GRBs as Probes of Massive Stars Near and Far

Johan P. U. Fynbo and Daniele Malesani

Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen,
DK-2100 Copenhagen O, Denmark
email: jfynbo@dark-cosmology.dk

Abstract. Long-duration gamma-ray bursts are the manifestations of massive stellar death. Due to the immense energy release they are detectable from most of the observable universe. In this way they allow us to study the deaths of single (or binary) massive stars possibly throughout the full timespan massive stars have existed in the Universe. GRBs provide a means to infer information about the environments and typical galaxies in which massive stars are formed. Two main obstacles remain to be crossed before the full potential of GRBs as probes of massive stars can be harvested: *i)* we need to build more complete and well understood samples in order not to be fooled by biases, and *ii)* we need to understand to which extent GRBs may be intrinsically biased in the sense that they are only formed by a limited subset of massive stars defined by most likely a restricted metallicity interval. I describe the status of an ongoing effort to build a more complete sample of long-duration GRBs with measured redshifts. Already now we can conclude that the environments of GRB progenitors are very diverse with metallicities ranging from solar to a hundredth solar and extinction ranging from none to $A_V > 5$ mag. We have also identified a sightline with significant escape of Lyman continuum photons and another with a clear 2175 Å extinction bump.

Keywords. gamma rays: bursts – galaxies: distances and redshifts

1. Introduction

GRBs were discovered serendipitously in the late 1960's and first reported to the astrophysical community in the early 1970's (Klebesadel *et al.* 1973). For a long time their nature remained a mystery (e.g., Nemiroff 1994). For a review of the first decades of GRB research where only the prompt γ-ray emission was known see Fishman & Meegan (1995). The major breakthrough came in 1997 with the ability to determine celestial positions of GRBs thanks to the BeppoSAX satellite and the discovery of long-lived X-ray, optical and radio afterglows (e.g., Costa *et al.* 1997; van Paradijs *et al.* 1997; Frail *et al.* 1997). For a review of the early years of the so called afterglow era (after 1997) see van Paradijs *et al.* (2000).

GRBs come in at least two variants defined by their duration in the γ-ray band. The short bursts have duration less than about 2 se and the long bursts longer than this (Kouveliotou *et al.* 1993). In the reminder of this review we will only discuss the long duration bursts. The association between long-duration GRBs (LGRBs hereafter) and massive stars and hence the link between LGRBs and on-going massive star-formation found its first empirical basis with the detection of the first host galaxies (e.g., Hogg *et al.* 1999). Subsequently, the evidence was further strengthened with the discovery of supernovae (SNe) associated with LGRBs (Galama *et al.* 1998; Hjorth *et al.* 2003; Stanek *et al.* 2003; Malesani *et al.* 2004; Sollerman *et al.* 2006; Pian *et al.* 2006). For a recent review of the LGRB/SN association see Woosley & Bloom (2006).

Because of the link between LGRBs and massive stars and due to the fact that GRBs can be detected from both the most distant and the most dust obscured regions in the universe LGRBs were quickly identified to be very promising tracers of star-formation throughout cosmic history (e.g., Wijers *et al.* 1998). However, this potential has so far not really resulted in an improved census of the locations of massive stars due to complications discussed in the next section.

A major issue currently under discussion is if LGRBs are unbiased tracers of star formation. More precisely, it is not clear if LGRBs are caused by the same (small) fraction of all dying massive stars (unbiased tracers), or if LGRBs only trace a limited segment defined by parameters such as, e.g., metallicity or circumstellar density (biased tracers).

The currently operating *Swift* satellite (Gehrels *et al.* 2004) has revolutionized LGRB research with its frequent, rapid, and precise localization of LGRBs. Now it is for the first time possible in practice to use LGRBs as powerful probes. It is mandatory that this potential is exploited while *Swift* is still operating (at least until 2010).

2. Complications in the use of LGRBs as tracers of massive stars

2.1. *Dark bursts and incomplete samples*

A crucial issue when using LGRBs (or any other class of tracer) is sample selection. Whereas the detection of the LGRB itself poses no bias against dust obscured massive stars this is not the case for the softer afterglow emission which is crucial for obtaining the precise localization as well as measuring redshifts (see, e.g., Fiore *et al.* 2007).

In the samples of LGRBs detected with satellites prior to the currently operating *Swift* satellite the fraction of LGRBs with detected optical afterglows was only about 30% (Fynbo *et al.* 2001; Lazzati *et al.* 2002). Much of this incompleteness was caused by random factors such as weather or unfortunate celestial positions of the bursts, but some remained undetected despite both early and deep limits. It is possible that some of these so called "dark bursts" could be caused by LGRBs in very dusty environments (Groot *et al.* 1998) and hence the sample of LGRBs with detected optical afterglows could very well be systematically biased against dust obscured star formation (see also Jakobsson *et al.* 2004a; Rol *et al.* 2005; Rol *et al.* 2007 for recent discussions of the dark bursts).

