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Gamma Ray Bursts in the era of reionization

N. R. Tanvir[1] and A. J. Levan[2]

[1] Department of Physics and Astronomy, University of Leicester, University Road, Leicester, LE1 7RH. United Kingdom
[2] Department of Physics, University of Warwick, Coventry, CV4 7AL. United Kingdom
e-mail: nrt3@star.le.ac.uk

Abstract. The birth of the first generations of stars and the era of reionization are topics at the forefront of contemporary cosmology. Direct observations of sources at such high redshifts ($z > 7$) are hard, and harder still to characterise their physical properties. Measurement of the scattering of the microwave background radiation from free electrons, and future detection of 21 cm radiation from the neutral hydrogen itself, provide potential windows on this cosmic phase change, but these approaches provide few clues to the sources of the dominant ionizing flux. Gamma-ray bursts (GRBs) offer an alternative, and complementary probe both of early star and galaxy formation, and for measuring the state of the interstellar medium of the host and the intergalactic medium, via afterglow spectroscopy. Here we review progress in finding and studying high redshift GRBs and their host galaxies, and consider how they may help in the future in piecing together a detailed picture of early structure formation in the universe.

Key words. dark ages, reionization, first stars – Galaxies: high-redshift – Gamma-ray burst: general – intergalactic medium

1. Introduction

Following recombination, at a redshift of $z \sim 1000$, the baryonic sector of the Universe consisted largely of neutral hydrogen and helium. By $z \sim 6$, however, the reservoir of gas between the nascent galaxies had become almost completely ionized (e.g. Malhotra & Rhoads 2004). This phase change must reflect the onset of an ionizing (far-ultraviolet and/or X-ray; see e.g. Loeb 2009; Mirabel et al. 2011) radiation field. If, as is frequently argued, this radiation is produced by early generations of massive stars, then the era of reionization is intimately connected to the collapse and turning on of the first galaxies. Thus, understanding this period has become one of the major challenges of contemporary extragalactic astronomy.

Unfortunately, sources at $z > 7$ are very hard to study directly, since galaxies and quasars were both smaller and fainter at early times, combined with high luminosity distance and the Lyα break being redshifted into the infrared. Only recently, with the re-observation of the Hubble Ultra-Deep Field HUDF with the Wide Field Camera-3 infrared channel, have significant numbers of candidate $z > 7$ Lyman-break galaxies been identified (Bunker et al. 2010; McLure et al. 2010; Bouwens et al. 2011a). Similarly, only with the latest wide-

