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# Long-Duration Gamma-Ray Burst Host Galaxies in Emission and Absorption

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**Abstract** The galaxy population hosting long-duration GRBs provides a means to constrain the progenitor and an opportunity to use these violent explosions to characterize the nature of the high-redshift universe. Studies of GRB host galaxies in emission reveal a population of star-forming galaxies with great diversity, spanning a wide range of masses, metallicities, and redshifts. However, as a population GRB hosts are significantly less massive and poorer in metals than the hosts of other core-collapse transients, suggesting that GRB production is only efficient at metallicities significantly below Solar. GRBs may

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also prefer compact galaxies, and dense and/or central regions of galaxies, more than other types of core-collapse explosion. Meanwhile, studies of hosts in absorption against the luminous GRB optical afterglow provide a unique means of unveiling properties of the ISM in even the faintest and most distant galaxies; these observations are helping to constrain the chemical evolution of galaxies and the properties of interstellar dust out to very high redshifts. New ground- and space-based instrumentation, and the accumulation of larger and more carefully-selected samples, are continually enhancing our view of the GRB host population.

**Keywords** Gamma-ray bursts, interstellar medium, dust, high-redshift galaxies

## 1 Introduction

The study of long-duration gamma-ray burst (GRB) host galaxies is, in essence, an attempt to use each of these two different astronomical objects (GRBs and galaxies) to understand the other. By studying the population of galaxies that produces GRBs and the locations of the GRBs inside their hosts, we hope to identify the GRB progenitor and how it is formed. The ubiquitously star-forming nature of the GRB host population is one of several lines of evidence linking GRBs to massive stars—but how does the progenitor star evolve to its final state and why does it explode?

The field is equally driven by interest in reversing this line of investigation to use GRBs to understand distant galaxies. Spectroscopy of a GRB optical afterglow provides rich detail on the properties of the absorbing system in a way that is not possible with other observational methods. In addition, since GRBs can be detected from galaxies of arbitrarily faint luminosities (even if their hosts cannot be detected in emission), they may provide a way to quantify and characterize the contributions to star formation of galaxy populations too faint, distant, or dusty to be easily studied by more traditional means.

In the following chapter we will discuss a number of ways in which GRB hosts are used to bridge the gap in understanding between GRBs and high- $z$  galaxies on both sides. We will first present what is known about the GRB host population in emission via studies of their host galaxy population after the burst had faded, and compare the population of known GRB hosts to other distant galaxy populations. Afterwards, we will outline the properties of GRB hosts in absorption, illustrating some of the ways in which spectroscopy of GRB afterglows can uniquely reveal the properties of distant galaxies.

## 2 Long GRB Hosts in Emission

### 2.1 Background and Theoretical Predictions

Since nearly any observational technique or wavelength range that can be used to study other populations of distant galaxies can also be applied to GRB hosts, and because known GRBs span a vast redshift range ( $0.008 < z < 9.4$ ; Galama et al. 1998; Cucchiara et al. 2011), the observational study of GRB hosts involves many different kinds of data and similar challenges as high- $z$  galaxy astronomy generally. For most of its history these investigations have been limited to small samples of objects and subject to uncertain selection effects, but in the past five years the scene has changed dramatically as the large sample of positions provided by the Swift satellite (nearly 1000 GRBs localized within  $2''$  [Gehrels et al. 2004; Butler 2007; Evans et al. 2009], and several hundred within  $0.5''$  and with known redshift [Perley and Kemper 2008]) is systematically exploited with a range of modern observatories, including powerful new instruments such as WFC3 on the Hubble Space Telescope and X-shooter at the Very Large Telescope.

The link between GRBs and the explosions of massive stars is now well-established (Hjorth and Bloom 2012), so we expect GRBs to be found only in galaxies that are undergoing active star-formation (with the exception of short GRBs, which are not addressed in this review chapter). Of course, the diversity of star-forming galaxies is vast, and any attempt to establish the expectations for *which* star-forming galaxies GRBs should be found in at what frequency requires establishing assumptions about how the environment influences their rate.

It is helpful to start by imagining the simplest possible case: the assumption that the GRB rate is independent of all factors other than the overall rate of star-formation itself, such that a fixed fraction of all newly-formed stars explode as GRBs without regard to any of the chemical, physical, or other properties of the galaxy in which those stars formed. Observationally, this implies that GRBs should stochastically sample the locations of cosmic star-formation throughout the volume of the Universe in which they can be observed. The probability that any given galaxy will host a GRB during some period of time is proportional to its SFR.

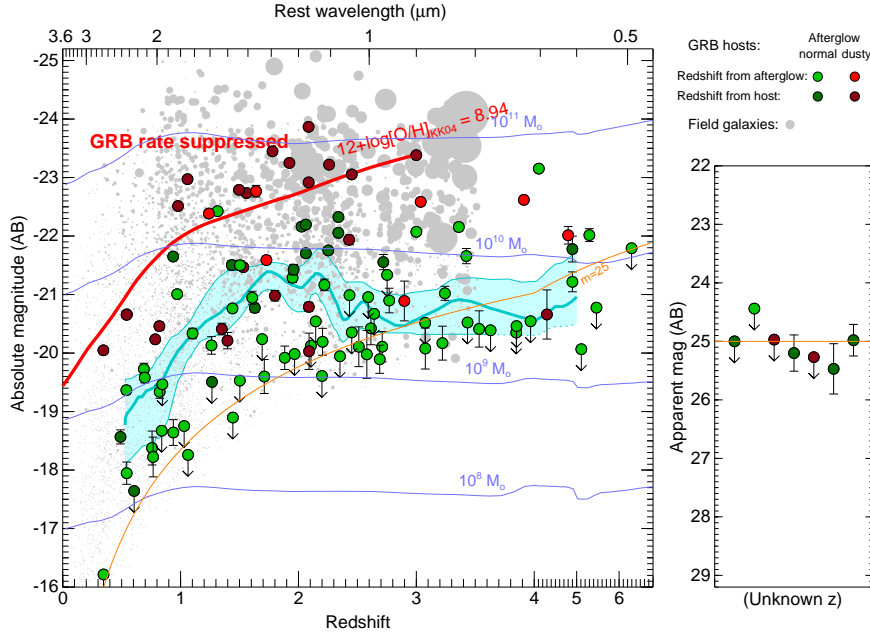
Theoretically, there are various reasons to expect that reality may be more complicated than this. The most frequently-invoked possibility is a dependence of the GRB rate on metallicity. A fundamental challenge in producing a GRB is the need to eliminate the progenitor star's hydrogen envelope (which would smother the jet, and produce emission lines in the associated SN that are not observed) without spinning down the angular momentum that the central engine—a fast-rotating black hole or neutron star—needs to launch the jet in the first place. The (initial) metallicity of a star can affect this process in several ways: a higher metal abundance produces stronger stellar winds, greater mass loss, and less interior mixing (Crowther et al. 2002; Heger et al. 2003; Vink and de Koter 2005; Hirschi et al. 2008). Low metal abundance

will both discourage mass (angular momentum) loss and encourage mixing of the hydrogen layer into the core, and single-star models (MacFadyen and Woosley 1999; Hirschi et al. 2005; Yoon and Langer 2005; Yoon et al. 2006; Langer and Norman 2006; Woosley and Heger 2006) robustly predict that GRBs should occur exclusively or preferentially in very metal-poor ( $Z < 0.2\text{--}0.3Z_{\odot}$ ) environments. Binary channels offer alternative means of exchanging mass and/or angular momentum (Izzard et al. 2004; Fryer and Heger 2005; Podsiadlowski et al. 2010), although these may also be metal-sensitive to a lesser extent.

Other environmental factors aside from metallicity may also be expected to impact the likelihood of producing a gamma-ray burst. Variations in the stellar IMF or close-binary fraction could lead to more massive stars and/or more close binaries, and a higher rate of GRBs, in some environments (Davé 2008; Wang and Dai 2011). Some GRB progenitor models appeal to dynamical effects between multiple stars (van den Heuvel and Portegies Zwart 2013); these would only be important in very dense environments and would cause GRBs to prefer the most intensely star-forming galaxies with many dense young star clusters.

In any case, from the observer’s standpoint the general methodology to distinguish the possibilities above is straightforward: catalog the known population of GRB hosts as thoroughly as possible and measure its parameter distribution across as many metrics as possible—and then compare these to the distribution expected under the environment-independent null hypothesis (and to the predictions of specific theories, if possible) to identify what factors do and do not matter for GRB production.

