The host galaxies of short Gamma-ray bursts

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ABSTRACT

The discovery of short GRB afterglows in 2005 provided the first insight into their energy scale, environments and host galaxies. Since then, 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. The occurrence of short GRBs in both star-forming and early-type galaxies indicates that their progenitors can be associated to both young and old stellar population. In recent years, the spectacular detection of the first electromagnetic counterpart of a gravitational wave event detected by the LIGO/Virgo interferometers and originated by the coalescence of a double neutron star system (GW 170817) occurred in the early-type NGC 4993 galaxy at 41 Mpc marked the dawn of a new era for astronomy. The short GRB 170817A associated to this GW event provided the long-sought evidence that at least a fraction of short GRBs are originated by NS-NS merging and that relativistic jets can be launched in the process of a NS-NS merger. In this paper I will present an observational review on short GRB host galaxies and updates with results from the LIGO/Virgo observing runs.

KEY WORDS: gamma-ray burst; galaxies; gravitational waves

1. Introduction

Two classes of GRBs (at least), short and long, have been identified. Short GRBs are those with burst duration less than about two seconds and with harder high-energy spectra with respect to long bursts (Kouveliotou et al. 1993). While it has been firmly established that long GRBs originate in core-collapse supernova (SN) explosions (Hjorth & Bloom 2012), according to the most popular model short GRBs are produced by the merger of compact objects (neutron stars, NSs, and black holes, BHs). The knowledge of the class of short GRBs experienced an impressive boost in the last 15 years. The discovery of short GRB afterglows in 2005 by the *Neil Gehrels Swift Observatory* (*Swift*) and the *HETE-II* satellites represented a watershed moment in the study of these sources, providing the key to unravel their distance, energy scale, environments and host galaxies (Gehrels et al. 2005; Fox et al. 2005; Villasenor et al. 2005; Hjorth et al. 2005; Barthelmy et al. 2005; Berger et al. 2005; Covino et al. 2006). To date, about 150 short GRBs have been found by *Swift* (~ 10/yr). A sizeable fraction of them have X-ray and optical afterglows detections, a few have been detected also in radio (Fong et al. 2015). Short GRB afterglows are fainter on average than those of long GRBs and the great majority of short GRB redshifts are obtained through optical spectroscopy of their associated host galaxies. To this end, the precise localisation with *Swift* is a crucial asset to achieve a firm short GRB-host galaxy association (D'Avanzo et al. 2014). Properties like the absence of associated SNe, the afterglow faintness, the occurrence in early type galaxies, the offset and redshift distribution definitely point towards a compact star origin, at variance with what observed for long GRBs (Berger 2014; D'Avanzo 2015). All these findings are in agreement with the compact object binary progenitor model (Eichler et al. 1989; Narayan et al. 1992; Nakar 2007). These progenitors are also expected to be sources of high-frequency gravitational waves (GWs). Another key signature of a NS-NS/NS-BH binary merger is the production of a so-called kilonova, whose electromagnetic emission is powered by the decay of heavy radioactive species produced by rapid neutron capture (r-process) and ejected during the merger process (Li & Paczyinski 1998; Rosswog 2005; Metzger et al. 2010). The compact object binary progenitor model for short GRBs has been spectacularly confirmed on Aug 17 2017, when the first GW event ever originated by a NS-NS merger was detected by LIGO/Virgo (GW 170817) and associated to the weak short GRB 170817A and to the bright kilonova AT2017gfo (Abbott et al. 2017a; Goldstein et al. 2017; Savchenko et al. 2017; Pian et al. 2017). The emergence, days after the GW/GRB event, of a X-ray and radio counterpart suggested for the possibility of off-axis GRB afterglow emission (Hallinan et al. 2017; Troja et al. 2017). Besides providing the long-sought "smoking gun" of short GRB progenitors, the case of GW 170817 / GRB 170817A demonstrated that the GRB emission geometry differs from a simple uniform jet (Mooley et al. 2018; Ghirlanda et al. 2019).

2. Short GRB host galaxies properties

Although indirect, 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, Kulkarni & Djorgovski 2002; Fruchter et al. 2006; Wainwright, Berger & Penprase 2007; Savaglio, Glazebrook & Le Borgne 2009). On the other hand, the occurrence of short GRBs in both star-forming and early-type galaxies (Fig. 1, 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). Considering the short GRB-elliptical host galaxies associations proposed on chance probability arguments and those whose optical afterglow was found to lie within the host galaxy light with a sub-arcsecond precision, Fong et al. (2013) estimates that about 20% of short GRBs are associated with early-type host galaxies. In these 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 (e.g. Barthelmy et al. 2005, Berger et al. 2005, Malesani et al. 2007, Fong et al. 2011). 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 & Berger 2010), an higher value with respect to the median stellar mass found for long GRB hosts ($10^{9.2}\, M_\odot$; Savaglio, Glazebrook & Le Borgne 2009; Leibler & 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, occuring in star-forming galaxies only. Indeed, as reported in Leibler & 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, Berger 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)>$\sim 8.8 \sim 1 Z_\odot$ (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 those events with an observed optical afterglow could a firm GRB-galaxy association be established (Berger 2014). Among the bursts with an optical (sub-arcsec) localization, about 17% 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; see, e.g, Stratta et al. 2007; Perley et al. 2009; Fong, Berger & Fox 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 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. 1, right panel). A statistical study carried out by Tunnicliffe et al. (2014) pointed out that the proximity of these events to nearby galaxies is higher than is seen for random positions on the sky, in contrast with the high-redshift scenario.