Send offprint requests to: N. R. Tanvir

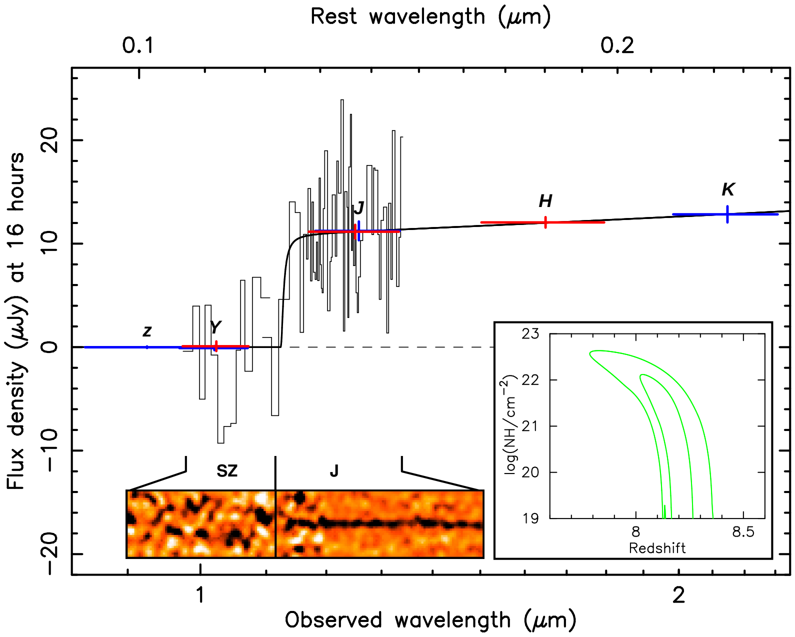

Fig. 1. The composite infrared spectrum of the afterglow of GRB 090423. Plotted are the 1D and 2D spectra obtained with the VLT using the Infrared Spectrometer And Array Camera (ISAAC). Also plotted are the sky-subtracted photometric data points obtained with the Gemini-N/NIRI (red) in Hawaii, and VLT/HAWKI and Gemini-S/GMOS (blue) in Chile (scaled to 16 hours post burst and expressed in μJy). The vertical error bars are 2σ (i.e. 95% confidence), whilst the horizontal lines indicate the widths of the filters (i.e. they are not error bars). A model spectrum showing the HI damping wing for a host galaxy with hydrogen column density $N_{\rm HI} = 10^{21}$ cm^{-2} at a redshift $z = 8.23$ is overplotted (solid black line), and provides a good fit to the data. Allowing for a wider range in possible host $N_{\rm HI}$ gives the 1σ (68%) and 2σ (95%) confidence contours shown in the inset panel.

area, deep infrared surveys has the first $z > 7$ quasar been found (Mortlock et al. 2011).

Other potential techniques for studying the era of reionization are to search for the evidence of scattering of microwave background photons from the electrons freed during reionization, and to detect directly emission from neutral hydrogen in 21 cm radio observations. The former has provided limits on the redshift range during which reionization took place: modelling the 7-year Wilkinson Microwave Anisotropy Probe (WMAP) data Komatsu et al. (2011) find $z = 10.4 \pm 1.2$ if reionization was an instantaneous event. The latter is hoped to be detectable with new radio facilities such as the Low Frequency Array (LOFAR) (e.g. Harker et al. 2010).

Gamma-ray bursts offer an alternative and complementary probe of the early Universe. They pinpoint their host galaxies and allow us to conduct a census of the locations and rates of massive star formation. Spectroscopy of their afterglows can reveal not only redshifts, but also detailed physical properties of the hosts such as chemical abundances (e.g. Vreeswijk et al. 2004; Chen et al. 2005; Fynbo et al. 2006; Prochaska et al. 2007), molecular content (e.g. Prochaska et al. 2009), dynamics, and dust properties (e.g. Schady et al. 2010; Zafar et al. 2011a,b). Measurements of the red damp-

