GRBs and shows how the study of these properties can be used as a tool to unveil their elusive progenitors and provide information on the nature of the central engine powering the observed emission. The increasing evidence for compact object binary progenitors makes short GRBs one of the most promising sources of gravitational waves for the forthcoming Advanced LIGO/Virgo experiments.

1. Introduction

Gamma-ray bursts (GRBs) are rapid, powerful flashes of radiation peaking in the gamma-ray band, occurring at an average rate of one event per day over the whole sky at cosmological distances. The high energy prompt emission is followed by a broadband (X-rays to radio ranges) fading afterglow emission, (Costa et al., 1997; van Paradijs et al., 1997; Frail et al., 1997; Bremer et al., 1998; Heng et al., 2008) that can be observed up to weeks and months after the onset of the event.

The distribution of GRB durations observed by the BATSE[1] instrument (Fishman et al., 1989) is bimodal, with peaks at $T_{90} \sim 0.2$ and $T_{90} \sim 20$ s and a boundary at $T_{90} \sim 2$ s (Kouveliotou et al., 1993).[2] These two classes of long ($T_{90} > 2$ s) and short GRBs ($T_{90} \leq 2$ s) show substantial evidences for different origins. Long GRBs, or at least a significant fraction of the nearby events (with redshift $z \leq 1$) for which it has been possible to search for the presence of a supernova (SN), are associated with the core-collapse explosions of massive stars (see Hjorth and Bloom, 2012, for a recent review), while the nature of short GRB progenitors is still under debate. Current models suggest that they are associated with the merging of compact objects in binary systems, such as a double neutron star (NS), or an NS and a black hole (BH) system (Eichler et al., 1989; Narayan et al., 1992; Nakar, 2007). These systems can originate from the evolution of massive stars in a primordial binary (Narayan et al., 1992) or by dynamical interactions in globular clusters during their core collapse (Grindlay et al., 2006; Salvaterra et al., 2008). A direct evidence supporting the merger scenario has been recently claimed by Tanvir et al. (2013) and Berger et al. (2013) who reported the possible detection of a kilonova (originated by r-process nucleosynthesis) associated to the short GRB 130603B (but see Jin et al., 2013 for further discussion).

Short and long GRBs are not distinguished only by their duration. Considering the observed prompt emission, negligible spectral lag (Norris et al., 2000, 2001) and harder spectra (Kouveliotou et al., 1993) are common for short GRBs. On the other hand, the prompt emission properties of short GRBs are similar to the first 1–2 s of long events (Ghirlanda et al., 2004) and both classes of objects show a similar spectral evolution (Ghirlanda et al., 2011). This might suggest a common emission mechanism for both long and short GRBs.

Since 2005, with the advent of the fast-repointing *Swift* satellite (Gehrels et al., 2004), the discovery of short GRBs afterglows and the identification of their host galaxies made pos-

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[1] Burst and Transient Source Experiment, on board the *Compton Gamma Ray Observatory*.

[2] T_{90} is defined as the time during which the cumulative counts increase from 5% to 95% above background, adding up to 90% of the total GRB counts.

http://dx.doi.org/10.1016/j.jheap.2015.07.002
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sible to study their distances, energy scales and environments (Gehrels et al., 2005). The present *Swift* sample consists of more than 80 short bursts (about 10% of the GRBs detected by *Swift*). Short GRBs are found to be typically less energetic (their isotropic equivalent energy, E_{iso}, is of the order of 10^{49}–10^{51} erg) than long GRBs and to occur at a lower redshift (Nakar, 2007; Berger, 2011; Fong et al., 2013). Their afterglows tend to be significantly fainter on average than those of long GRBs (Kann et al., 2011; Nicuesa Guelbenzu et al., 2012; Margutti et al., 2013). Concerning the host galaxies, short GRBs occur in both early and late type galaxies with low star formation rate and are associated with an old stellar population (Berger, 2009; Leibler and Berger, 2010; Fong et al., 2013). A different origin for short GRBs with respect to the long GRB class is also supported by the lack of detection of the underlying SN in the light curves of their optical afterglows down to very stringent magnitude limits (Hjorth et al., 2005a, 2005b; Fox et al., 2005; Covino et al., 2006; Kann et al., 2011; D'Avanzo et al., 2009) and by their inconsistency with the correlation, valid for long GRBs, between the rest frame spectral peak energy and E_{iso} (E_{peak}–E_{iso} correlation; Amati et al., 2002). On the other hand, Ghirlanda et al. (2009) showed that short GRBs are consistent with the same E_{peak}–L_{iso} correlation (where L_{iso} is the prompt emission isotropic peak luminosity) defined by long GRBs (Yonetoku et al., 2004). The distributions of the intrinsic X-ray absorbing column densities of long and short GRBs do not show significant differences when compared in the same redshift range ($z \leq 1$; Kopac et al., 2012; Margutti et al., 2013; D'Avanzo et al., 2014). An alternative approach to classify GRBs, that goes beyond the prompt emission properties, has been proposed by Zhang et al. (2009) using several criteria (mostly based on the whole, prompt, afterglow and host galaxy, GRB properties) that are more directly related to the nature of GRB progenitors (see also Lu et al., 2010). Finally, given that the measured duration of the GRB prompt emission can vary for different instruments (e.g. due to the different energy band used), it has been recently proposed that the value of T_{90} used to divide the long and short GRBs should be reduced to about 0.8 s for the *Swift* bursts (Bromberg et al., 2013). A recent review of the properties of short GRBs has been presented by Berger (2014).

