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The environments and hosts of neutron star mergers and short GRBs

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Abstract. The hosts of binary neutron star (BNS) mergers and hence short GRBs are not only galaxies with old stellar populations, infact most short GRB hosts are at least mildly star-forming galaxies. According to theoretical studies of merger populations, both short and long merging time-scales are expected. The immediate environments of BNS mergers are not as directly related to the property of the progenitor system as for long GRBs, since the system usually travelled a significant distance from their birth place. However, studying the stellar population properties across the host can still give us vital information on the contribution of formation channels and on merger timescales. Here we review the properties of NS merger hosts in emission using integrated-light and resolved observations. The afterglows of short GRBs furthermore serve to study the interstellar medium in their host galaxies in absorption. We present our best example to date, GRB 160410A at $z = 1.7$, one of the highest redshift short GRBs.

Keywords. stars: neutron, gamma rays: bursts, galaxies: ISM, galaxies: abundances

1. Introduction

Short gamma-ray bursts (GRBs) have now been securely linked to the merger of two neutron stars (NSs) with the detection of a gravitational wave (GW) signal from a corresponding event (Abbott et al. 2017; Goldstein et al. 2017). The sensitivity of current GW detectors, however, restricts the detection in GWs from binary neutron star (BNS) mergers out to a current maximum of a few 100 Mpc and the corresponding expected detection rate is at most a few events per year (e.g. Yu et al. 2021). Knowing their possible environments and host properties allows to better pinpoint possible host galaxies within the large error boxes provided by GW detections alone, and to understand the population of BNS mergers. With the few available GW detections, understanding the properties of the general short GRB population is crucial.

Short GRB afterglows are on average 5-6 mag fainter than long GRB afterglows (Kann et al. 2011) and their average redshift is also lower, which might be a bias of their lower luminosity (see e.g. Dimple et al. 2022). Although BNS mergers are one secure progenitor channel, it is an open question whether other merger events such as black hole-neutron star (BH-NS) mergers might also cause short GRBs. A possibly special class of short GRBs are those with extended emission (EE) after the main short γ emission with durations of up to several minutes (Gehrels et al. 2006). This emission might come from prolonged central engine activity or it might be a simple issue of viewing angle. Another possibility is that this class might be related to a different progenitor system, e.g. a BH-NS merger (see e.g. Dichiara et al. 2021 and references therein).

2. Short GRB hosts in emission

2.1. *Overview*

Long GRBs are connected to the collapse of massive stars and hence their hosts are expected to be highly star-forming galaxies. Indeed, they show very high specific star-formation rates (de Ugarte Postigo et al. 2020) and low metallicities (Krühler et al. 2015), needed to retain the angular momentum to produce a GRB upon collapse of the star. The average long GRB host population has low masses, at least up to redshifts of ∼2 (Perley et al. 2016), which is not surprising given that most of the star-formation at low redshift happens in dwarf galaxies. There are some exceptions of higher mass hosts with lower metallicities, e.g. the host of GRB 171205A (Thöne et al. in prep, de Ugarte Postigo et al. in prep.), however the local metallicity has never been found to be high.

For short GRB hosts the situation is more complex: Originally expected to be early type galaxies, confirmed by the first putative short GRB host of GRB 050509B, an elliptical galaxy (Bloom et al. 2006), there are now many examples known of at least mildly star-forming short GRB hosts, e.g. GRB 050709 (Hjorth et al. 2005) or GRB 130603B (de Ugarte Postigo et al. 2014). Even though, some partially resolved studies found properties at the GRB site different from those of long GRBs. An example is the host of GRB 080905 at z=0.12 (Rowlinson et al. 2010; Nicuesa Guelbenzu et al. 2021), a spiral galaxy, however there was no star-formation or emission lines found at the actual GRB site, contrary to lGRB sites (Lyman et al. 2017). In the following sections we will review what we currently know (and expect) from short GRB hosts observed in emission.

2.2. *The short GRB host population*

Current short GRB samples show that only about 20% are hosted in early-type galaxies (see e.g. Berger 2014, a recent sample, currently being analyzed by Corre et al. show rather similar numbers). Also very few short GRB hosts are found in clusters (for an exception see Nugent et al. 2020). The main issue is the large number of unsecure host-GRB identifications, which could be over 1/3 of the sample. Many also do not show any host galaxy at all, despite deep imaging observations. Only three short GRB afterglow spectra (GRB 130603B, GRB 160410A, and GRB 201221D) have so far been obtained and only absorption lines in the spectrum allow us to definitely pinpoint the actual redshift and secure the host galaxy identification.