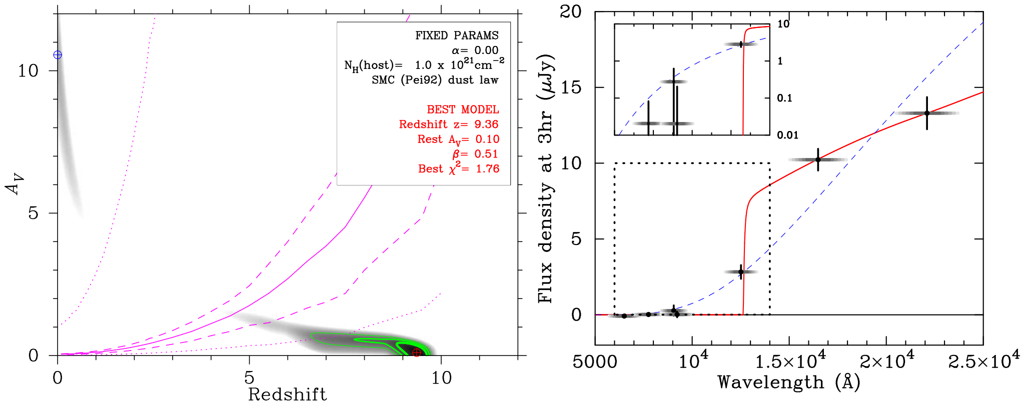

Fig. 2. Photometric redshift estimate for GRB 090429B. [Left panel:] shows likelihood contours in a plane of redshift versus rest-frame extinction obtained by fitting an intrinsic power-law spectral energy distribution with dust attenuation, to the observed afterglow photometry. The three (green) contours overlaying the greyscale represent 90%, 99% and 99.9% confidence respectively. The most likely value of the redshift is determined to be $z \approx 9.4$. [Right panel:] the bold (red) line shows the best fitting model, and the solid vertical bars the error ranges for the photometry. The horizontal bars indicate the approximate widths of the broad-band filters. The best-fit low redshift solution is shown as a dashed (blue) curve, and is formally ruled out at high significance. (The inset shows the dashed region but with a logarithmic flux axis).

ing wing of the Lyα absorption line may even provide constraints on the neutral fraction of the intergalactic medium at the location of the burst (Miralda-Escude 1998; Barkana & Loeb 2004; McQuinn et al. 2008). In this paper we review progress to-date in studying high redshift GRBs, and consider prospects for the future.

2. The search for high redshift GRBs

By their nature, GRBs are hard to observe since their occurrence and locations are unpredictable, and they fade on a short timescale. Thus rapid observations (and flexible procedures) are required if they are to be characterised and have their redshifts measured.

The first $z > 6$ GRB to be spectroscopically identified was GRB 050904 at $z = 6.30$ (Kawai et al. 2006), following photometric evidence which showed it to be a dropout source in the optical (Haislip et al. 2006). This burst had an intrinsically very bright afterglow which allowed a fairly good spectrum to be obtained with Subaru even 3 days post-burst. This spectrum showed metal absorption lines giving an accurate redshift, and provided a weak constraint on the IGM neutral fraction (Totani et al. 2006). Subsequently, GRB 080913 was found at $z = 6.73$ (Greiner et al. 2009; Patel et al. 2010) with the Very Large Telescope (VLT), and also showed a single metal absorption line.

The record spectroscopic redshift secured to-date is that of GRB 090423 at $z \approx 8.2$ (Tanvir et al. 2009; Salvaterra et al. 2009). Unfortunately, the afterglow was not bright enough, even at early times, to provide a high signal-to-noise spectrum, and in practice the first spectrum was only obtained after ~ 14 hr when the afterglow had faded further. The VLT/ISAAC spectrum, which provided the best redshift measurement, is shown in Fig. 1. Thus, on this occasion, it was not possible to detect absorption lines of other species which would have provided a more accurate redshift, and possibly abundance estimates. Neither was it possible to put a useful constraint on the neutral fraction of the intergalactic medium, or the column density of neutral hydrogen in the host, from the red damping wing of the Lyα line. Nevertheless, this event proved that GRBs were being produced at these early times in the universe, beyond any spectroscopically measured galaxy or QSO redshift, and gave an in-