The majority of the studies reported above is based over the entire sample of short GRBs with measured redshifts. Although this approach has the clear advantage of describing the intrinsic physical properties of these objects, it can be severely affected by observational biases, given that almost 3/4 of the *Swift* short GRBs are lacking a secure redshift measurement. With the aim of overcoming this problem, D'Avanzo et al. (2014) selected a sub-sample of the full *Swift* short GRB database with favorable observing conditions for redshift determination from the ground and which are bright (in terms of the observed peak flux) in the 15–150 keV *Swift*-BAT energy band. An analogous, although less tight, cut was used in Salvaterra et al. (2012) to built the BAT6[3] sample of long GRBs. Although relatively small (16 events up to June 2013), this sample of short GRBs (named S-BAT4[4]) is complete in flux and has the highest completeness in redshift (70%) with respect to the short GRB samples presented in the literature to date. Through the paper, we will mainly refer to the results obtained on the S-BAT4 sample when discussing the rest-frame physical properties of short GRB prompt and afterglow emission.

[3] This flux-limited sample selects long GRBs having the 1-s peak photon flux $P \geq 2.6$ ph s^{-1} cm^{-2} in the 15–150 keV *Swift*-BAT energy band. This corresponds to an instrument that is ~ 6 times less sensitive than *Swift*.

[4] This flux-limited sample selects short GRBs having the peak photon flux $P \geq 3.5$ ph s^{-1} cm^{-2} using the 15–150 keV *Swift*-BAT light curves binned with $\delta t = 64$ ms. This corresponds to an instrument that is ~ 4 times less sensitive than *Swift*.

2. Clues for progenitors

As discussed in Section 1, short GRB progenitors (binary systems of compact objects) can originate from the evolution of massive stars in a primordial binary (i.e. a system born as binary) or by dynamical interactions and capture in globular clusters during their core collapse. In primordial systems, the delay between binary formation and merging is driven by the gravitational wave inspiral time, which is strongly dependent on the initial system separation. Some systems are thus expected to drift away from the star-forming regions in which they formed, before merging takes place, also because they experience a natal kick at the time of the formation of the compact object. Simulations (Belczynski et al., 2002, 2006) show that a large fraction of the merging events should take place in the outskirts or even outside the galaxies, in low density environments. A low density circumburst environment is expected also for short GRBs of dynamical origin occurring in globular clusters. For these events, the resulting time delay between star-formation and merging would be dominated by the cluster core-collapse time and thus be comparable to the Hubble time (Hopman et al., 2006). A much faster evolutionary channel has been proposed (Belczynski and Kalogera, 2001; Perna and Belczynski, 2002; Belczynski et al., 2006), leading to merging in only $\sim 10^6$–10^7 yr, when most systems are still immersed in their star-forming regions. According to the above scenario, with the exception of the events originated by the "fast" primordial channel, short GRBs are generally expected to occur in regions where the density of the diffuse medium is low, giving rise to fainter afterglows, setting in at later times than those of long GRBs (e.g. Vietri, 2000; Panaitescu et al., 2001; Salvaterra et al., 2010).

Key issues that could help in discriminating between the different theoretical scenarios summarized above and, more in general, in confirming the validity of the current short GRB progenitor model are the study of the afterglows and host galaxies properties, accurate measurements of the spatial offsets between afterglows and host galaxy centers, reliable redshift determinations, the absence of associated supernovae, evidences for *r*-process kilonova emission and the emission of associated gravitational waves over a sufficiently large sample of events.

3. Prompt emission

3.1. Extended emission

A fraction (15% over the *Swift* sample) of short GRBs exhibits the presence of an extended γ-ray emission that is softer than the prompt spike, last tenths of seconds and may rise with a delayed onset. Such an emission component has a softer spectrum with respect to the initial prompt spike (Lazzati et al., 2001), and can dominate (in terms of fluence) the prompt spike emission (Perley et al., 2009). This soft extended component was initially interpreted as the onset of the X-ray afterglow (Lazzati et al., 2001), until a study by Norris and Bonnell (2006) identified it as a prompt emission component. Troja et al. (2008) suggested that differences in the spatial offsets from their hosts observed for short GRBs with and without extended emission can be indicative of distinct progenitors for the two classes of objects. Lazzati et al. (2010) suggested that short GRBs with extended emission may be produced from the same massive star progenitors as long GRBs, but with a wide off-axis viewing angle. Norris et al. (2011) argued that bursts with extended emission have longer prompt-emission timescales and higher initial X-ray afterglow fluxes, potentially indicative of larger energy injections powering the afterglows and of differences in the central engine. However, despite several attempts, no clear distinguishable features were found when performing comparison studies between the properties of their afterglows, offsets and host galaxies with respect to those of short GRBs without extended emission (Fong and Berger, 2013; Fong et al., 2013; D'Avanzo et al., 2014). Different authors (Metzger et al., 2008; Bucciantini et al., 2012; Gompertz et al., 2014) claimed that the soft extended emission can be interpreted as a signature of a newly-born magnetar powering the observed short GRB emission (see Section 10).

3.2. Precursors

Precursor γ-ray emission, preceding the main event by a quiescent time that may be comparable to the T_{90}, has been found in at least 15% of long GRBs (Lazzati, 2005; Burlon et al., 2009). In some cases, more than one precursor has been observed in the same burst. A systematic search carried out by Troja et al. (2010) over the *Swift* sample found significative evidences for precursor emission in short GRBs too.