Calculating this expected distribution requires detailed knowledge of galaxy evolution and cosmic star-formation at a variety of redshifts, since a detailed mapping of the star-formation history as a function of a wide variety of observables is required. This knowledge can come directly from observations, or from theory. Many studies simply use the observed distribution of total star-formation rate as a function of galaxy parameters in known surveys and apply empirical laws relating galaxy properties to each other (e.g. the mass-metallicity relation) to calculate the cosmic GRB rate as a function of various observable parameters (Wolf and Podsiadlowski 2007; Kocevski et al. 2009; Trenti et al. 2015) and determine the best-fit rate-dependence model. Theoretical techniques have also been employed to avoid the dependence on observations from field surveys, which can be incomplete (or lacking entirely) at high redshifts and low galaxy luminosities. In particular, semi-analytic models of galaxy formation (Lapi et al. 2008; Campisi et al. 2009; Chisari et al. 2010), and cosmological hydrodynamic simulations (Nuza et al. 2007; Niino et al. 2011; Salvaterra et al. 2013; Elliott et al. 2015) have been employed. However, these techniques are still limited by the uncertain physics surrounding star formation and feedback, as well as the difficulty in achieving sufficient resolution to compute internal structure within galaxies and sufficient volume to reproduce the cosmological population of galaxies at the same time.



**Fig. 1** Near-infrared luminosities of GRB hosts as a function of redshift for a large and unbiased sample of 119 GRB hosts from the SHOALS sample (Perley et al. 2016a,b), compared to star-forming galaxies (gray, from Kajisawa et al. 2011). The NIR luminosity can be used as a stellar mass proxy: the horizontal blue curves indicate equivalent stellar masses. GRBs sample galaxies of all masses and redshifts, but rarely occur in the most luminous galaxies, especially at low redshift ( $z < 1.5$ ). This is probably because GRBs are strongly suppressed in metal-rich galaxies, leading to a soft “upper limit” on the host stellar mass that increases with  $z$  due to the evolving mass-metallicity relation: the red curve shows the luminosity of a galaxy at the metallicity threshold of  $12+\log[\text{O}/\text{H}]=8.94$  (the value inferred by Perley et al. 2016b) as calculated using the mass-metallicity relation of Zahid et al. (2014). The strong correlation between host luminosity and the degree of attenuation of the afterglow can also be seen: nearly all GRBs with dusty or “dark” afterglows are hosted within galaxies at the upper end of the mass distribution.

During this process, great care must be taken to be sure that the observed GRB host sample being analyzed is chosen without selection bias. There are at least two obvious potential sources of bias when constructing samples. The first is dust extinction: significant star-formation occurs in heavily dust-obscured regions (Casey et al. 2014); if these stars produce GRBs, then their optical afterglows will be obscured and the afterglow position will need to be measured to  $\sim$ arcsecond precision at another wavelength (radio or X-rays) to localize the host; these data are not always available. Furthermore, luminous GRB hosts are easier to detect and more likely to be reported (and scrutinized in the literature) than low-luminosity hosts, especially at high redshift. For these reasons, the means by which a sample was constructed should always be kept in mind when interpreting observations.

## 2.2 Photometric Properties

It was noticed early on that the GRB host population is relatively faint in comparison to other star-forming galaxies found at the same redshift (Le Floc’h et al. 2003) with a curious lack of massive, luminous galaxies with large populations of older stars among the pre-Swift (1997–2004) host population. Of course, the number of small galaxies in the Universe is much larger than the number of massive galaxies, and the manner in which GRBs select galaxies means that their hosts are frequently expected to be faint compared to galaxies found by flux-limited surveys, even if GRB formation is environmentally-independent. A more quantitative treatment was adopted by Wolf and Podsiadlowski (2007), who used archival data from a sample of hosts at  $0.2 < z < 1.0$  to calculate the rest-frame optical luminosity distribution for GRB hosts and compare it to a model of the star-formation weighted galaxy luminosity distribution. Consistent with earlier reports, they found a deficiency of GRBs in the brightest galaxies: although the difference is not enormous, and if interpreted as a metallicity “cap” on GRB production they estimated that the limit would have to be approximately Solar ( $12 + \log[\text{O}/\text{H}]_{\text{KK04}} < 8.7 \pm 0.30$ ). While these studies primarily examined nearby GRBs, optical-afterglow-selected high-redshift samples from Swift (Laskar et al. 2011) also showed very few luminous hosts.

The colors and SEDs of the population have also attracted interest; the same pre-Swift samples used in the above studies appear to exhibit relatively blue colors, due to low extinctions and star-formation rates that are quite high for galaxies of their mass (Chary et al. 2002; Castro Cerón et al. 2006, 2010; Savaglio et al. 2009). While not quantified in detail, the apparent absence (or at least rarity) of more mature or dusty systems again suggested a trend towards a galaxy population that is metal-poor.

The pre-Swift GRB sample was localized primarily via optical afterglow, and the results above were subject to the significant caveat that they omitted dust-obscured “dark” GRBs (see §3.7). Such events were already known to exist in significant numbers in the Swift sample (Cenko et al. 2009; Perley et al. 2010), and a handful of individual cases suggested their hosts may indeed be quite different from host galaxies selected optically (e.g., Levan et al. 2006; Berger et al. 2007; Castro-Tirado et al. 2007; Rol et al. 2007; Hashimoto et al. 2010; Hunt et al. 2011; Svensson et al. 2012). Systematic studies of large numbers of optically-reddened or optically-undetected bursts confirmed this, establishing that most (albeit not all) dust-obscured GRBs are hosted within luminous, massive, reddened systems of exactly the type that GRBs were previously found to be deficient in (Krühler et al. 2011; Rossi et al. 2012; Perley et al. 2013). Even so, heavily dust-obscured GRBs are not large contributors to the GRB population as a whole: events with  $A_V > 1$  mag represent perhaps 20% of the population in total (Greiner et al. 2011). Perley et al. (2013) therefore argued that they were not enough to eliminate the apparent deficiency of GRBs in luminous, red hosts.

Given the clear impact of the selection method on the nature of the host galaxy population that is probed, any proper quantitative assessment of the host population requires selecting a single sample (of both ordinary and obscured bursts) in a uniform manner, free of afterglow-related selection biases. These and similar considerations motivated the construction of several large uniform host-galaxy samples known by various acronyms: TOUGH (Hjorth et al. 2012, containing 69 hosts), BAT6 (Salvaterra et al. 2012; 58 hosts), and SHOALS (Perley et al. 2016a; 119 hosts). In each case, a subset of GRBs from the full Swift catalog is targeted for extensive host follow-up independent of afterglow properties (using the Swift XRT to localize the host if ground-based observations were not acquired) to provide as complete and unbiased a sample as possible. The selection criteria employed in constructing the three samples are similar, usually combining a Sun-distance constraint, a foreground-extinction limit, and a requirement that Swift slewed to the position within a short timeframe in order to acquire XRT observations. BAT6 and SHOALS also require a minimum peak flux and fluence (respectively) to exclude faint bursts although TOUGH does not, while TOUGH and BAT6 (but not SHOALS) exclude bursts near the celestial poles. By eliminating bursts with poor-observability in this way and pursuing spectroscopic redshift measurements for any unknown-redshift GRBs which pass the cuts (which are typically dark GRBs), these techniques have been able to raise the redshift completeness from an initial value of  $\sim 30\%$  (for the unrestricted Swift sample) to 90% or better.

Vergani et al. (2015) analyzed the  $K$ -band luminosity distribution of low- $z$  GRBs from BAT6, and found that even in this unbiased sample a strong deficiency of massive galaxies remained. Since the NIR luminosity is a tracer of a galaxy’s stellar mass, which in turn is strongly correlated with metallicity, this can be interpreted as evidence in favor of a metallicity bias, although does not necessarily rule out other models. The role of metallicity specifically can be tested by extending this analysis to higher redshifts: thanks to the evolving mass-metallicity relation (Tremonti et al. 2004; Erb et al. 2006), higher- $z$  galaxies are more metal-poor at a given mass than lower- $z$  galaxies, and the mass- and luminosity trends should therefore evolve with redshift in a consistent way (Fynbo et al. 2006; Kocevski et al. 2009).

This behavior has recently been confirmed by Perley et al. (2016b), who measured the luminosity/mass “ceiling” for efficient GRB production within a galaxy and found a significant increase in this value with redshift, to a degree consistent with a simple model in which the GRB rate is uniform with respect to metallicity below a critical value of  $\log[\text{O}/\text{H}]=8.94$  (under the Kobulnicky and Kewley 2004 system) but drops by about an order of magnitude in galaxies more metal rich than this (Figure 1). This critical value is somewhat higher than, but consistent with, the estimate by Wolf and Podsiadlowski (2007) obtained many years previously. A redshift-dependent luminosity cut-off has also been observed using rest-frame UV luminosities, which should also correlate with stellar mass and metallicity (albeit with significantly more scatter). Schulze et al. (2015) analyzed the distribution of UV luminosities for



galaxies within TOUGH and found a strong preference towards faint galaxies at low redshift but not at high redshifts. Consistently, Greiner et al. (2015) found good agreement between the GRB host and LBG luminosity functions at  $z \sim 3$ . Curiously, however, at *very* high redshifts of  $z > 5$ , Schulze et al. (2015) again found a trend towards fainter galaxies: this is difficult to interpret and will need to be confirmed with larger samples.