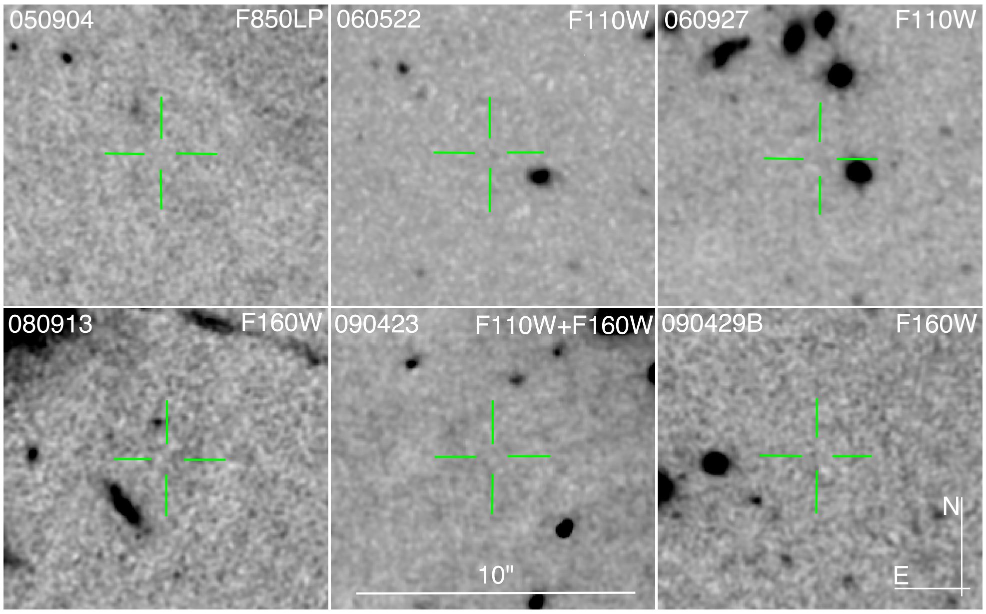

Fig. 3. Mosaic of infrared images (corresponding to rest-frame ultraviolet) for the locations of six $z >$ 5 GRBs. The images were all obtained at late times where the contribution from afterglow light should be negligible. In no case is there a significant ($> 2\sigma$) detection at the afterglow location (indicated by green cross-hairs). This finding suggests that the majority of star formation at high redshifts is occurring in galaxies below deep *HST* detection limits.

dication what would be required to use them as high-z probes in the future.

An even more distant event may have been found: GRB 090429B had a best-fit redshift based on photometry of its afterglow of $z \approx 9.4$, however it was unfortunately not possible to obtain a spectrum of this event due to high winds at Mauna Kea (the best placed major observatory) which forced the closure of most telescopes. A lower redshift, down to about $z \sim 7$, would be allowed if there is a modest amount of rest-frame dust extinction (see Fig. 2; full details of the observations and modelling procedure are given in Cucchiara et al. 2011).

3. The hosts of high redshift GRBs

To date, no host of a GRB at $z > 5$ has been detected directly. For example, Berger et al. (2007) imaged the field of GRB 050904 with both *HST* and *Spitzer*, finding no evidence of significant host emission. Stanway et al. (2011) conducted a search for molecular line emission (specifically CO 3–2) from the host of GRB 090423 using the Australia Telescope Compact Array (ATCA), setting an upper limit on the molecular hydrogen content of $\sim 5 \times 10^9\ M_\odot$.

The locations of six $z > 5$ GRBs have deep, late time infrared imaging from *HST* (Fig. 3). In no case is significant flux detected at the location of the burst (it is reasonable to measure fluxes at the GRB location given that GRBs at lower redshifts are preferentially located on