3.3. Spectral hardness

One of the key properties characterizing the short GRBs is their prompt emission spectrum, which is found to be typically harder with respect to long GRBs (Kouveliotou et al., 1993). Considering the GRB prompt emission spectrum as described by a Band function (Band et al., 1993), the short GRB spectral hardness is found to be due to a combination of a harder low-energy spectral component (the α index of the Band function) and to a higher spectral peak energy (Ghirlanda et al., 2009). However, these differences become less significant when the analysis is restricted to the first 1–2 s of the long GRBs prompt emission (Ghirlanda et al., 2004, 2009). At the same time, Ghirlanda et al. (2004) showed that for the brightest short GRBs detected by BATSE, the difference in the spectral hardness with respect to long GRBs is mainly driven by a harder low energy spectral index present in short bursts, rather than due to a different peak energy. Such result is corroborated by a study performed by D'Avanzo et al. (2014) on a sub-sample of bright *Swift* short GRBs (the S-BAT4 sample).

3.4. Spectral lags

As reported in Section 1 the spectral lag has been proposed as a distinctive feature of short and long GRBs with the former having null lag (Norris et al., 2000, 2001). Several possible interpretations have been proposed for the origin of the observed GRB spectral lag. Among them, there are the spectral evolution during the prompt GRB phase (implying the time evolution of the peak energy cross energy bands) or curvature effect of the shocked shell (Ukwatta et al., 2012 and references therein). It has been shown that also long GRBs can have null lag (Norris, 2002; Krimm et al., 2006; Troja et al., 2012; Bernardini et al., 2015), although those are the events with the highest peak luminosities and occupy different regions of the lag–luminosity plot with respect to the zero lag, low peak luminosity short GRBs (Norris and Bonnell 2006; Gehrels et al., 2006). However, a recent analysis (carried out using the BAT6 and S-BAT4 complete samples of short and long GRBs) of the spectral lags in the rest frame has shown that short GRBs are consistent with the long ones in the lag-luminosity plane, with the indication that the lag–luminosity relation could be a boundary (Bernardini et al., 2015). The physical origin of the spectral lag and its use as a tool to discriminate between long and short GRBs remains thus uncertain.

3.5. Spectral energy correlations

Short GRBs are found to be consistent with the E_{peak}–L_{iso} correlation, which holds also for long GRBs (Yonetoku et al., 2004; Nava et al., 2012). D'Avanzo et al. (2014) reported evidence for an E_{peak}–L_{iso} correlation followed by short GRBs being systematically fainter than the correlation defined by long GRBs. Although such finding is intriguing, they caution that it can be affected by the choice of the temporal bin in the estimate of the isotropic peak luminosity for both long and short GRBs. Concerning the E_{peak}–E_{iso} plane, most of the short GRBs lie at more than 3σ from the correlation defined by long GRBs (Amati et al., 2002), and systematically on the left with respect to the best-fitting line of long GRBs. This may be indicative of the existence of a short GRB region that has the same slope as the long GRBs relation, but a different normalization (see also Amati, 2008; Piranomonte et al., 2008; Ghirlanda et al., 2009; Zhang et al., 2012). Calderone et al. (2015) showed that considering the intrinsic E_{peak}, E_{iso} and L_{iso} spectral quantities, the spectra of both the short GRBs and the first 0.3 s (rest frame) of long ones are actually indistinguishable, despite the likely different progenitors and different total energy involved. In particular, if a long GRB (whatever its progenitor) should last less than 0.3 s (rest frame) we would not be able to distinguish it from a short GRB with current detectors. Finally, both short and long GRBs lie on the three parameter correlation E_{iso}–E_{peak}–E_X correlation (with E_X being the afterglow energy emitted in the soft X-ray band; Bernardini et al., 2012; Margutti et al., 2013). These findings suggests that a common process may be at work in both short and long GRBs.

4. Afterglows

In 2005, mainly thanks to the fast re-pointing capabilities of the *Swift* satellite, the first afterglows of short GRBs were detected in the X-rays, optical, NIR and radio bands (Gehrels et al., 2005; Fox et al., 2005; Hjorth et al. 2005a, 2005b; Barthelmy et al., 2005; Berger et al., 2005; Covino et al., 2006). Since then, relatively sparse studies of short GRB afterglows have been carried out, in particular if compared to the progresses achieved in the long GRB field. However, some useful insights about short GRB properties like energetic efficiency, environment and jet opening angles could be obtained from the current dataset. As reported in Berger (2014), the broadest and most homogeneous data set for short GRB afterglows is in the X-ray band from *Swift*/XRT, with about 50 X-ray detections. Among these, about one half have a detection in the optical band, and only for a few events a radio afterglow could be detected. Due to the scarceness of multi-band afterglow observations, the information of jet opening angles (θ_j) for short GRBs is relatively poor. Combining the measured opening angles and lower limits available in Fong et al. (2014) estimates a median $<\theta_j> \sim 10°$ for short GRBs. As for the long GRBs, signatures of deviations from the standard afterglow model (like steep decay, flares and plateaus) are observed in the X-ray light curves of short GRB afterglows (Evans et al., 2009; Margutti et al., 2013). While there is general consensus on the association of the initial steep decay and of early time X-ray flares ($t \leq 1000$ s) with the prompt emission (Kumar and Panaitescu, 2000; Tagliaferri et al., 2005; Burrows et al., 2005; Nousek et al., 2006; Chincarini et al., 2007, 2010; Margutti et al., 2010, 2011) and of the normal decay with pure external forward shock afterglow emission (Sari et al., 1998; Chevalier and Li, 2000), the nature of the plateau decay phase is still debated. The usual explanation of this phase (holding for both short and long GRBs) is that the observed emission is a combination of external forward shock (afterglow) and energy injection coming from late-time activity of the central engine (see, e.g., Zhang et al., 2006 and references therein). Late time X-ray flares/excesses have been also observed in short GRBs, with possible correspondence also in the optical/NIR (Campana et al., 2006; Grupe et al., 2006, Malesani et al. 2007; Perley et al., 2009; Fong et al., 2013). These late-time flares (observed in long GRBs