### 2.3 Long-Wavelength Observations

Galaxies emit radiation beyond the UV/optical/near-infrared range as well: in particular, many of the most luminous galaxies contain copious amounts of dust that reprocesses nearly all of the UV starlight into FIR/submillimeter radiation (we will loosely refer to these types of galaxies as DSFGs, for dusty star-forming galaxies; Casey et al. 2014). The star-forming conditions in these systems are among the most extreme in the Universe, and the GRB fraction originating from these galaxies represents another way to investigate the impact of local conditions on the GRB efficiency.

The literature on this topic can be confusing: the importance of selection bias, the limited sensitivities of observations at these wavelengths and small samples, and the controversies over the exact contribution of luminous and dusty galaxies to cosmic star-formation in the first place often lead to contradictory conclusions (Berger et al. 2003; Tanvir et al. 2004; Le Floc’h et al. 2006; Michałowski et al. 2012). Studies using large samples (including dark bursts) and sensitive instruments (Perley et al. 2013, 2015a; Hunt et al. 2014; Schady et al. 2014; Kohn et al. 2015) indicate that DSFG hosts are not uncommon, but still constitute a small minority ( $\sim 10\text{--}30\%$ ) of the entire GRB host population. This is similar to the fraction of cosmic star-formation found in these systems, so GRBs neither strongly prefer nor avoid DSFGs overall. On the other hand, GRB-selected DSFGs do not look like field-selected DSFGs: they are much lower in mass, but younger, higher in sSFR and in dust temperature (Michałowski et al. 2008; Perley et al. 2015a). This could indicate that the apparent agreement in overall rate is in fact a coincidence: GRBs avoid metal-rich, dusty DSFGs but are strongly preferred in intensely star-forming environments within the less-massive and younger subset of the population.

More detailed investigation will be needed to confirm this trend. The Atacama Large Millimeter Array (ALMA) is expected to play major role in characterizing obscured star formation within GRB hosts in the future, since it is able to detect submillimeter emission from even “normal” ( $\sim L_*$ ) galaxies out to very high redshifts. Indeed, ALMA observations have already detected submillimeter emission from a few GRB hosts, even out to  $z \sim 3$  (Wang et al. 2012; Hatsukade et al. 2014). Observations of a larger sample will permit the full demographics of the population at these wavelengths to be studied in the near future.

Recently, several observers have also explored the possibility of studying GRB host galaxies in long-wavelength line emission, in particular in HI

(Michałowski et al. 2015) and CO (Hatsukade et al. 2014). Samples of objects studied via these methods remain very small, but appear to be consistent with a general picture in which GRB hosts, and GRB sites within their hosts, are typically gas-rich but poor in metals and deficient in molecular gas.

## 2.4 Spectroscopic Properties

Spectroscopic measurements are more time-intensive than photometric ones and until recently have been limited to only the lowest-redshift GRBs, so the available catalog of spectroscopic host measurements is significantly smaller than what is known from photometric studies. Nevertheless, given the theoretical arguments presented earlier, the observed metallicity of the GRB host (which is estimated via emission-line ratios measured from optical spectra) is a key parameter of interest from the point of view of distinguishing GRB models, and so spectroscopy is critical to establish a firm understanding of GRB formation.

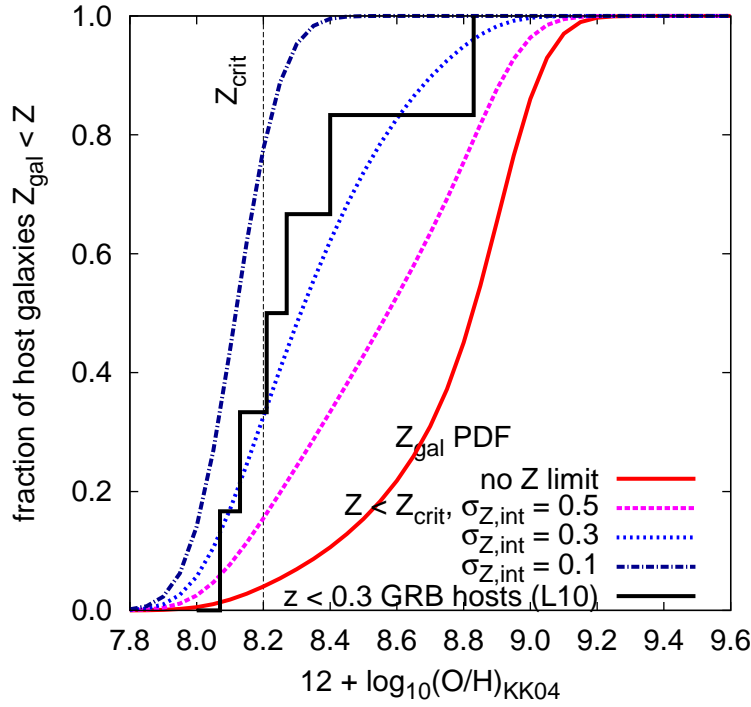
Some GRB hosts have been known to be very metal poor almost since the earliest studies. Stanek et al. (2006) analyzed a small sample and proposed a metallicity-dependent limit on the GRB luminosity (i.e., luminous GRBs can be produced only by very metal-poor galaxies, although less luminous GRBs can form at higher metallicity). This specific model has not been borne out by subsequent studies (Levesque et al. 2010b): nevertheless, the more general notion that the GRB rate is lower in metal-rich galaxies does appear to be supported. In particular, Modjaz et al. (2008) compared the metallicities of the hosts of GRBs to those of SNe Ic-BL without GRBs (GRBs are always or almost always associated with SN Ic-BL, but SN Ic-BL are observed without associated GRBs, even off-axis ones: Soderberg et al. 2006). They found that GRBs were hosted in significantly metal-poorer systems than the SNe Ic-BL: in fact, the two populations seemed to be divided at critical value (of approximately  $\log[\text{O}/\text{H}]=8.5$  on the Kewley and Dopita 2002 scale) above which SNe Ic-BL were never associated with GRBs and below which they were always associated with GRBs. Both the GRB and SN samples were small, however, and follow-up of larger samples of GRBs including dark bursts has demonstrated that it is not quite this simple. In particular, several dark GRB hosts, as well as some more recent ordinary GRB hosts, have been found to be metal-rich (Levesque et al. 2010a; Elliott et al. 2013) and SN Ib/c without GRBs have been found in very metal-poor environments as well (Modjaz et al. 2011), so the most up-to-date GRB vs. star-formation and GRB vs. SN metallicity comparisons (Graham and Fruchter 2013) do show significant overlap. Nevertheless, a strong difference in metallicity between GRB hosts and all other classes of transient host remains—suggesting that metallicity plays a key role in encouraging the successful launch of the GRB jet.

Emission-line studies are currently undergoing a renaissance thanks largely to the prolific capabilities of a single new instrument: X-shooter at the VLT (Vernet et al. 2011). X-shooter has observed over 100 GRB hosts, and for the

majority of these targets, multiple line detections permit chemical abundance analysis. The existing X-shooter sample is not unbiased, but it includes both obscured/dark and unobscured GRBs, and the derived properties present a picture that is quite similar to what is inferred from the photometric properties of GRB hosts (Krühler et al. 2015; Piranomonte et al. 2015). At every redshift, GRBs in very metal-rich (super-Solar) galaxies are uncommon but present, representing about 10% of the sample. The median GRB host is moderately enriched ( $\log[\text{O}/\text{H}] = 8.5$ ), and very metal-poor hosts are again uncommon. These properties further support the conclusion that the metallicity sensitivity of GRBs exhibits a sharp transition at around Solar metallicity that suppresses (but does not necessarily prevent) their formation in metal-rich (super-Solar) galaxies, but does not exert much impact on the rate in low versus moderate metallicity galaxies. It does not necessarily rule out the influence of other parameters on the GRB rate—however, the small number of luminous GRB hosts with measured metallicities tend to be metal-poorer than field-selected star-forming galaxies of the same mass (Levesque et al. 2010c; Graham and Fruchter 2013; Hashimoto et al. 2015), providing some evidence that metallicity is a dominant factor.