The reason for this might be that the progenitor systems have been kicked, during one of the NS explosions, out of their original star forming regions and can be even found at large distances from their host galaxies, complicating the identification of the actual host. In fact, the offset of short GRBs from their host galaxy centres is about 5× larger than for lGRBs and still 1.5× if normalized to the galaxy size (Fong & Berger 2013).

Short GRB hosts are typically more massive and less star-forming that long GRB hosts. They also show no correlation with bright, star-forming regions as is the case for long GRB sites. It is still unclear whether the metallicity distribution of short GRB hosts might be higher than those of long GRB hosts, though it should be expected given that the host galaxies seem to host somewhat older stellar populations (Fong & Berger 2013; Berger 2014).

2.3. *Short GRB hosts at z>1*

Interestingly, the properties of GRBs at $z > 1$ might be different from those at low redshift. A study by Dichiara et al. (2021) showed that their properties might be more similar to those of long GRB hosts with higher star-formation rates and lower galaxy masses. Interestingly, about 60% of short GRB at $z > 1$ are EE-sGRBs and they rather match the Amati relation for long GRBs than for short GRBs. The question remains whether those EE-sGRBs might actually be long GRB “impostors” or whether those might be different progenitor systems, e.g. from a BH-NS merger. There might also be a simple redshift evolution due to the change in the average galaxy population, however this should mainly play a role at even higher redshifts.

The current record for the highest short GRB redshift is for GRB 111117A (Selsing et al. 2018). This burst had no detected optical afterglow, but an X-shooter spectrum showed a faint source with several emission lines from the putative host at $z = 2.1$. The environment shows a high density from X-ray derived absorption. The high redshift of the GRB sets tight constraints on the merger time (at $z = 2.1$ the age of the Universe was only 3 Gyr), and sets a limit on the initial separation of the merger system of $<3.2 R_\odot$.

2.4. *Expectations from population models*

There are two main formation channels to produce the binary neutron star system giving rise to a short GRB: Common evolution of two moderately massive stars and dynamical encounter of two compact objects in dense environments such as globular clusters (GCs) and nuclear star clusters. Both channels actually favour short merger delay times, for GCs, <70% merge in less than a Gyr (Belczynski et al. 2018). The common evolution channel has a strong peak in numbers at a few hundred million years and then decays roughly like t^{-1} (Chruslinska et al. 2018).

Stellar population synthesis modeling together with cosmological simulations (Mapelli & Giacobbo 2018; Giacobbo & Mapelli 2018) show that BNS preferentially merge in larger galaxies with masses of log M=9–12 $M_\odot$ and with short delay times. Since their formation is rather independent on metallicity, their formation probability is proportional to the stellar mass and hence they are preferentially found in larger galaxies. BH-NS mergers (and binary black hole, BBH, mergers) are, however, found in lower mass galaxies since their formation is metallicity dependent. Their host galaxy distribution seems to be inconsistent with those of the general short GRB host population, however, this might explain the properties of EE-sGRBs at high z (see Sect. 2.3) and hence indeed point to a different progenitor for those systems.

2.5. *Resolved short GRB hosts*

Studying short GRB hosts with integral field spectroscopy (IFS) is still in its infancy. For short GRB hosts it is more complicated to infer directly properties of the progenitor from the environment since the GRB has usually travelled far from its birth site. The tasks is therefore rather to study the stellar population across the entire host to infer a possible progenitor age. Determining its chemical composition is less straightforward than for long GRBs and probably less relevant for a NS progenitor.

The best studied host in 3D is the host of GRB/GW 170817, an S0 galaxy with a high stellar mass of log M=11.15 $M_\odot$/yr. The galaxy hosts an active galactic nucleus (AGN) and MUSE IFS showed a spiral structure in [NII] emission within the elliptical host, possibly from a dry merger (Levan et al. 2017). The galaxy host predominantly an old (>5 Gyr) population and no GC has been found near the GRB site. Its location well inside the host implies a low natal kick of the system of <200 km s−1 (Abbott et al. 2017; Blanchard et al. 2017). The lack of absorption lines in the afterglow spectrum does not allow to determine, however, whether the actual distance from the host was larger than its projected position implies. Most BNS merger models prefer a shorter merging time than implied by its old stellar population, hence the detection of a short GRB in this host poses some challenges to the population models.