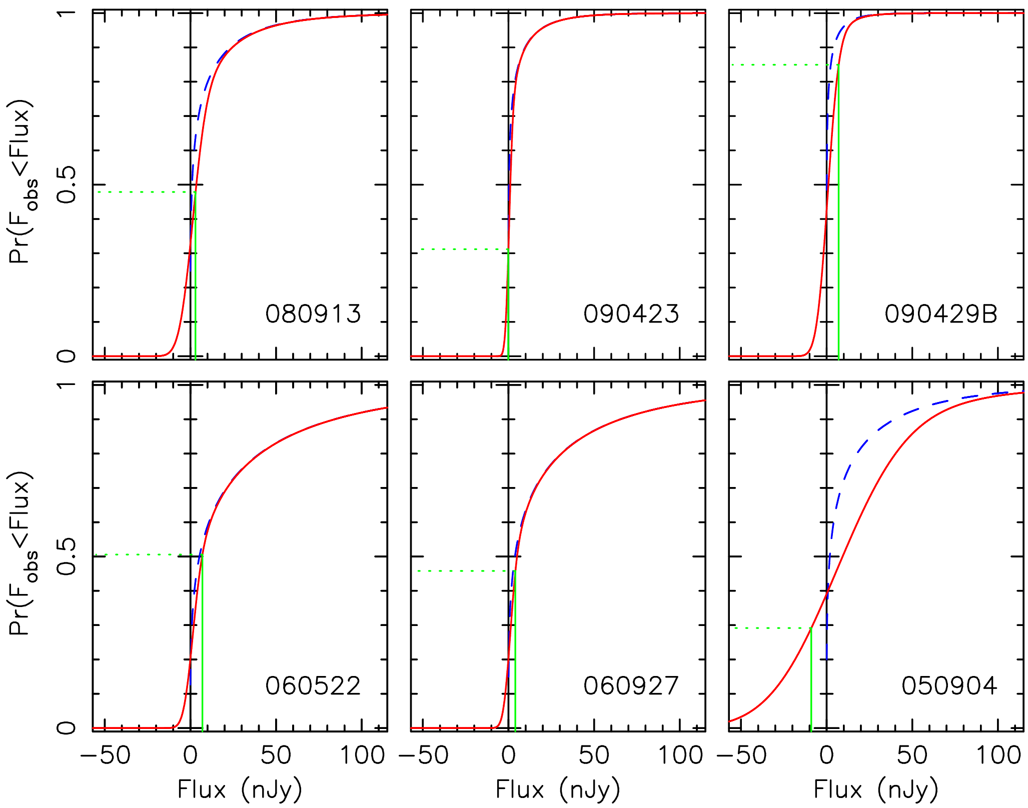

Fig. 4. For the six high redshift GRB fields observed with HST we construct a probability density function for the observed host magnitude by convolving the luminosity-weighted galaxy luminosity function appropriate to the GRB redshift found by Bouwens et al. (2011, illustrated here by blue dashed lines) with the observed measurement errors (producing solid red curves). This approach assumes that GRB rate is proportional to UV luminosity (which seems reasonable since both are produced by massive stars), and negligible dust extinction (which is plausible at early times, and consistent with the blue colours of both high-z galaxies found in the HUDF and of the afterglows themselves when the colour has been well-determined; e.g. Zafar et al. 2011b) The observed, sky subtracted, fluxes in fixed apertures at the location of the afterglows are indicated by vertical green lines. If our assumptions are correct, then these should be selected randomly between probabilities zero and unity, and indeed the data are consistent with that. Redshifts used are: $z = 5.11$ for GRB 060522 (Cenko et al. 2006), $z = 5.47$ for GRB 060927 (Ruiz-Velasco et al. 2007), $z = 6.30$ for GRB 050904 (Kawai et al. 2006), $z = 6.73$ for GRB 080913 (Patel et al. 2010), $z = 8.23$ for GRB 090423 (Tanvir et al. 2009) and $z = 9.4$ for GRB 090429B (Cucchiara et al. 2011).

the brightest parts of their hosts; Fruchter et al. 2006). We note that even relatively modest integrations can provide deep constraints since, unlike galaxies found in deep field samples which require relatively high-S/N detections and multiple bands to perform photometric redshift analysis, for the GRB hosts we can accept even 2 or 3σ detections as meaningful, given we know both redshift and position in advance.

The likelihood of this result can be assessed by taking the galaxy UV luminosity functions estimated from *HST* deep field observations, weighting these by luminosity (thus providing a probability density function for the host galaxy luminosities, assuming GRB rate is proportional to UV luminosity), and finally