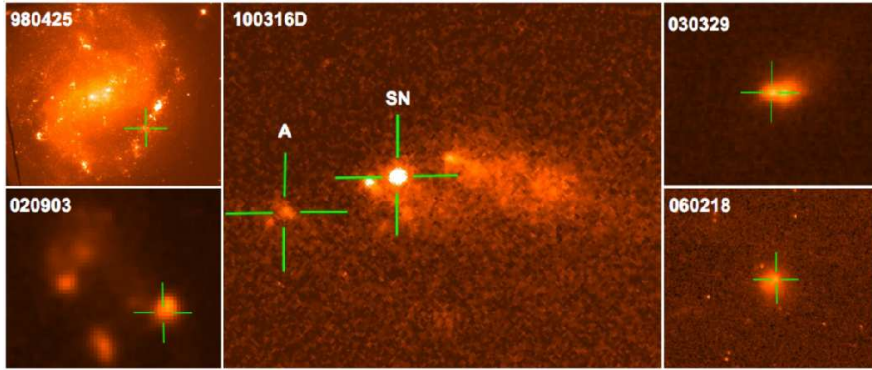
When interpreting these results, it should be kept in mind that individual galaxies also have significant internal chemical heterogeneity (e.g., Afflerbach et al. 1997; Smartt et al. 2001; Cioni 2009; Sanders et al. 2012), and the measured metallicity of a GRB host galaxy may therefore be different from the actual metallicity of the GRB progenitor. Niino (2011) predicted the expected metallicity distribution of long GRB host galaxies under the assumption in which long GRBs trace *only* low-metallicity stars using a model in which the internal variation of metallicity within galaxies is taken into account, assuming that a similar internal metallicity variation as seen in local galaxies such as the Milky Way also exists within GRB host galaxies. They found that both the existence of a few high metallicity hosts as well as the systematically low metallicities of more typical GRB hosts can be explained at the same time, even if the GRB progenitor is exclusively a moderately metal-poor ( $< 0.3Z_{\odot}$ ) star (Figure 2). While these results have not yet been updated to incorporate data from the large, unbiased samples mentioned earlier, they clearly suggest that the “true” metallicity threshold for GRB production is likely to be somewhat lower than the  $\sim 1 Z_{\odot}$  value preferred if all galaxies are assumed to be chemically homogeneous. Determining this value will require a careful accounting of the metallicity distribution within and between galaxies at a variety of masses and redshifts in the future. Spatially-resolved spectroscopy (which we will discuss in the next section) will also be informative.

Spectroscopic properties other than strong-line metallicity diagnostics have also been used to investigate the GRB progenitor and rate dependence, although so far the results of these analyses have been relatively inconclusive. For example, early samples suggested that strong Lyman- $\alpha$  emission might be much more common in GRB hosts than in star-forming galaxies generally (Fynbo et al. 2003; Jakobsson et al. 2005), although this was not confirmed by larger and more uniform samples (Milvang-Jensen et al. 2012). Other authors



**Fig. 2** The metallicity (expressed as the oxygen abundance,  $12+\log(\text{O}/\text{H})$ ) distribution of GRB host galaxies predicted in Niino (2011). The red solid curve represents the case in which long GRBs occur at the same rate regardless of metallicity. Dashed, dotted, and dot-dashed curves (magenta, blue, and dark-blue, respectively) represent cases in which only low metallicity stars below the assumed metallicity threshold of  $12+\log(\text{O}/\text{H}) = 8.2$  (shown with vertical dashed line) produce GRBs when they collapse, and stars formed in each galaxy have variation of metallicity with  $\sigma = 0.5, 0.3$ , and  $0.1$  dex around the mean value of the galaxy, respectively. Due to the internal metallicity variation within each galaxy, GRB host galaxies frequently have higher metallicity than the assumed threshold. Metallicities of observed GRB host galaxies at  $z < 0.3$  (from Levesque et al. 2010c, using the calibration of Kobulnicky and Kewley (2004, KK04)) are also shown.

have searched for Wolf-Rayet and other very short-lived starburst features in nearby hosts in an attempt to constrain the population age (Han et al. 2010) and found some indication that the progenitor is likely to be very young, but the small and possibly biased nature of the samples suitable for this analysis makes it difficult to make firm conclusions about the entire GRB population. Finally, detailed analysis of the rich data set provided by the large X-shooter host spectroscopic sample—which also provided information on specific star-formation rates, ionization states, and velocities—is likely to be a promising avenue for host investigations in the future (see also Krühler et al. 2015), although comparison of this type of spectroscopic data against field galaxy samples is not straightforward, since the samples of both GRB hosts and high-



**Fig. 3** Host galaxies of five of the nearest GRB host galaxies (from Starling et al. 2011). Most GRB hosts at  $z \sim 0$  are irregular, compact, star-forming galaxies—quite unlike the host population of core-collapse supernovae, which is dominated by more massive spiral galaxies (Fruchter et al. 2006).

redshift field galaxies chosen to be targeted for deep spectroscopic follow-up are subject to complex biases.

## 2.5 Spatially Resolved Analysis

Most GRBs are sufficiently distant that their host galaxies appear only as marginally-extended point sources in typical ground-based seeing conditions and it is difficult to extract much information about their internal structure without spaceborne observations. However, a small number of GRB hosts are close enough that some spatially-resolved analysis has been possible (Christensen et al. 2008; Thöne et al. 2008; Levesque et al. 2010a, 2011); Figure 3 shows five of the nearest and best-resolved examples. Observations of these systems have given some support to the conclusions of Niino (2011), showing that in at least some instances the metallicity at the GRB site may be (slightly) lower than the metallicity of the host overall. However, even in these cases, the spatial resolution of these observations is limited to kpc scales. Significant metallicity variation within a galaxy is observed even on scales of  $< 1$  kpc in the local universe (33% of neighboring pairs of HII regions with distance  $< 0.5$  kpc in M31 have different oxygen abundance by more than 0.3 dex, Sanders et al. 2012). If such small scale variation of metallicity exists in GRB host galaxies, the metallicities observed on a few kpc scale may still be different from that of the direct environment (and the progenitor) of the long GRBs (Niino et al. 2015), a possibility that should be incorporated in future efforts.

For the vast majority of GRB hosts, only space-based observations (specifically, observations from the Hubble Space Telescope) provide a hope of spatially resolving the galaxy. While it is not yet practical to perform spatially resolved spectroscopy of GRB hosts from space, HST observations have nevertheless been instrumental in constraining the identity of the GRB progenitor

in other ways—helping to constrain its age, and providing some evidence for influences beyond metallicity on the GRB rate.

Fruchter et al. (2006) and Wainwright et al. (2007) analyzed the morphologies of GRB hosts within a moderately large sample of pre-Swift observations with HST, and noted that GRB hosts are smaller than other galaxies and have a higher abundance of irregular and merging systems compared to the population expected for a “uniform” tracer. This behavior is expected for a metallicity-biased tracer, although morphologies are difficult to quantify, making it difficult to directly distinguish between progenitor models using this observation. More recently, Kelly et al. (2014) carried out a similar but more quantitative analysis, measuring the characteristic sizes (half-light radii) of galaxies in the GRB host sample in comparison to a variety of massive-stellar explosions (SN Ib/c and SN II). Consistent with earlier work, they found that the GRB hosts are significantly smaller. In particular, they found that they are smaller even at the same stellar mass. As the size of a galaxy at a fixed stellar mass does not correlate with metallicity significantly, this seems to provide strong evidence that the GRB progenitor must prefer dense stellar environments *in addition to* any preference towards low metallicity.

The location of a GRB within a resolved map of its host galaxy can also be used to constrain the progenitor, by studying whether or not it exhibits a preference or aversion for different types of environment on subgalactic scales. Such an analysis was first carried out by Bloom et al. (2002) using the nucleus-site offset distribution for a sample of 20 GRBs; they concluded that GRBs trace the galaxy light. Analysis based on the offset distribution alone is not sensitive to azimuthal structure of the source, however, and these data were subsequently re-analyzed by Fruchter et al. (2006) (and, later, by Svensson et al. 2010 and Blanchard et al. 2015 with expanded samples), who compared the UV surface brightness at the GRB host position compared to that of the galaxy as a whole, pixel-by-pixel. They found a significant preference for brighter regions (pixels) of the galaxy. Importantly, the same trend is not seen among ordinary core-collapse supernovae (but *is* seen in Type Ib/c supernovae; Kelly et al. 2008).

This result has been interpreted as suggestive of a very short progenitor lifetime (and, possibly, a large initial mass): on subgalactic scales, the sites of the most recent star-formation within a galaxy are expected to be brighter than locations for which a slightly longer time has passed since their formation episode, since the most massive stars have not yet exploded. If the GRB progenitor exploded faster than the “typical” star responsible for a galaxy’s UV luminosity—as would be expected if the progenitor star was particularly massive—a concentration towards the brightest (youngest) concentrations of young stars is expected. In this model, the observational constraints suggest an initial mass in the range of  $> 20 - 45 M_{\odot}$  (Larsson et al. 2007; Raskin et al. 2008).