Table 1. Summary of current short GRB afterglow spectra

GRB	**redshift**	$\log\left(\frac{E_{iso}}{erg}\right)$	**LSP**	**metallicity**	**host M_r (mag)**
GRB 130603B	0.356	51.29	0.20±0.13	—	–20.50±0.06
GRB 160410A	1.7177	52.60	–1.92±1.07	[Fe/H]=–2.7	< -18.17
GRB 201221D	1.0450	51.53	0.04±0.05	—	–20.46±0.15

Notes:
The line-strength parameter (LSP) was calculated according to de Ugarte Postigo et al. (2012) comparing the EW of the GRB spectrum with those of a large sample of long GRBs.

Only two other short GRBs have been studied with IFS so far. The host of GRB 050709, a star-forming, irregular dwarf galaxy (log M=8.8 $M_\odot$) with low extinction, about 0.5 solar metallicity and prominent emission lines (Nicuesa Guelbenzu et al. 2021). No emission lines, however, are detected at the GRB site, contrary to what we observe for long GRB sites. HST imaging shows some possibly star-forming regions kpcs from the GRB site. ATCA detected a faint emission in the Eastern part of the galaxy near the GRB site. The galaxy properties are in line with other star-forming short GRB hosts and would support a shortish merger delay time. Lately, Nicuesa Guelbenzu et al. (2021), did also a 2D study of the face-on spiral of GRB 080905 (see Sect. 2.1) and did not find any emission either at the GRB site. Several strongly star-forming regions are found in the host, but none close to the GRB site. The authors suggest that neither of them is the likely birthplace of the BNS progenitor system.

3. Short GRB hosts in absorption

GRB afterglows can also be used as powerful lighthouses to study the interstellar medium (ISM) in their host galaxies and any galaxy in the line-of-sight via absorption lines. For long GRB hosts there are over 100 GRB afterglows with optical spectroscopy ranging from very low to high redshifts with the current spectroscopic record being z=8.2 (Salvaterra et al. 2009; Tanvir et al. 2009). For short GRBs, this has turned out to be far more challenging: Due to the faintness of their afterglows, obtaining spectra requires exceptionally fast triggering and usually 8-10m class telescopes. There are currently only three short GRBs with afterglow spectroscopy and detected absorption lines: GRB 130603B, GRB 160410A, GRB 201221D, and only for one of them we have been able to derive an absorption line metallicity (Table 1).

3.1. *GRB 160410A: The first sGRB metallicity*

GRB 160410A was discovered by *Swift* and observed with the X-shooter instrument starting only 8 min after the GRB when its afterglow had a magnitude of $r = 20.29 \pm 0.06$ (Selsing et al. 2016). Absorption lines revealed a redshift of 1.7177 and two intervening systems at redshifts of z=1.584 and z=1.444 (Agüí Fernández et al. 2021). This is the second highest confirmed redshift of a GRB. The coverage down to almost 3000 Å of X-shooter and the relatively high redshift allowed, for the first time to detect and measure the Lyman-α absorption line for a short GRB afterglow, and together with other absorption features, determine a metallicity.

The absorption lines in the host system are weak compared to the average strength for long GRB afterglow spectra, determined by the equivalent width (EW) of the lines. We detect absorption lines of FeII, SiII, CII, AlII and OI consisting of a single absorption component. High ionization lines, commonly observed in GRBs, such as CIV and SiIV are absent, pointing to a low ionization of the observed medium. Fine-structure lines are not detected either in the spectra. A fit to Ly-α reveals a damped-lyman alpha (DLA) system with an N_H of 21.3 cm^{-3}.