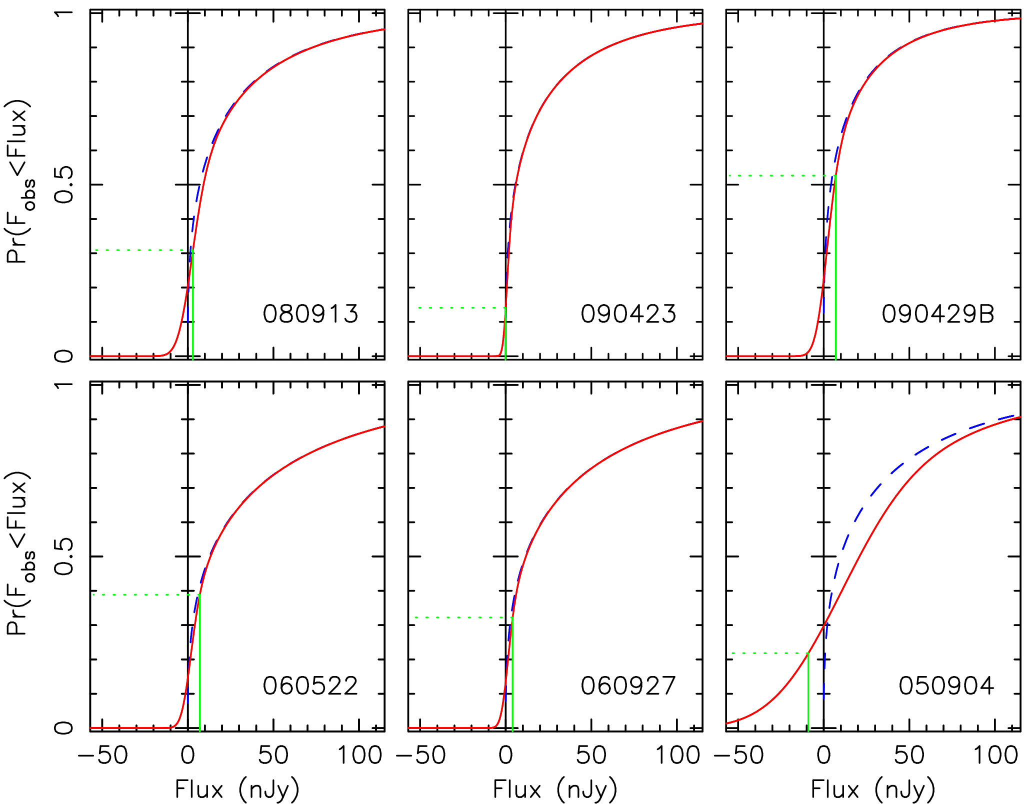

Fig. 5. Similar plot to Fig. 4, except here we have taken the galaxy luminosity function shape not to evolve at high-redshift. It can clearly be seen that, particularly for the higher redshift bursts, a non-evolving galaxy LF shape predicts a considerably higher rate of detectable hosts than for the evolving LF. In this case the sky-subtracted fluxes measured at the host locations correspond to around the median probability or less. Formally this is disfavoured at the ∼90% level.

convolving with observational errors appropriate to each dataset. This should provide a probability density function for the *observed* flux at each host location, which can be compared to the results from the images themselves. Fig. 4 shows this graphically, and we conclude that the observations are consistent with having been drawn from this population of galaxies.

However, a key question is whether the galaxy luminosity function evolves significantly at high redshifts. There are indications that the faint end slope is becoming even steeper, and the knee of the luminosity function becoming fainter, but this is based on detections of just the brightest galaxies at $z \sim 8$. The luminosity functions used in the above analysis presume a rapid evolution of the LF. We can repeat the analysis with a non-evolving LF, and this is shown in Fig. 5. In this case the bulk of the measurements at the host location are around or less than the median expectation.

With the present sample this is only sufficient to marginally reject a non-evolving LF shape (at the ∼ 90% level). However, this analysis illustrates the key role GRBs may play in the future study of star formation in the era of reionization. If the galaxy luminosity function is indeed as steep as suggested, then the large bulk of star formation at $z \sim 8$ is occurring in galaxies well below the *HST* Ultra-Deep Field depth, and even challenging for *JWST*. GRBs, therefore give access to this population of faint