However, it is also possible that is the actual density and not age-brightness effects that are responsible: regions of particularly intense star-formation may be more likely to produce very massive stars or close massive binaries, or inter-

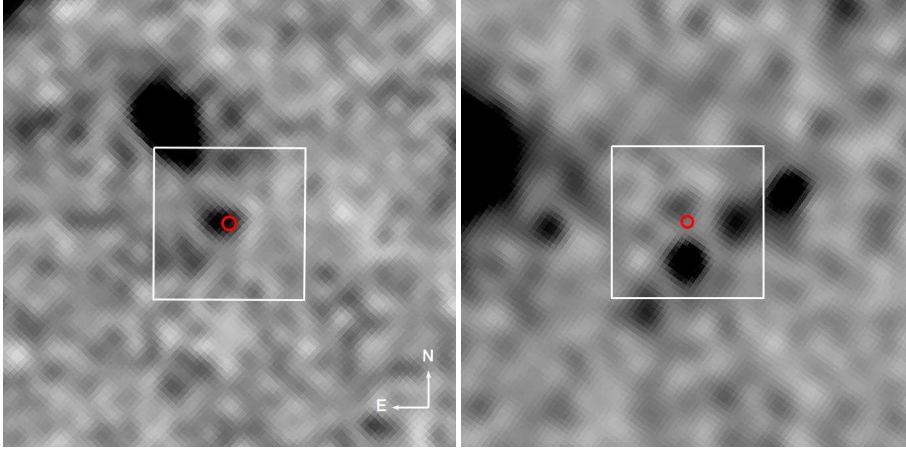
actions in dense stellar nurseries could also play a fundamental role. Indeed, the compact sizes of nearby GRB hosts noted by Kelly et al. (2014) is not well-explained by an age effect, but this result and the concentration result are naturally explained if GRBs preferentially occur in regions of vigorous star-formation.

## 2.6 GRB hosts at high redshift

Although studies of GRB hosts in emission are typically oriented towards using the galaxy properties to better understand the progenitor (e.g., measuring its metallicity tolerance), at the highest redshifts the direction of understanding reverses: instead, it is hoped that by observing the properties of the GRB host distribution we can better understand the properties of star-forming galaxies at that time. Indeed, a majority of the star-formation in the universe at  $z \gtrsim 6$  is thought to occur in galaxies too faint to detect even in deep *HST* observations. However, GRBs from arbitrarily faint and distant galaxies are readily detectable, providing us a way to confirm and constrain these predictions independently. Of course, the GRB rate at high- $z$  will also be affected to some degree by the progenitor's dependence on metallicity. But as high- $z$  galaxies are thought to be safely well below the  $0.3\text{--}1.0 Z_{\odot}$  threshold discussed above, there is reason to think that the impact of this limitation will be rather small in practice.

Until recently, searches for GRB hosts in emission had failed to find any above  $z \sim 5$  (e.g., Stanway et al. 2011; Berger 2014). This is consistent with the bulk of star formation occurring in very faint galaxies in this era (Tanvir et al. 2012), indicative of a steep faint end slope of the galaxy luminosity function, as has also been found in successively deeper *HST* deep field campaigns (e.g., Bouwens et al. 2015). Since a steep luminosity function would allow a global star formation rate factors of several above that seen in galaxies detected to *Hubble* Ultra-Deep Field depths at  $z \sim 8$ , this reduces the tension between the far-ultraviolet radiation density required to maintain a reionized intergalactic medium, and the production of radiation from massive stars. It should be noted that addressing this problem via GRB hosts has the important advantage that no particular form of the galaxy luminosity function is required, since it ultimately depends only on the fraction of hosts found above the detection threshold (e.g., Trenti et al. 2012).

Recently, new, deeper *HST* observations (program GO13831, PI: Tanvir) have for the first time identified two high-redshift GRB hosts, specifically of GRBs 050904 and 140515A, at  $z \approx 6.3$  (Fig. 4; McGuire et al. 2015). The luminosity of these hosts suggests they are consistent with being faint examples of the Lyman-break galaxies found in other deep *HST* surveys, roughly 20% and 10% of  $L_*$  at that redshift respectively (taking the luminosity function of Bouwens et al. 2015). In each case the afterglow spectroscopy had shown that the metallicities are  $< 10\%$  of Solar (Thöne et al. 2013; Hartoog et al. 2015;



**Fig. 4** Deep *HST* F140W filter images (lightly smoothed) of the locations of GRBs 050904 (left) and 140515A (right). Both bursts had redshifts of  $z = 6.3$  and in each case the host is detected at AB magnitude  $\approx 28$ , underlying the GRB positions (indicated by red circles). These are the first GRB host galaxies found in emission at  $z > 5$ . The white boxes are 2 arcsec on a side. Modified from McGuire et al. 2015.

Chornock et al. 2013), confirming that galaxies at this epoch are well below the threshold on GRB production inferred by lower-redshift studies.

### 3 Long GRB Host Galaxies in Absorption

Thanks to their exceptional luminosities, GRB afterglows can also be used as probes of their host galaxies in *absorption*. Gas and dust in front of the GRB selectively absorb certain wavelengths of light, imprinting their signatures onto the optical and X-ray spectra of the afterglow where they can be revealed by spectroscopic observations. Other matter along the line of sight is also unveiled, including the inter-galactic medium (IGM) and any foreground galaxies along the sightline.

While this type of study can also be performed with other extragalactic continuum sources (in particular, QSOs), there are many factors that make GRBs particularly powerful absorption probes of galaxy evolution and the high redshift universe, even into the reionization epoch. First of all, GRBs and their afterglows can be extremely luminous (much more so than QSOs), making them accessible to current-day optical spectrographs even out to very high redshifts (Lamb and Reichart 2000; Bloom et al. 2009). Because GRBs are associated with the death of massive stars, they are indeed expected to exist at extremely high redshifts of  $10 < z < 20$  (whereas QSOs, which require time for supermassive black holes to assemble, may not), so they uniquely probe chemical enrichment far into the epoch of reionization. But even at lower redshifts, GRBs have advantages. Their association with massive stars also means they are located within the disks of typical star-forming galaxies



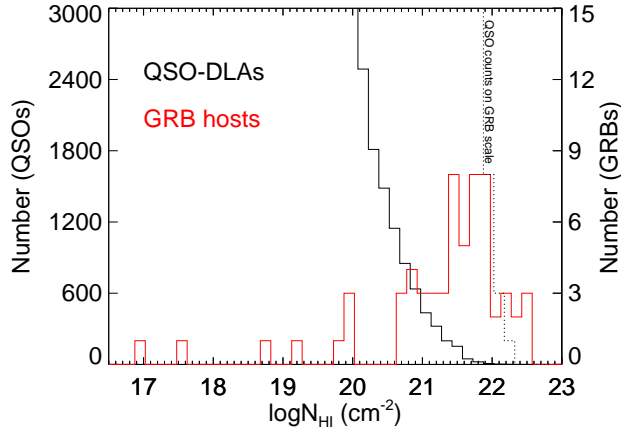
and provide a more effective means to select high-density gas columns (Figure 5; Pontzen et al. 2010). Because the afterglow continuum is intrinsically expected to be a simple power-law, it can be used to constrain broad absorption features (such as DLA wings or, especially, extinction profiles) more reliably than QSOs, which have complex intrinsic spectra. Finally, because the afterglow emission fades away over time, the same GRB host galaxy characterized in absorption can also be studied in emission using the techniques outlined in the previous section. In particular, GRBs offer a unique opportunity to systematically investigate both the neutral gas using absorption lines in the the afterglow spectra *and* the ionized gas using the emission lines in the host galaxy spectra.

The transient nature of GRBs is, on the other hand, also the main disadvantage of the use of these sources as cosmological probes. The optical/near-infrared afterglow observations necessary to provide a position of sufficient accuracy ( $< 0.5''$ ) to point an optical spectrograph, as well as the spectroscopic observations themselves, must take place as early as possible after the GRB prompt emission detection. And unlike with QSOs, it is not possible to carry out observations over long integration times (more than a few hours) in order to increase the signal-to-noise (S/N) for faint objects. To date, less than 30% of GRBs have a measured redshift, and less than  $\sim 10\%$  have a spectrum with a high S/N sufficient for detailed analysis of faint lines and uncommon chemical species.