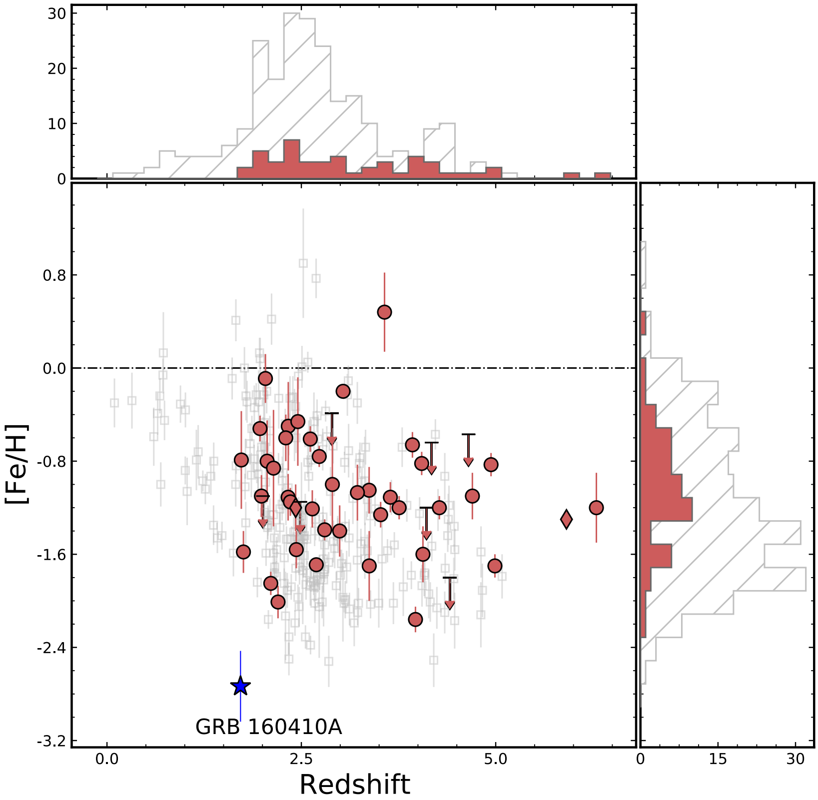

Figure 1. Absorption line metallicities vs. redshift of currently measured long GRBs (red dots) and the only short GRB value to date for GRB 160410A (blue star). Grey dots are values of quasar absorption systems from De Cia et al. 2018

The absorption lines were fitted with Voigt profiles using the VoigtFit code (Krogager 2018) to obtain column densities, although for the saturated line of OI we only give a lower limit. From this we determine a very low metallicity of [Fe/H]=–2.7, hence almost 1/1000th solar metallicity, the lowest metallicity ever measured for any GRB (see Fig. 1. We also measure the depletion due to dust according to the method described by De Cia et al. (2016) and do not find any indication for dust depletion.

No host galaxy was detected in deep observations of the field using OSIRIS/GTC down to a limit of $r > 27.17$ mag (observed) or $M_r > -18.44$ (absolute). The very low metallicity, the absence of depletion, low ionization and the non-detection of a host galaxy might indicate that this short GRB either exploded at larger distance from its host or that the host is a low-mass galaxy, which seems unusual for a short GRB.

3.2. *Comparison to other short and long GRB afterglows and environments*

There are only two other short GRBs with detected afterglow spectra to compare their ISM properties. GRB 130603B, the first short GRB with a confirmed kilonova (Tanvir et al. 2013), was hosted in a star-forming, disturbed spiral galaxy with a star-formation rate of 4.5 $M_\odot$/y, half solar metallicity and both old and young (<10 Myr) stellar populations (de Ugarte Postigo et al. 2014). Here we only detected absorption lines from MgII and CaII due to its low redshift of 0.356, however with a line strength close to the average for long GRB spectra. GRB 201221D at z=1.0450 only showed absorption lines of Fe II and MgII in a rather low S/N spectrum from GTC 2.76 h after the burst,