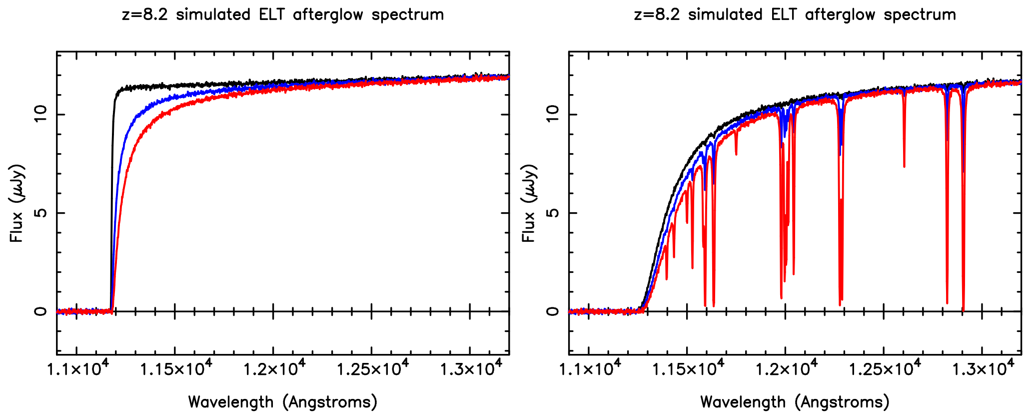

Fig. 6. Simulated spectra obtained with a ~40 m telescope such as the proposed E-ELT. In both cases the afterglow magnitude and integration time is taken to be approximately the same as that obtained for GRB 090423 observed by the VLT (Tanvir et al. 2009). [Left panel:] is for the situation of very low neutral hydrogen column within the host galaxy, and the three curves show the effect of an IGM neutral fraction of 0%, 50% and 100% from top to bottom. Although this is a simplified situation (for example, one might also image the host galaxy could have other feedback effects, such as creating a small ionized bubble around itself), the simulation illustrates that an ELT observation would have sufficiently high signal-to-noise that detailed model fitting would be possible. [Right panel:] in the case where the host itself has a high column density of hydrogen, it will be harder to measure the IGM neutral fraction but much easier to measure abundances in the host. The particular simulation has $N_{\rm H,host} = 10^{22}\,{\rm cm}^{-2}$ (offset slightly between models for clarity), and metallicity of 0.1%, 1% and 10% of Solar from top to bottom.

star-forming galaxies, since even without detecting the hosts directly, we can infer their contribution to the total massive star formation rate.

4. Future prospects

As mentioned above, in principle modelling the red damping wing of the Lyα absorption trough can distinguish absorption due to the IGM from features due to the host galaxy. In practice, this will frequently be difficult due to the large neutral gas columns often found in GRB host galaxies (e.g. Jakobsson et al. 2006; Chen, Prochaska, & Gnedin 2007), and the possibility that they (and their neighbours) also produce other effects on the shape of the absorption profile, in particular by ionizing some region around the galaxy. It is likely that very high signal-to-noise spectra will be required to confidently disentangle these components in most cases. Such spectra could be acquired with present technology for unusually bright afterglows, but more likely will have to await larger future telescopes. In Fig. 6 we show a simulation of an afterglow spectrum (in fact based on the parameters of GRB 090423) as it might be seen with a next-generation ground-based telescope like the proposed European Extremely Large Telescope (E-ELT). The quality of the spectra is easily sufficient to accurately measure the neutral fraction of the IGM if the gas column in the host is small. For larger host columns this will be more difficult (although useful results may still be obtained with reduced accuracy), but in compensation such systems will allow abundance measurements from metal absorption features down to very low metallicities.

Even with such observations, as emphasised by McQuinn et al. (2008), the expected variance from sight-line to sight-line of the neutral fraction at any given redshift, will mean that many high-z GRBs would need to be observed in order to provide a detailed timeline of reionization and an indication of its topology.

This naturally prompts the question as to what will be the capabilities for high-z GRB detection on timescales of the next decade or so. *Swift* has now been functioning well for over six years, but is already well over its original two-year baseline mission. Lacking any consumables, it was always envisaged that *Swift* would likely enjoy a longer lifetime, but it seems unlikely that it will remain free of hardware failures and still be functioning well in the 2020s. Currently the only planned new mission is the *Space-based multi-band astronomical Variable Objects Monitor* (*SVOM*; see Paul et al. 2011). This Chinese-French satellite builds on the *Swift* concept, with a wide-field gamma-ray burst monitor, X-ray telescope, but a more powerful 0.5 m optical telescope sensitive to $\sim 1\,\mu$m. Several other dedicated GRB mission concepts have been developed in recent years, but to-date none has been selected to be built (see, e.g., Burrows et al. 2011, this volume). To fully exploit GRBs as probes of the reionization era and beyond will certainly require new facilities which provide an enhanced rate of high-z discoveries.