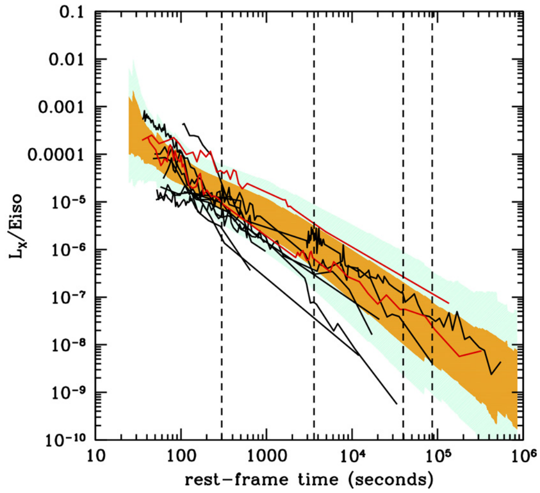

Fig. 1. Best fit of the X-ray luminosity light curves of the SGRBs with redshift of the S-BAT4 sample normalized to their E_{iso} (from D'Avanzo et al., 2014). The X-ray luminosities were computed for each GRB in the common rest frame 2–10 keV energy band. The vertical dashed lines mark the rest frame times 5 min, 1 h, 11 h, and 24 h. The dark (light) shaded area represents the 1σ (2σ) scatter of the same plot obtained for the long GRBs of the BAT6 sample (D'Avanzo et al., 2012).

too) are likely due to variability of the afterglow (external shock) emission (Bernardini et al., 2011).

When compared to long GRBs, the X-ray and optical afterglows of short GRBs are found to be significantly fainter (Margutti et al., 2013; Kann et al., 2011; Nicuesa Guelbenzu et al., 2012). This can be due to a different energetic (with short GRB afterglows being fainter because they are less energetic) or being indicative of a different density environment (with short GRBs occurring in environments with a lower density scale). The rest-frame luminosity of both long and short GRBs correlates with the isotropic equivalent energy, E_{iso} in the X-rays (Nysewander et al., 2009; Margutti et al., 2013; D'Avanzo et al., 2012, 2014; Berger, 2014) and in the optical (Nysewander et al., 2009; Berger, 2014). At early times ($t \leq 1$ h), both long and short GRBs show a good correlation between their rest frame X-ray luminosity and E_{iso}. In particular, short and long GRBs are consistent with the same L_X–E_{iso} scaling (D'Avanzo et al., 2012, 2014), although Margutti et al. (2013) reported that short GRBs tend to lie below the best-fitting law holding for long bursts. At later times, the same correlation becomes weaker and more scattered (Fig. 1). The existence of a same L_X–E_{iso} scaling for all GRBs becomes less significant (D'Avanzo et al., 2014) with an increasing evidence that short GRBs have a fainter X-ray luminosity with respect to long bursts, even when compared in the same E_{iso} range (Margutti et al., 2013; Berger, 2014). The decrease of significance of these correlations with time indicates that the GRB early X-ray luminosity is still dominated by the prompt emission, while at late times the most significant contribution to the X-ray luminosity is given by the external shock afterglow emission. As for the X-ray luminosity, also the late time rest-frame optical luminosity is found to correlate with E_{iso} for all GRBs, with short GRBs having systematically weaker optical afterglow emission compared to long GRBs when compared in the same E_{iso} range (Berger, 2014). In conclusion, the intrinsic faintness of short GRB afterglows can just be partly the consequence of a lower energy scale. Particularly at late times ($t > 1$ h), where the external shock afterglow emission is expected to be dominant, a lower density of the circumburst medium may also be invoked to explain the observed afterglow luminosities. This is also supported by the faint detections and limits currently available in the radio band (Berger, 2014).

5. Host galaxies

A key observational evidence that long and short GRBs are originated by two distinct classes of progenitors comes from the study of their host galaxies. As expected for young massive star progenitors, long GRBs are found to occur in star-forming galaxies (Bloom et al., 2002; Fruchter et al., 2006; Wainwright et al., 2007; Savaglio et al., 2009). On the other hand, the occurrence of short GRBs in both star-forming and early-type galaxies (Fig. 2, left and central panels) indicates that their progenitors can be associated to both young and old stellar population (Berger et al., 2005; Fox et al., 2005; Bloom et al., 2006, Fong et al., 2011, 2013). In particular, the association with elliptical galaxies has been secured for two short GRBs whose optical afterglow was found to lie within the host galaxy light with a sub-arcsecond precision (GRBs 050724A and 100117A). In both cases, the study of the galaxies' optical spectra and optical/NIR spectral energy distributions provided evidence for low star-formation activity (<0.1 $M_\odot$ yr^{-1}) and old stellar population (≥ 1 Gyr), leading to a secure identifications for these hosts as early-type galaxies (Barthelmy et al., 2005; Berger et al., 2005, Malesani et al., 2007; Fong et al., 2011). By including also short GRB-elliptical host galaxies associations proposed on chance probability arguments Fong et al. (2013) estimates that about 20% of short GRBs are associated with early-type host galaxies.