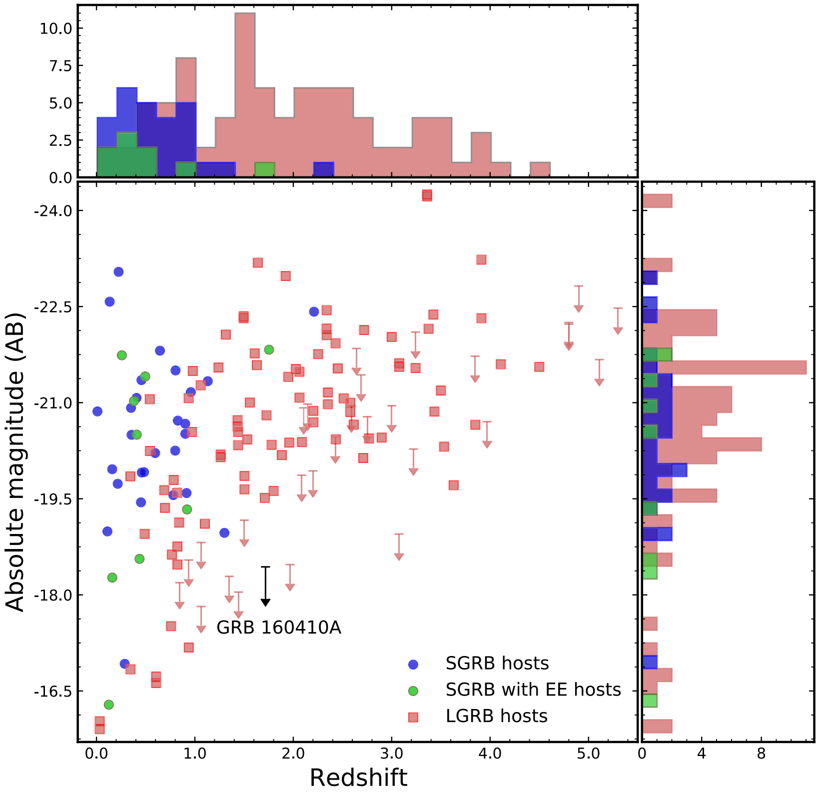

Figure 2. Distribution of absolute magnitude with redshift for both long (squares) and short (circles) GRB hosts. Short GRB hosts are furthermore divided into normal and EE-sGRBs.

but again with a very similar line strength compared to long GRBs. Both GRB 130603B and GRB 201221D had emission lines from their (star-forming) hosts present in the same afterglow spectrum, hence establishing a clear connection between GRB and its host.

It is difficult to establish any trend with only three short GRBs with afterglow spectra so far. Two of them show rather average properties compared to long GRB environments. The only GRB with very low line strength was also a short GRB with extended emission. One could argue that EE-sGRBs might have different environments and hence different progenitors compared to normal short GRBs, however, the luminosity distribution of their hosts does not show a trend compared to normal short GRB hosts (see Fig. 2). Further data are needed to make any connection between the environment and the sub-classes of short GRBs.

4. Conclusions

Short GRB host samples are still less studied than those of long GRB hosts, this particularly applies to afterglow spectra of short GRBs. Their larger offsets from the host and the faintness of the afterglow makes observations much more challenging than for long GRB hosts. After almost two decades of short GRB host studies it seems clear that only a small fraction of short GRB hosts are actually early-type galaxies and that most systems prefer a shorter merger time when the galaxy is still actively forming stars. However, they do show properties different from those of long GRB hosts: Their star-formation tends to be lower, the stellar population older and, most importantly, the

GRB site does not indicate (a lot of) active star-formation, in stark contrast to what we observe for long GRB sites.

Studying the immediate environment to infer progenitor properties is not as straightforward as it is for long GRB environments, who are still close to their birth place. Instead, we have to study the galaxy and its stellar population and star-formation history as a whole and match them with merger population models and their time delays. Such models suggest that there might be a metallicity dependence for BH-NS and BBH mergers but not for BNS mergers and that the latter might merge in larger galaxies while e.g. BH-NS mergers could merge in smaller and younger galaxies.

The latter has been suggested as one of the progenitors explaining EE-sGRBs. This would fit to the observation that EE-sGRBs are much more frequent at redshifts >1 and their possible difference in host galaxies, although current samples do not see a clear trend. The nature of EE-sGRBs remains unclear and their relation to a possibly different progenitor system.

We are finally also able to study the ISM in short GRB hosts in absorption in the direct sightline of the GRB and try to establish differences to long GRB sight lines. Only for one GRB we currently have a measurement of metallicity, GRB 160410A, and the value is lower than for any other long GRB measured. However, two other, lower redshift, short GRBs show more average ISM properties. A larger sample is warranted here, but requires very fast follow-up due to the lower afterglow luminosity of short GRBs.

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