5. Conclusions

Thanks to the brightness of the prompt and afterglow emission of long-duration GRBs, they offer a powerful probe of star formation and galaxy evolution in the early universe. They provide us with a means of studying massive star formation, its rate, location and environments, in principle even when it is taking place in galaxies beyond the detection limit of current or planned future telescopes. If the evolution of the galaxy luminosity function is proceeding as rapidly as some studies suggest, then such galaxies could dominate the total star formation activity in the peak era of reionization, and at even earlier times. This is consistent with the non-detection by *HST* of the highest redshift GRB hosts, and strongly motivates the development of new missions which are capable of finding significant numbers of GRBs at extreme redshifts.

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References

Barkana R., Loeb A., 2004, ApJ, 601, 64
Berger E., et al., 2007, ApJ, 665, 102
Bouwens R. J., et al., 2011a, ApJ, 737, 90
Bouwens R. J., et al., 2011, ApJ submitted, arXiv:1105.2038
Bunker A. J., et al., 2010, MNRAS, 409, 855
Burrows D. N., et al., 2011, arXiv:1106.0749
Cenko S. B., Berger E., Djorgovski S. G., Mahabal A. A., Fox D. B., 2006, GCN, 5155
Chen H.-W., Prochaska J. X., Bloom J. S., Thompson I. B., 2005, ApJ, 634, L25
Chen H.-W., Prochaska J. X., Gnedin N. Y., 2007, ApJ, 667, L125
Cucchiara A., et al., 2011, ApJ, 736, 7
Fruchter A. S., et al., 2006, Nature, 441, 463
Fynbo J. P. U., et al., 2006, A&A, 451, L47
Greiner J., et al., 2009, ApJ, 693, 1610
Haislip J. B., et al., 2006, Nature, 440, 181
Harker G., et al., 2010, MNRAS, 405, 2492
Jakobsson P., et al., 2006, A&A, 460, L13
Kawai N., et al., 2006, Nature, 440, 184
Komatsu E., et al., 2011, ApJS, 192, 18
Loeb A., 2009, JCAP, 3, 22
Malhotra S., Rhoads J. E., 2004, ApJ, 617, L5
McLure R. J., et al., 2010, MNRAS, 403, 960
McQuinn M., et al., 2008, MNRAS, 388, 1101
Mirabel I. F., Dijkstra M., Laurent P., Loeb A., Pritchard J. R., 2011, A&A, 528, A149
Miralda-Escude J., 1998, ApJ, 501, 15
Mortlock D. J., et al., 2011, Natur, 474, 616
Patel M., Warren S. J., Mortlock D. J., Fynbo J. P. U., 2010, A&A, 512, L3
Paul J., Wei J., Basa S., Zhang S.-N., 2011, CRPhy, 12, 298
Prochaska J. X., et al., 2007, ApJ, 666, 267
Prochaska J. X., et al., 2009, ApJ, 691, L27
Ruiz-Velasco A. E., et al., 2007, ApJ, 669, 1
Salvaterra R., et al., 2009, Nature, 461, 1258
Schady P., et al., 2010, MNRAS, 401, 2773
Stanway E. R., et al., 2011, MNRAS, 410, 1496
Tanvir N. R., et al., 2009, Nature, 461, 1254
Totani T., et al., 2006, PASJ, 58, 485
Vreeswijk P. M., et al., 2004, A&A, 419, 927
Zafar T., et al., 2011, A&A, 532, A143
Zafar T., et al., 2011, ApJ, 735, 2