In terms of properties like mass, stellar population age, specific star formation rate and metallicity, the host galaxies of short GRBs are found to be significantly different with respect to galaxies hosting long GRBs. As inferred from the modeling of their optical/NIR spectral energy distributions, the short GRB host galaxies have a median stellar mass $< M_* > \sim 10^{10.0}$ $M_\odot$ (Leibler and Berger, 2010), a higher value with respect to the median stellar mass found for long GRB hosts ($10^{9.2}$ $M_\odot$; Savaglio et al., 2009; Leibler and Berger, 2010). As reported above, short GRBs are associated to a mixed population of early and late-type host galaxies. This is indicative of a wide range of stellar population ages, that can be expected to be on average older with respect to the one associated to long GRB, occurring in star-forming galaxies only. Indeed, as reported in Leibler and Berger (2010), the median stellar population age is of $< \tau_* > \sim 0.25$ Gyr and $< \tau_* > \sim 60$ Myr for the host galaxies of short and long GRBs, respectively. The median specific star formation rate (star formation rate as a function of luminosity) for long GRB host galaxies is 10 $M_\odot$ yr^{-1} L_*^{-1} (Christensen et al., 2004), about an order of magnitude higher than that of short GRB hosts (Berger, 2009, 2014). Also in terms of metallicity, the short GRB hosts span a wide range of values, with $12 + \log(O/H) \sim 8.5$–9.2, with a median value of $<12 + \log(O/H)> \sim 8.8 \sim 1Z_\odot$ (Berger, 2009; D'Avanzo et al., 2009). More in general, when compared to survey field star-forming galaxies in similar ranges of redshift and luminosity, short GRBs host galaxies (at variance with long GRB hosts) reveal a very good agreement in terms of specific SFRs and metallicity (Berger, 2009).

To date, an associated host galaxy candidate has been found for about half of the Swift short GRBs. In particular, almost all well localized short GRBs ($< 5''$ error radius) have a candidate host galaxy inside their position error circle, but only for fifteen events with an observed optical afterglow could a firm GRB-galaxy association be established (Berger, 2014). Among the bursts with an optical (subarcsec) localization, four (GRB 061201, GRB 070809, GRB 080503, 090515) currently lack a secure host identification in spite of the careful observing campaigns carried out down to deep magnitude limits ($R \sim 25$–28 mag; Stratta et al., 2007; Perley et al., 2009; Fong et al., 2010; Berger, 2010). As discussed in Berger (2010), the "host-less" nature of these short GRBs may be caused by a progenitor having been kicked out from its host (or that is sited in an

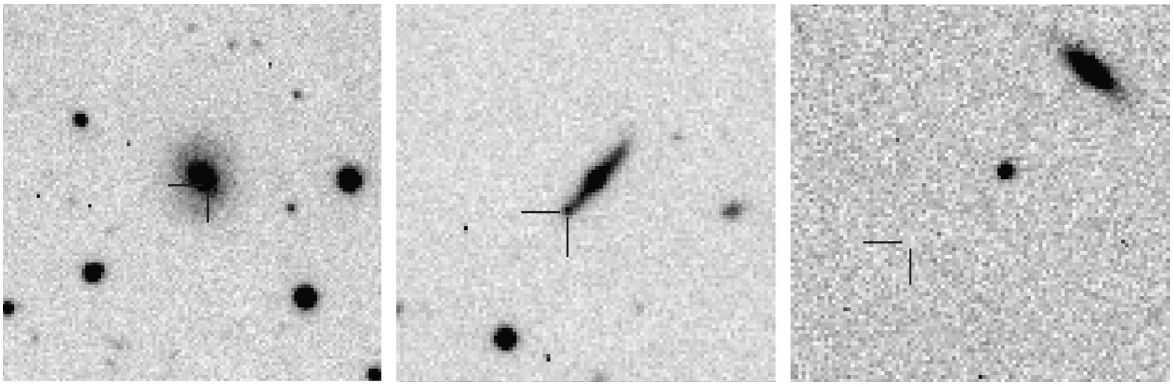

Fig. 2. The diversity of short GRBs host galaxies. The early type host galaxy of GRB 050724 (Barthelmy et al., 2005; Malesani et al. 2007; left panel), the late-type host galaxy of GRB 071227 (D'Avanzo et al., 2009; central panel) and the host-less GRB 061201 (Stratta et al., 2007; Berger, 2010; right panel). All images were obtained in the R-band with the ESO-VLT equipped with the FORS camera. Each box is $25'' \times 25''$ wide. North is up and East is left. The solid lines mark the position of the optical afterglow.

outlying globular cluster) or by high-redshift ($z > 1$) events, whose host galaxies are too faint to be detected by the current observational campaigns (Fig. 2, right panel).