In any case, such a high incompleteness imposes a large uncertainty on statistical studies based on LGRB host galaxies derived from these early missions. It should be stressed that the conclusions based on these samples may only be relevant for a minority of all LGRBs. Due to the much more precise and rapid localization capability of *Swift* it is now possible to build much more complete samples.

2.2. *Are some LGRBs not associated with massive stellar death?*

Recently, it has been found that some LGRBs are not associated with SNe, namely GRB 060505 (Fynbo *et al.* 2006a; Ofek *et al.* 2007) and GRB 060614 (Fynbo *et al.* 2006a; Della Valle *et al.* 2006; Gal-Yam *et al.* 2006). This means that either some massive stars die without producing SNe brighter than about $M_V = -13.5$ (Fynbo *et al.* 2006a, Della Valle *et al.* 2006) or, alternatively, some LGRBs are caused by other mechanisms than collapsing massive stars (Gal-Yam *et al.* 2006; Ofek *et al.* 2007).

At least for the case of GRB 060505 the evidence points to the former. The burst was located in a star-forming region in a relatively low metallicity region in the outer part of a spiral host (Fynbo *et al.* 2006a; Ofek *et al.* 2007; Thöne *et al.* 2008; see also Fig. 1). The burst itself displayed a significant spectral lag, which has so far never been seen for the short bursts that are believed to originate from merging compact objects (McBreen *et al.* 2008; Norris & Bonnell 2006). If some LGRBs indeed are caused by other progenitors

than massive stars then a new classification that can distinguish between LGRBs from massive stars and those from other mechanisms is required. So far no such scheme has been found (see Gehrels *et al.* 2006).
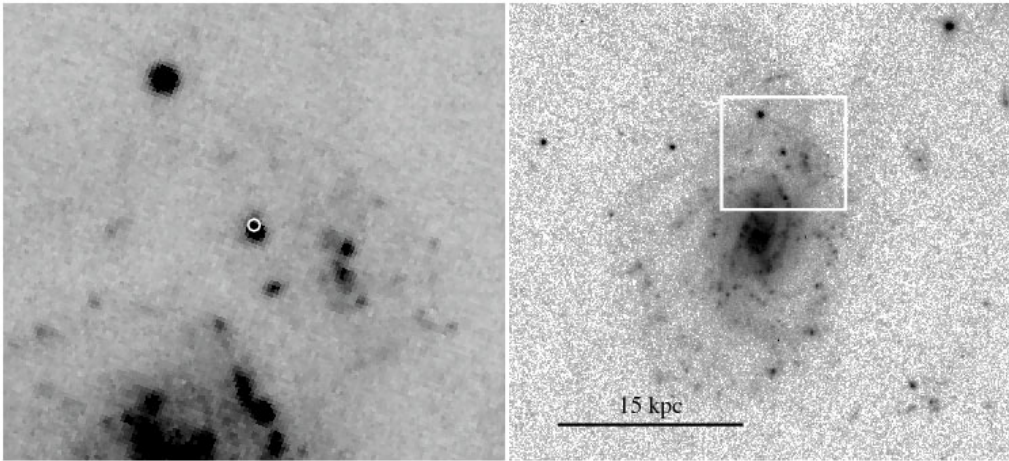
Figure 1. The host galaxy of GRB 060505 as observed with the HST (Ofek *et al.* 2007; Thöne *et al.* 2008). The white circle shows the error-circle of the burst consistent with a star-forming region in a spiral arm. This is strong evidence that the progenitor was a massive star. The properties of this host is also within the range found for other LGRBs. As an example, the host galaxy of GRB 050824 is very similar in terms of luminosity, R_{23} and star-formation rate (Sollerman *et al.* 2007), and the location within the host is similar to the location of other LGRBs in spiral hosts (Fynbo *et al.* 2000a; Sollerman *et al.* 2002; Le Floc'h *et al.* 2002; Jakobsson *et al.* 2005a).