To achieve the scientific goals mentioned above, medium/high resolution afterglow spectra with good S/N are necessary. Observations starting as soon after the GRB trigger as possible—when the afterglow is brightest—provide the best signal and are richer in information than observations taken later, so fast response to new GRBs is essential. For these reasons, target-of-opportunity afterglow follow-up programs exist at a variety of telescopes around the world, including Keck, Gemini, GTC, Subaru, and Magellan. However, it is the ESO Very Large Telescope (VLT) that has been the driving force in GRB afterglow spectroscopy for much of the past decade, for a variety of reasons. First, year-round target-of-opportunity observations (including dedicated rapid response-mode observations executed by the Observatory staff) are available. Even more importantly, X-shooter has been just as revolutionary in the study of GRB afterglows in absorption as it has been in studies of GRB hosts in emission: its wide wavelength coverage and ideal combination of resolution and sensitivity have permitted detailed studies of the environments of even faint and high-redshift afterglows.

### 3.1 Damped Lyman Alpha Systems

The most prominent absorption line seen in high-redshift GRB spectra is, unsurprisingly, the Lyman- $\alpha$  line of neutral hydrogen (HI) at  $1217\text{\AA}$ , which is accessible to ground-based spectrographs at redshifts higher than approximately  $z \gtrsim 1.9$ . The strength of this line causes it to inevitably saturate,

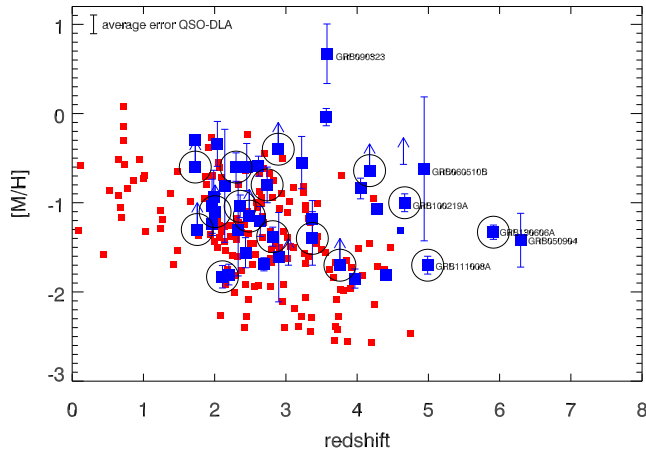


**Fig. 5** HI column density measurements for more than 12000 QSO DLAs and for 52 GRB absorbers. The QSO histogram is plotted with a full-drawn line relative to the left-hand ordinate axis and with a dotted line relative to the right-hand ordinate axis. As seen, typical GRBs probe column densities that are extremely rare or absent among QSO-DLAs.

but the absorption column can be derived by fitting the wings of the profile using the same techniques derived for QSOs, producing a direct and accurate measurement of the neutral hydrogen column density  $N_{HI}$ . In addition to this Lyman-alpha absorption, the afterglow spectra also typically reveal many metal lines at the same redshift, present in both their low and high ionization state. It is also occasionally possible to detect the absorption line from molecules such as  $H_2$ , as well as fine structure lines associated with gas excited by the GRB afterglow itself. The combination of a neutral gas column and measurements of numerous metal lines can be used for a variety of purposes, described in the following sections.

### 3.2 Metallicity

The metallicity of the intervening gas towards a GRB can be directly measured using the ratio of the strengths of metal lines and HI in absorption, even in galaxies up to the highest redshift. For example, X-shooter observations have succeeded in measuring the metallicity of GRB 130606A at  $z = 5.9$  (Hartoog et al. 2015; see also Chornock et al. 2013 and Totani et al. 2014). By comparing systems at high redshift to others at more moderate redshifts, GRB DLAs allow us to probe the metallicity evolution of the ISM of star-forming galaxies. The data collected to date show that GRBs explode generally in sub-solar metallicity environments—but measured metallicities are not extremely low, even at high redshift, demonstrating that galaxies were already metal enriched (see Fig. 6).



**Fig. 6** Absorption-based metallicity measurements as a function of redshift for QSO intervening-system DLAs (red symbols) and GRB host DLAs (blue symbols). The two populations evolve differently with redshift, probably because they probe different locations within the galaxy: with GRB DLAs the metallicity of the inner regions of star-forming galaxies are probed, while QSO DLAs typically probe more outlying regions of foreground galaxies. Adapted from Thöne et al. (2013) and Sparre et al. (2014).

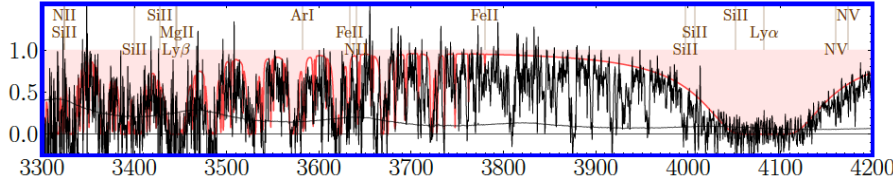
### 3.3 Dust Depletion

Refractory elements, such as Fe, Ni, and Cr, can be heavily depleted into dust grains (e.g. Savage and Sembach 1996), and thus can be missing from the gas-phase abundances. To estimate the level of depletion in the ISM (and therefore the presence of dust), the relative abundance of heavily depleted species into dust grains, as Fe, towards those undergoing little depletion, as Zn, is used. Then, using different methods (e.g. Vladilo et al. 2006; Bohlin et al. 1978; Prochaska and Wolfe 2002; De Cia et al. 2013), it is possible to estimate the iron dust-phase column density, the dust-to-gas ratio, and the flux attenuation. The depletion patterns can be compared to the Galactic ones to estimate the origin of the gas and of dust, and/or to look for evolution of the dust-to-metal ratio (e.g. De Cia et al. 2013; Zafar and Watson 2013).

GRB afterglows can also be used to study the shape of the dust extinction curve, as will be discussed in Section 3.7

### 3.4 Molecules

As GRB DLAs should probe the gas associated with star-forming regions, a direct detection of absorption lines due to molecules is expected in their afterglow spectra. The detection of absorption lines from rotationally and vibrationally-excited  $H_2$  transitions, however, has proven to be difficult: these  $H_2$  transitions are typically blended with the Lyman-alpha forest, and disentangling the often-



**Fig. 7** X-shooter spectrum of GRB 120815A between 3300 and 4200Å illustrating the presence of H<sub>2</sub> absorption. The solid red line denotes the synthetic H<sub>2</sub> model (including HI Lyman-alpha and Lyman-beta absorptions). Also marked are prominent metal absorption lines previously detected in GRB-DLAs and foreground absorbers. From Krühler et al. (2013).

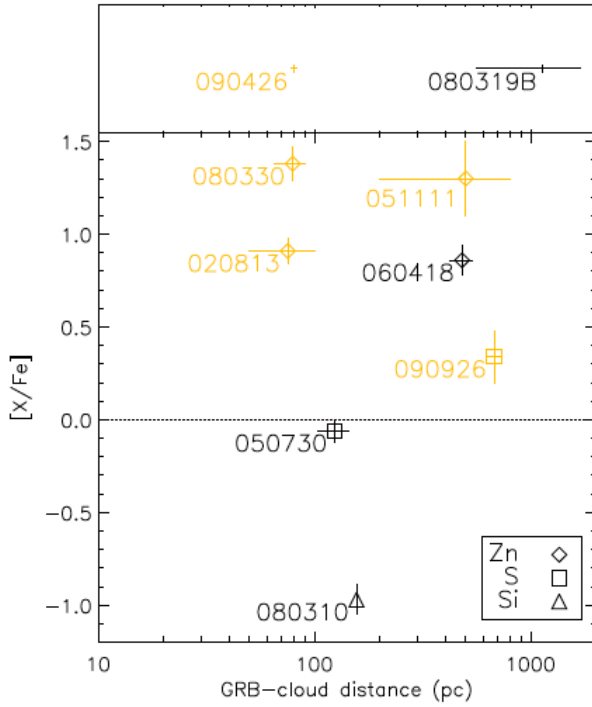
faint H<sub>2</sub> features from the forest is much easier in spectra with high spectral resolution and S/N. This favours bright afterglows. Physically, however, the H<sub>2</sub> column density is correlated with metallicity and dust depletion, and a large H<sub>2</sub> column is more likely for sightlines that are significantly obscured (and therefore much fainter in the rest-frame UV). As a result, afterglows that are both bright and heavily H<sub>2</sub>-absorbed are uncommon. The combination of resolution and sensitivity available with the X-shooter spectrograph should make the detections of molecules more frequent than in the past. Indeed, three detections of H<sub>2</sub> and one of CH<sup>+</sup> in X-shooter afterglow spectra have been published to date (Fig. 7; Krühler et al. 2013; D’Elia et al. 2014; Friis et al. 2015; Fynbo et al. 2014), compared to only one robust detection of molecules in GRB DLAs before the advent of X-shooter (Prochaska et al. 2009).

In general, the fraction of H<sub>2</sub> found along GRB sightlines seems to be quite low compared to the HI content. The comparison of the content of molecules and neutral hydrogen may be useful to better understand the processes triggering star-formation, especially if extended to HI and CO detections (or limits) obtained at millimeter and radio wavelengths with ALMA and ATCA (e.g. Hatsukade et al. 2014; Michałowski et al. 2015).