6. Offsets

In the context of double compact object progenitors, the offset distribution of the short GRB afterglows with respect to their host galaxies contains information on the merging times and thus on the evolutionary channels regulating binary systems evolution (Salvaterra et al., 2010). Preliminary studies of short GRB offsets (Berger et al., 2005; Fox et al., 2005; Bloom et al., 2006; Soderberg et al., 2006; Troja et al., 2008; D'Avanzo et al., 2009) reveal a somewhat larger projected physical offsets than for long GRBs, although no conclusive evidence was found for afterglows lying outside the light of their hosts and/or presenting evidence for low local absorption in their X-ray spectra (D'Avanzo et al., 2009). Evidences for local X-ray absorbtion, with no correlation with the short GRBs offset has been reported also by Kopac et al. (2012). A first, systematic study performed by Fong et al. (2010) shows that the observed distribution of projected physical offsets for short GRBs is about five times larger than that for long GRBs and in good agreement with the predicted offset distributions for (NS–NS) binary mergers. On the other hand, the distinction between the two offset distributions is significantly reduced when considering host-normalized offsets, due to the larger size of short GRB hosts. However, even when taking into account the host galaxy size, the short GRB normalized offsets are still on average about 1.5 times larger than the values found for long GRBs (Fong and Berger, 2013). Furthermore, these authors report that the spatial distribution of short GRBs inside their host galaxies do not track the hosts' rest-frame UV or optical light, an indication that these systems migrate from their birth sites to their eventual explosion sites.

In the scenario of compact binary progenitors, these results suggest that most short GRBs are likely originated by the merging of "primordial" binary compact object systems. However this conclusion can be valid only for those short GRBs with a secure host galaxy association.

7. Redshift distribution

Recently, the redshift of the exceptionally bright short GRB 130603B has been measured through spectroscopy of its optical afterglow. This is the first clean absorption spectrum obtained for the optical afterglow of a securely-classified short GRB (Cucchiara et al., 2013; de Ugarte Postigo et al., 2014). Optical afterglow spectroscopy of short GRBs have been reported in the past also for GRB 090426 and GRB 100816A (Antonelli et al., 2009; Levesque et al., 2010; Tanvir et al., 2010; Gorosabel et al., 2010), whose classification as short GRBs is however highly uncertain (Nicuesa Guelbenzu et al., 2012; D'Avanzo et al., 2014), while with a $T_{90} = 0.18$ s, a hard spectrum and negligible spectral lag, GRB 130603B can be classified as a short GRB beyond any doubt (Barthelmy et al., 2013; Norris et al., 2013; Golenetskii et al., 2013). However, apart from such exceptional event, the remaining short GRB redshifts are obtained through spectroscopy of their associated host galaxies. A direct consequence of this is that the short GRB-host galaxy association can only be secured when the optical afterglow is detected and found to lie within the host galaxy light with a sub-arcsecond precision or proposed on chance probability arguments (and not, e.g., by matching the redshift measured through spectroscopy of both the optical afterglow and the host galaxy). In light of this, we will consider as GRBs with a secure redshift measurement only those events for which an optical afterglow was found to lie within the host galaxy light or those events having a host galaxy whose position is within a precise X-ray error circle. To this end, the use of X-ray telescope with good angular resolution, like *Chandra*, clearly provides a major asset (see, e.g., Margutti et al., 2012; Sakamoto et al., 2013).

The redshift distribution of short GRBs can provide an indirect tool to constrain the nature of their progenitors and discriminate among the evolutionary channels. The redshift distribution of merger events of dynamically formed double compact object systems is expected to be different from that of primordial binaries. In particular, given the relatively short delay between formation and merging (<1 Gyr), short GRBs originated by the "fast" primordial channel should have a redshift distribution which broadly follow that of the star formation, especially at low redshift. D'Avanzo et al. (2014) reported an average (median) redshift for the short GRBs of their sample of $< z > = 0.85$ (0.72). This value is higher than the one obtained by Fong et al. (2013) by considering the whole *Swift* short GRB sample ($< z > \sim 0.5$) while it is in agreement with the mean redshift ($< z > = 0.72$) reported by Rowlinson et al. (2013) for their short GRB sample limited to the events with $T_{90} \leq 2$ s (which is thus excluding all short GRB with extended emission). Indeed, an average redshift of $z \sim 0.7$–0.8 is consistent with the expected peak for the redshift distribution of short GRBs originated by the primordial formation channel (Salvaterra et al., 2008). D'Avanzo et al. (2014) compared their observed redshift distribution with the expected distribution of short GRBs originated by primordial binary systems having a delay time distribution function $f_F(t) \propto t^n$. To this end, they used three different values of n, namely $n = -1.5$, $n = -1$ and $n = -0.5$, with characteristic delay times varying from $\sim$20 Myr to $\sim$10 Gyr. As shown in Fig. 3 it is clear that the model with $n = -0.5$ can be firmly discarded.

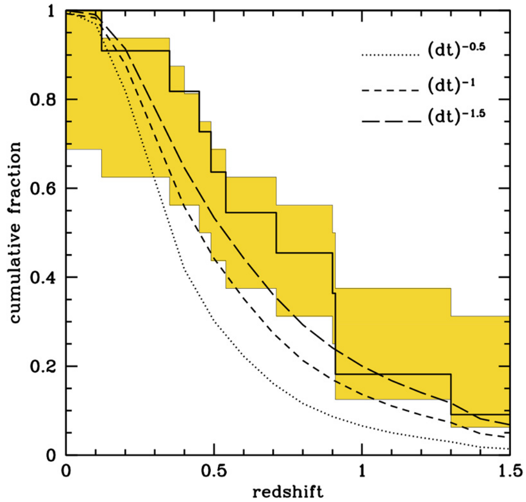

Fig. 3. Redshift distribution of the S-BAT4 sample of SGRBs (from D'Avanzo et al., 2014). The shaded are takes into account the uncertainties due to the lack of redshift measurement for five bursts in the sample. Model results for $n = -1.5$, -1, and -0.5 are shown with the long-dashed, short-dashed and dotted line, respectively. In computing the expected redshift distribution for the different model we apply the same photon flux cut, $P_{64} \geq 3.5$ ph s^{-1} cm^{-2} in the *Swift*-BAT 15–150 keV band, used in the definition of the sample.