2.1. 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, Berger & Fox (2010) shows that the observed distribution of projected

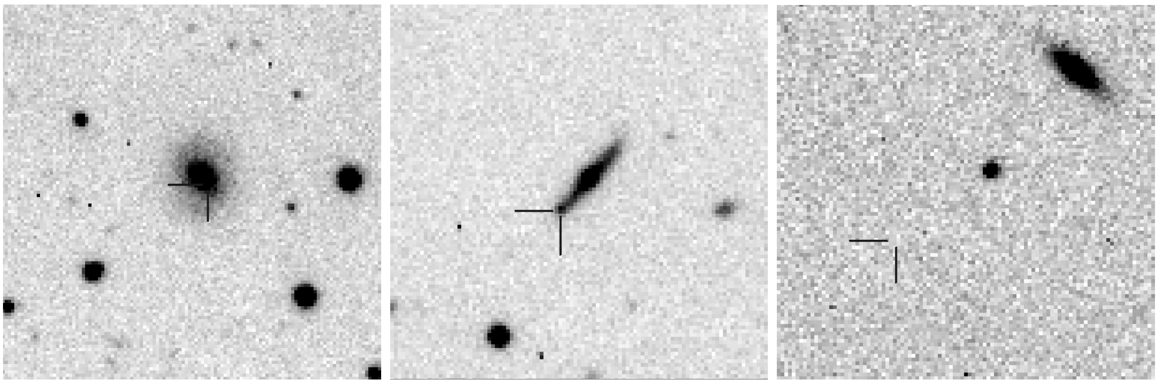

Fig. 1. The diversity of short GRBs host galaxies. The early type host galaxy of GRB 050724 (Barthelmy et al. 2005; Malesani et al. 2007; left panel), the late-type host galaxy of GRB 071227 (D'Avanzo et al. 2009; central panel) and the host-less GRB 061201 (Stratta et al. 2007; Berger 2010; right panel). 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.

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 & 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.

3. The host galaxy of GW 170817 / GRB 170817A

So far, GRB 170817A is the only short GRB unambiguosly associated with a NS-NS GW event and with a kilonova (Abbott et al. 2017b). Its host galaxy has been identified as NGC 4993, an early-type S0 galaxy at 41 Mpc (Hjorth et al. 2018; Cantiello et al. 2018), hosting a weak active nucleus observed in the X-rays with Chandra and XMM-Newton (Troja et al. 2017; D'Avanzo et al. 2018). Detailed optical imaging reveals large, face-on shell-like structures and dust lanes suggesting that NGC 4993 experienced a relatively recent galaxy merger (Levan et al. 2017; Im et al. 2017; Palmese et al. 2017). The galaxy properties, including the observed offset of the counterpart location with respect to the galaxy centre, are typically consistent with those of the population of short GRB host galaxies. Optical spectroscopy carried out at the transient location provides no evidence for narrow interstellar medium features, implying low extinction, and that the binary system may be located in front of the host galaxy. Inspection of the location of the counterpart carried out with *HST* revealed that no globular cluster can be detected, with a limit of a few thousand solar masses (Levan et al. 2017).

4. Conclusions and future perspectives

We are now at the dawn of a new, exciting era for short GRB studies. 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. Properties like the absence of associated supernovae, the afterglow faintness, the occurrence in early type galaxies, the offset and redshift distribution and the association with GW and kilonovae, definitely point towards a non-massive star origin, at variance with what observed for long GRBs. During the third LIGO/Virgo observing run (O3), a number of GW events originated by the coalescence of binary systems of compact object containing at least a NS has been detected (five NS-NS and five NS-BH events[1]). Despite the huge efforts in the follow-up observational campaigns, for none of these events it was possible to find an associated short GRB nor an electromagnetic counterpart, mainly due to the large distances and/or the poor positional accuracy. The most remarkable case was the NS-BH GW event S190814bv, localised by LIGO/Virgo within 23 deg^2 (90% c.l.). For this event, meaningful limits on the presence of an associated short GRB and kilonova have been reported in the literature (Gomez et

*1 https://gracedb.ligo.org/superevents/public/O3/

al. 2019; Andreoni et al. 2019; Ackley et al. 2020).

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