### 3.5 Distance of the gas from the GRB

The GRB afterglow radiation is intense enough to have an important impact on its environment at the time of the explosion. In particular, the UV radiation ionizes the neutral gas (e.g. Perna and Lazzati 2002) and destroys molecules and dust grains up to tens of parsecs away (Waxman and Draine 2000; Draine and Hao 2002). The metastable states of existing species (O I, Si II, Fe II) are populated by UV pumping followed by radiative cascade (Prochaska et al. 2006; Vreeswijk et al. 2008).

From the presence or absence of neutral, low and high ionization metal line absorptions, and thanks to the different fine-structure and metastable line transitions (due to UV pumping followed by radiative cascade) it is possible to establish the distances of the gas clouds absorbing the afterglow light. Indeed,



**Fig. 8** The abundance ratio of zinc, sulphur or silicon over iron, compared to the GRB-absorber distance inferred from absorption-line modelling (black points come from high-resolution spectra and are more reliable). From Vreeswijk et al. (2012).

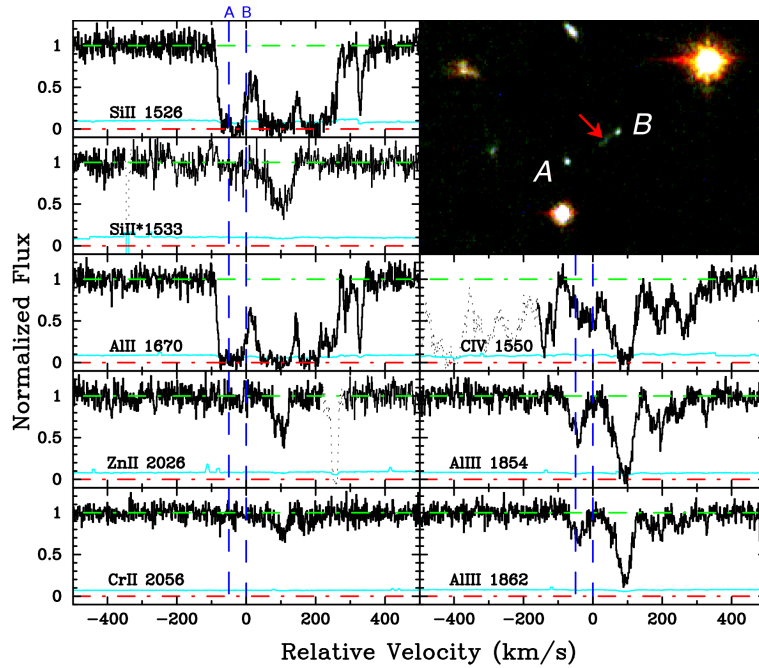
because the GRB afterglow fades rapidly, recombination prevails and the populations of the metastable levels change, making these absorptions vary and disappear. The detection of these time-dependent processes, with timescales ranging from seconds to days in the observer frame, can lead to interesting information on the burst itself and on the ISM of the host, in particular on the distance of the absorbing clouds.

To date, this analysis has been possible for  $\sim 10$  GRBs. It demonstrated that the gas is at least at  $\sim 100$  pc from the GRB explosion site (see Fig. 8), and that the GRB ionizes its surrounding gas at least up to 20 pc (Vreeswijk et al. 2008; Prochaska et al. 2008; Vreeswijk et al. 2012; D’Elia et al. 2014). Therefore, through optical spectroscopy, we are not probing the close environment of the GRB progenitor, but possibly its star-forming region, the inner region of its host galaxy and its circumgalactic gas.

Many attempts to find signatures of the close (pc-scale) GRB environment have been carried out. Unfortunately, there are no robust identifications to date, and possible evidences have been found only in a couple of cases (Fox et al. 2008; Castro-Tirado et al. 2010, but see Chen et al. 2007). On the other hand, by studying the profile of high ionization lines, some evidence of outflows has been found (Fox et al. 2008).

### 3.6 Comparison between ISM and ionized gas

Once the afterglow vanishes, it is possible to carry out photometric and spectroscopic campaigns to study the properties of the GRB host galaxy. Most exciting is the combination of the gas properties obtained by the afterglow spectroscopy and those retrieved by the host observations. A systematic study in this sense can provide important information on the physical processes of galaxy evolution and cosmological star-formation. The kinematics and geometry of the gas can be assessed as well, looking for inflow/outflow signatures. The physical state of the gas and its connection with the star-formation activity in the host galaxy can also be modelled. It is possible to obtain unique information to understand the link between the properties of the ISM and star formation activity at any redshift.



**Fig. 9** HST image of the field of GRB050820 at  $z = 2.6$ , superimposed on some absorption lines from the afterglow spectrum. The arrow indicates the afterglow position. The comparison between the velocities of the afterglow absorption lines and the emission lines of interacting galaxies A and B (represented by blue-dashed lines) indicates that the GRB occurred in an extension of galaxy B. Adapted from Chen (2012).

First attempts in this direction have been performed by Vergani et al. (2011) and Chen (2012) (see Fig.9). With the larger samples of afterglow and host galaxy spectra now available, it will be possible to perform more systematic studies on this topic.

### 3.7 Extinction

The issue of dust extinction in GRB afterglows has been central in the study of GRBs, their afterglows, host galaxies and birth sites since the first afterglows were detected in 1997 (e.g., Groot et al. 1998; Djorgovski et al. 2001). The advantage of GRB afterglows for the study of extinction is (at least) three-fold: *i*) afterglows can be extremely bright, allowing for actual detection of the spectra even when affected by substantial dust extinction; *ii*) afterglows have intrinsic relatively simple spectra consisting of power-law segments; *iii*) afterglows cover a very broad range of frequencies from radio to gamma-rays allowing for a study of the effects of dust over this broad range of frequencies.

A rich literature on the issue of extinction in GRB afterglows has developed over the past 20 years. Early studies focused on the issue of “dark” bursts (Groot et al. 1998; Djorgovski et al. 2001; Fynbo et al. 2001; Lazzati et al. 2002), the name given to bursts that evaded detection in the optical. Evidence then already suggested that these events were fairly common (perhaps as much as 50% of the sample) and that a majority of these are partially or entirely the result of dust extinction. A study of dust-extinction in pre-Swift afterglows can be found in Kann et al. (2006). However, because follow-up of pre-Swift GRBs was usually delayed until the afterglow faded significantly and because observations at dust-unobscured (e.g. X-ray) wavelengths could not always be obtained, large and systematically-complete analyses of dust extinction were not possible in the early years.

Swift has allowed much larger and more complete studies to be built. First of all the concept of *dark burst* became more precisely defined based on the expected power-law slopes of GRB afterglows between the optical and X-ray bands (Jakobsson et al. 2004; Rol et al. 2005; van der Horst et al. 2009). Examples of single-event studies of well observed and dust extinguished dark bursts are in Watson et al. (2006); Krühler et al. (2008); Elíasdóttir et al. (2009); Prochaska et al. (2009). Efforts to build complete samples in particular allowed for more robust statistics on the amount of extinction towards GRBs: in particular the fraction of dark bursts (as defined, e.g., by Jakobsson et al. 2004) was found to be about  $\sim 40\%$ , and about half of these (i.e.,  $\sim 20\%$  of GRBs) are *very* obscured (e.g., Cenko et al. 2009; Perley et al. 2009; Fynbo et al. 2009; Kann et al. 2010; Greiner et al. 2011; Hjorth et al. 2012; Melandri et al. 2012; Perley et al. 2013; Covino et al. 2013; Littlejohns et al. 2015).

An important, still open issue is that of photoelectric absorption and dust destruction. Galama and Wijers (2001) first noted that there were cases of afterglows with very strong photoelectric absorption in the X-rays and yet apparently rather limited extinction in the optical. This raised the issue of dust destruction (e.g., Fruchter et al. 2001). The issue of photoelectric absorption in the X-rays is further discussed in several dedicated papers (Behar et al. 2011; Watson and Jakobsson 2012; Watson et al. 2013; Starling et al. 2013; Krongold and Prochaska 2013), but without consensus. A possibly related phenomenon is bursts with high dust depletion of refractory elements, but limited extinction

in the optical (Savaglio et al. 2003; Savaglio and Fall 2004; Perley et al. 2008; Friis et al. 2015).