A model with $n = -1$ is still acceptable, while the model with a time delay distribution $f_F(t) \propto t^{-1.5}$ looks to be favored in accounting for the observed redshift distribution of the SGRBs of our sample, suggesting that they are mainly originated by primordial double compact object systems merging in a relatively short time.

We note that a significant contribution of short GRBs with dynamical origin would require a lower mean redshift (Salvaterra et al., 2008; Guetta and Stella, 2009), suggesting that the contribution of this formation channel to the short GRBs should be negligible and/or limited to the faintest events (which are not included in our flux-limited sample). A tentative estimate of the fraction of short GRBs with dynamical origin in our sample is given in the next section.

8. Environment

When compared in the same redshift bin ($z \leq 1$), the distribution of the intrinsic X-ray absorbing column densities obtained from X-ray afterglow spectroscopy of long and short GRBs are fully consistent (Kopac et al., 2012; Margutti et al., 2013; D'Avanzo et al., 2014). Although this result can be interpreted as the evidence of a common environment for long and short GRBs, we caution that the intrinsic X-ray N_H might be a good proxy of the GRB host galaxy global properties but not for the specific properties of the circumburst medium. Furthermore, the possibility that gas along the line of sight in the diffuse intergalactic medium or intervening absorbing systems can contribute to the absorption observed in the X-ray emission of GRBs has to be taken into account (Behar et al., 2011; Campana et al., 2012; Starling et al., 2013). However, such effect is expected to dominate at $z \geq 3$, while at lower redshifts, comparable to the values found for short GRBs, the absorption within the GRB host galaxy is expected to dominate (Starling et al., 2013). For long GRBs, the massive star progenitor is expected to significantly enrich the surrounding environment with metals (whose X-ray N_H is a proxy) before the collapse with its stellar wind. Alternatively, it has been recently proposed that the Helium in the H II regions where the burst may occur is responsible for the observed X-ray absorption in long GRBs (Watson et al., 2013). Under these hypothesis, a high intrinsic X-ray N_H, can be interpreted as the evidence of a dense circumburst medium. Something similar can happen for short GRBs, under the condition that a short time (of the order of Myrs) separates the supernova explosions which gave origin to the compact objects in the primordial binary system progenitor and its coalescence, with the result that the burst would occur inside its host galaxy and near its star forming birthplace (Perna and Belczynski, 2002). Such formation channel of "fast merging" primordial binaries is in agreement with the observed redshift distribution discussed in the previous section. Indeed, the only case for which combined X-ray and optical afterglow spectroscopy could be performed for a genuine short GRBs (GRB 130603B, which is included in our sample), provided evidence for a progenitor with short delay time or a low natal kick (de Ugarte Postigo et al., 2014).

Short GRBs originated by double compact object systems which experienced a large natal kick or which are dynamically formed in globular clusters are expected to be associated with a low-density environments. As discussed in Berger (2010) "hostless" short GRBs may lie at moderately high redshifts $z > 1$, and have faint hosts, or represent a population where the progenitor has been kicked out from its host or is sited in an outlying globular cluster. A statistical study carried out recently by Tunnicliffe et al. (2014) pointed out that the proximity of these events to nearby galaxies is higher than what is seen for random positions on the sky, in contrast with the high redshift scenario. By taking into account the fraction of "hostless" short GRBs, together with those events having tight upper limits on the intrinsic X-ray N_H, D'Avanzo et al. (2014) propose that about 10%–25% of short GRBs might have occurred in low-density environments because formed via the dynamical channel (or having experienced a large natal kick).

9. Lack of supernova associations and kilonova emission in short GRBs

Several attempts of search for associated supernovae (SNe) to sufficiently nearby short GRB have been carried out so far. However, at variance with the findings obtained for long GRBs, no signature of underlying SN in the light curves of eight short GRB optical afterglows have been found to date (namely, GRB 050509B, GRB 050709, GRB 050724, GRB 051221A, GRB 070724A, GRB 071227, GRB 080905A, GRB 130603B; Hjorth et al., 2005a, 2005b; Fox et al., 2005; Covino et al., 2006; Soderberg et al., 2006; D'Avanzo et al., 2009; Rowlinson et al., 2010; Kocevski et al., 2010; Kann et al., 2011; Berger et al., 2013), in spite of the predominance of star-forming host galaxies for these events. In all cases, the search have been carried out down to very stringent magnitude limits (significantly fainter than the prototypical long GRB/SN 1998bw). At least for those short GRBs with deep SN limits, a massive-star origin can be safely excluded.[5]

A key signature of an NS–NS/NS–BH binary merger is the production of a so-called "kilonova"[6] due to the decay of heavy radioactive species produced by the r-process and ejected during the merger process that is expected to provide a source of heating and radiation (Li and Paczynski 1998; Rosswog, 2005; Metzger et al., 2010). Recent investigations of the opacities connected to r-process matter indicated that the bulk of kilonova emission is expected to peak in the NIR on a timescale of a few days (Kasen et al., 2013; Grossman et al., 2014; Tanaka and Hotokezaka, 2013). The first short GRB–kilonova association has been proposed for GRB 130603B ($z = 0.356$) by Tanvir et al. (2013) and

[5] A recent work by Bromberg et al. (2013) proposed that the T_{90} value to be used to divide the long and short GRB classes (discriminating between a collapsar or merger origin) should be lowered from ~ 2 s to ~ 0.8 s for *Swift* GRBs. We note that one half of the *Swift* short GRB with secure SN non-detections listed above (namely, GRB 051221A, GRB 050724, GRB 071227, GRB 080905A) have $T_{90} > 0.8$ s.

[6] An equivalent terminology used in the literature is "macronova", "minisupenova" or "r-process supernova".

Berger et al. (2013). By performing a combination of early-time ground-based observations and late time (9 and 30 days after the burst) *HST* observations, these authors found evidence for a significative excess in the NIR flux with respect to the late-time afterglow temporal decay. Such excess was instead not detected in the optical band. The observed NIR flux and the red color of this late-time emission provided a good match with the predictions for a kilonova occurring at the redshift of GRB 130603B. In spite of the poor sampling of the GRB 130603B light curve (the observed NIR excess is based of just one photometric point) and the existence of alternative explanations (Jin et al., 2013) this results still provides a strong support to the compact object binary progenitor model for short GRBs, being the first attempt of providing a direct evidence of such a scenario. Another note-worthy case is represented by GRB 060614. This was a nearby ($z = 0.125$) burst with a duration of 102 s. While it can be classified as a long burst according to its duration, the prompt emission exhibited an initial spike with negligible spectral lag, typical of short GRBs, followed by a softer extended emission (Gehrels et al., 2006). Its host galaxy has a low luminosity typical of long GRB hosts, but a lower specific star formation rate (Gal-Yam et al., 2006). Furthermore, the burst was located at a significant offset from the host in a region with little evidence for ultraviolet emission (Gal-Yam et al., 2006). Despite the low redshift, no supernova association was found down to deep limits (Della Valle et al., 2006; Fynbo et al., 2006), suggesting a non-massive star progenitor. Interestingly, a recent re-analysis of the afterglow data of GRB 060614 collected with *HST* presented by Yang et al. (2015), show the evidence for a possible kilonova associated to this burst, suggesting that it may be originated from a double compact object progenitor.

10. Clues for a magnetar central engine

In the context of NS–NS binary progenitors, the system coalescence may lead to the formation of a transitory or stable magnetar (a rapidly spinning and highly magnetized neutron star; Usov 1992; Duncan and Thompson, 1992; Metzger et al., 2008). According to this scenario, a newly born magnetar can be the central engine powering the observed emission of (at least some) short GRBs. Different observational GRB properties have been proposed as signatures of magnetar activity. The extended emission observed in the prompt emission of some short GRBs (see Section 3.1) has been proposed to be powered either by the relativistic wind caused by the magnetar loss of rotational energy (spin-down; Metzger et al., 2008; Bucciantini et al., 2012) or by magnetic propelling of fall-back accreting material surrounding the magnetar (Gompertz et al., 2014). As proposed by Fan and Xu (2006), Rowlinson et al. (2013) and Gompertz et al. (2014) the magnetic dipole spin-down emission may be the source of energy powering the X-ray plateaus observed in some short GRB afterglow light curves (Section 4). The dipole radiation of a newly-born supermassive millisecond magnetar (formed in coalescence of double neutron stars systems) has been also proposed as the source of energy for the early X-ray flares observed in short GRB light curves (Gao and Fan, 2006). Finally, the precursors observed prior to the main prompt emission and the early X-ray flares (which may be also called "postcursors", being also originated by internal shocks as discussed in Section 4) can arise from accretion of matter onto the surface of the magnetar. The accretion process can be halted by the centrifugal drag exerted by the rotating magnetosphere onto the in-falling matter, allowing for multiple precursors and very long quiescent times. Although such scenario has been proposed for long GRBs (Bernardini et al., 2013), the occurrence of precursors and flares in both long and short GRBs (see Sections 3.2 and 4) may suggest that it can be valid for both GRB classes. A comprehensive review of magnetars signatures in GRBs is presented by Bernardini (2015) in this volume.

11. Conclusions and future perspectives

A decade of systematic short GRB observations of their prompt emission, afterglows and host galaxies provided an impressive advance in the knowledge of these sources and put strong constraints on the nature of these elusive sources. Properties like the absence of associated supernovae, the afterglow faintness, the occurrence in early type galaxies, the offset and redshift distribution and the detection of a possible kilonova associated to the short GRB 130603B, definitely point towards a non-massive star origin, at variance with what observed for long GRBs. On the other hand, a number of observational features shared with the long GRB class may suggest that (at least) a fraction of short and long GRBs may be powered by the same central engine (e.g. a magnetar). In the context of compact object binary progenitors, the short GRB properties are consistent with the scenario of primordial binary progenitors, with short coalescence times. However, a minor contribution (10%–25%) of dynamically formed (or with large natal kicks) compact binaries progenitors cannot be excluded. The detection of kilonovae and of gravitational waves are the most promising "smoking guns" to definitely proof the nature of these progenitors. Concerning this last point, predictions for the detection of both on- and off-axis emission from short GRBs (Coward et al., 2014; Cowperthwaite and Berger, 2015) suggest that these sources are promising electromagneting counterparts of the gravitational waves expected to be detected within the expected sensitivity volume ($\sim$200 Mpc) of the forthcoming advanced LIGO and Virgo detectors.

Acknowledgments

The author thank the anonymous referee for his/her useful comments, and M.G. Bernardini and S. Covino for valuable suggestions. The author acknowledge the Italian Space Agency (ASI) for financial support through the ASI-INAF contract I/004/11/1.

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