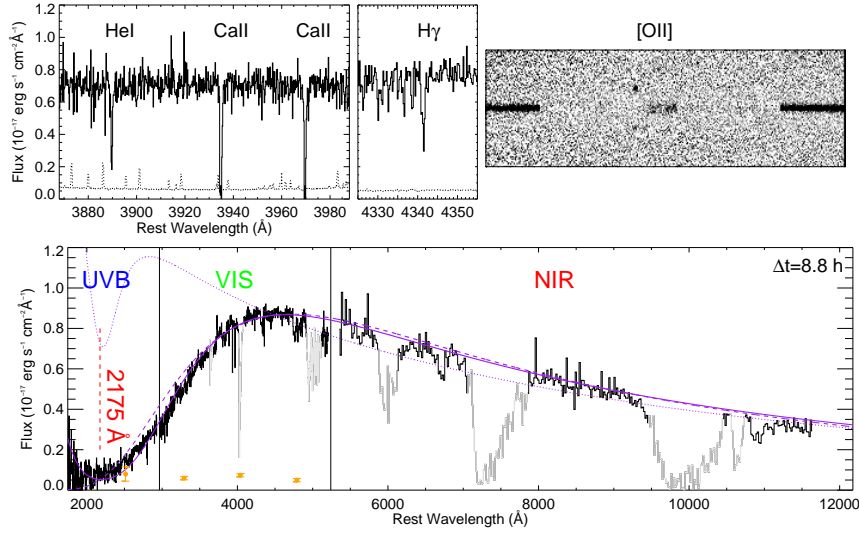
More detailed studies of extinction curves derived from afterglow spectra are presented in several sample papers: Starling et al. (2007); Zafar et al. (2011); Schady et al. (2010, 2012); Covino et al. (2013); Japelj et al. (2015). Extinction curves similar to those found towards stars in the Small Magellanic Cloud give the best fit for most GRB sightlines, but the 2175Å extinction bump is detected towards a handful of bursts.

Some GRB sightlines show evidence for extinction laws with no local analog: for example, the apparently-grey extinction towards GRB 061126 (Perley et al. 2008) or the unusual extinction towards the high-redshift GRB 071025 (Perley et al. 2010). Perhaps the most exotic system yet is that of GRB 140506A, whose extinction curve has been measured using X-shooter spectroscopy (Fynbo et al. 2014). This sightline shows several peculiarities: *i*) absorption lines from excited hydrogen and helium, *ii*) molecular absorption from  $\text{CH}^+$ , and most importantly for this discussion, *iii*) very strong dust reddening bluewards of about 4000 Å in the rest frame (see Fig. 10). Furthermore, the afterglow was observed on two consecutive nights and significant change in the shape of the reddening was found.

This strong reddening cannot be fitted by extinction curves known from the Local Group and its nature remains somewhat mysterious. It has some similarity to the sightline to SN 2014J in the starburst galaxy M82 (Amanullah et al. 2014). Along this sightline similar absorption line properties are also seen with strong Calcium absorption and absorption from  $\text{CH}^+$  (Ritchey et al. 2014). Another place where similar reddening has been observed is towards some QSOs (e.g., Hall et al. 2002; Leighly et al. 2014): the extinction curves for some reddened QSOs appear to be very steep (e.g., Fynbo et al. 2013) and one of the most remarkable QSOs in this regard, CQ0127+0114 (Hall et al. 2002), can be fitted with a similar prescription as the supernova in M82. There is also evidence for different extinction towards the central regions of the Galaxy (e.g., Sumi 2004; Nishiyama et al. 2008, 2009; Gosling et al. 2009; Nataf et al. 2015) and taken all together there seems to be a hint that extinction towards the central regions of galaxies is different and in particular steeper.

GRBs are strongly centred on the light of their host galaxies (Fruchter et al. 2006) and hence often probe the central regions of their hosts. Furthermore, there are still a significant number of bursts every year where we do not detect any afterglow light in the optical or near-IR so it appears quite plausible that this kind of unusual extinction could be more frequent for GRB sightlines than this (so far) only detection suggests. In fact, there is evidence that similar extinction was observed towards GRB 070318 (Watson 2009). Future GRBs may provide additional constraints on unusual extinction of this type and others.





**Fig. 10** Spectroscopy of GRB 140506A (Fynbo et al. 2014) and its unusual sightline. **Bottom panel:** An X-shooter spectrum taken 8.8 hr after the burst covering the range from about 2000 to 12000 Å in the rest frame of the  $z = 0.889$  GRB is plotted in black and late time host photometry is overplotted in orange. The spectrum shows a very steep drop in the blue, which is interpreted as the result of unusual extinction, either an extremely strong 2175 Å extinction bump (the dotted purple line shows a fit with the MW extinction curve and the full drawn line an extreme 2175 Å extinction bump) or more likely extinction similar to what is also seen towards some type Ia supernovae and AGN (the purple dashed line, see Fynbo et al. 2014 for a full discussion). **Top left:** The spectrum also shows very unusual absorption lines including absorption from excited helium and strong Calcium absorption as well as hydrogen Balmer lines and molecular  $\text{CH}^+$  lines (the latter not shown here, but in Fynbo et al. 2014) – never seen before in any afterglow spectra. **Top right:** Emission lines from the underlying host galaxy visible under the light of the afterglow; here [OII].

#### 4 Conclusions

GRBs, their afterglows, and their host galaxies provide powerful means of studying both the nearby Universe and the most distant galaxies. Studies of the population in different ways using different techniques (in emission and absorption, photometrically and spectroscopically, and at a wide range of wavelengths) provide unique insight into the factors governing GRB production and the nature and evolution of galaxies in the Universe.

Although the subset of GRBs with bright optical afterglows probes a low-metallicity, low-luminosity, low-mass host population compared to the population of galaxies that provide the bulk of the Universe’s star-formation over most of its history, optically-obscured dark GRBs probe a redder and more massive galaxy population and are essential to provide a complete view of the GRB host population. Even with these included, GRBs are not perfect tracers of all of cosmic star-formation: their lower abundance in high-mass and metal-rich galaxies and a tendency towards physically smaller systems point

to the existence of physical factors that operate to favor the production of GRBs (relative to other end-states of massive stellar evolution) in some environments over others. Metallicity is a leading candidate, and a model in which the GRB rate relative to star-formation is heavily suppressed above approximately solar metallicity but largely constant at lower metallicity appears to provide good consistency with photometric and spectroscopic observations of the GRB host population. On the other hand, other aspects of the host population are harder to explain by this model alone: the small sizes of GRB hosts, the concentration of GRB sites on the brightest star-forming regions, and the low-mass nature of the most luminous host galaxies may indicate that stellar density may play a supporting role in encouraging GRB production. These possibilities will soon be tested by detailed analysis of the large and uniform samples that have recently been acquired, and by more sophisticated modeling and analysis techniques (including the effects of chemical inhomogeneity within galaxies).

In either case, these environmental influences are expected, and observed, to become less significant at higher redshifts, where galaxies are uniformly small, star-forming, and metal-poor. GRBs are already being used in this way to place independent constraints on the sites of cosmic star-formation and sources of reionization. The nondetection of most  $z > 5$  GRB hosts in very deep HST observations is fully consistent with the leading view that reionization was driven by galaxies too faint to be currently observed—as is the recent detection of two  $z \sim 6$  GRB hosts.

GRB host studies using afterglow spectroscopy provide information independent of that deriving from the host light. Very detailed information about metal abundances, molecular content, escape of ionizing radiation, dust depletion patterns, and dust extinction curves can be inferred for host galaxies over a wide range of redshifts. Variability of fine structure lines provides unique information about the distance between the burst site and the absorbing material. In addition, information about the ionization state of the IGM can be inferred from the shape of the red damping wing of the Lyman- $\alpha$  line. However, absorption studies still provide only an incomplete view of the overall host population because optical afterglow spectroscopy generally requires a relatively unobscured afterglow. The few exceptions to this limitation (such as GRB 080607) suggest that sight lines towards GRBs in more mature and massive hosts are extremely rich in metals and molecules and there may be much to learn in the future when these sight lines can be studied with the next generation of extremely large telescopes.

For the past decade, Swift (supported by a wide range of ground-based observatories) has been the predominant facility for detecting and locating new GRBs, as well as a source of critical afterglow observations needed to characterize their sightlines and build complete samples. In spite of its achievements, Swift does have some limitations—in particular, difficulty in rapidly confirming the rare but valuable high-redshift ( $z > 6$ ) GRBs. For these purposes, a satellite capable of triggering on a larger number of high-redshift GRBs and earlier identification of the afterglow counterparts of these events

through optical and NIR photometry are essential. The SVOM mission<sup>1</sup> will be particularly useful in this sense, thanks to the sensitive Visible Telescope (VT) onboard and to the network of optical-NIR robotic telescopes dedicated to the photometric follow-up of SVOM GRBs. A further step forward towards a large sample of high-redshift GRB DLAs could be made with the proposed space mission THESEUS, specifically developed to detect high-redshift GRBs and observe their afterglows via on-board NIR photometry and spectroscopy.

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