2.3. *The contamination from chance projections*

The first important question to ask is: are LGRB host galaxies operationally well-defined as a class? In terms of an operational definition the case is not so clear. If we define the host galaxy of a particular burst to be the galaxy nearest to the line-of-sight, we need to worry about chance projection (Band & Hartmann 1998). In the majority of cases where an optical afterglow has been detected and localized with sub-arcsecond accuracy and where the field has been observed to deep limits a galaxy has been detected within an impact parameter less than 1 arcsec (see e.g., Bloom *et al.* 2002 and Fig. 2 for an example). The probability for this to happen by chance depends on the magnitude of the galaxy. The number of galaxies per arcmin^2 has been well determined to deep limits in the Hubble deep fields. In Fynbo *et al.* (2000b, their Fig. 2) the galaxy counts in the R and I bands based on the HDF-South can be found. To limits of R=24, 26 and 28 there are about 2, 6 and 13 galaxies arcmin^{-2}. Hence, the probability to find a R=24 galaxy by chance in an error circle with radius 0.5 arcsec is about 4×10^{-4}. For a R=28 galaxy the probability is about 3×10^{-3}. If the error circle is defined only by the X-ray afterglow with a radius of 2 arcsec in the best cases then we expect a random R=24 and R=28 galaxy in 0.6% and 5% of the error circles. For a sample of a few hundred LGRBs chance projection should hence not be a serious concern for LGRBs localized to sub-arcsecond precision, but for error-circles with radius of a few arcseconds we expect a few chance projections. In some cases it may be possible to eliminate the chance projects, e.g., based on conflicting redshift information from the afterglow and proposed host, but in general not.
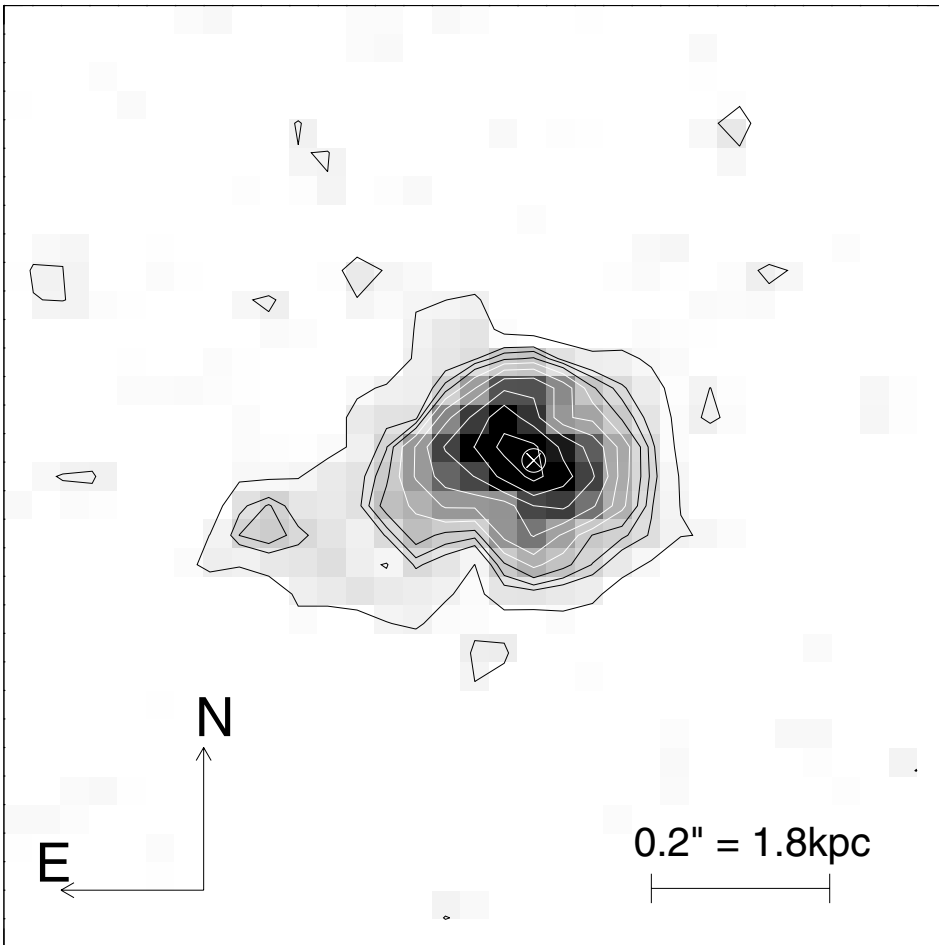
Figure 2. The 1×1 arcsec^2 field around the host galaxy of the $z = 2.33$ HETE-2 GRB 021004 observed with the *HST* (from Fynbo *et al.* 2005). The LGRB went off near the center of the galaxy. The position of the LGRB is marked with a cross and an error circle and it coincides with the centroid of the galaxy to within a few hundredths of an arcsec. In cases like this there is no problem in identifying the correct host galaxy. However, in cases of bursts localized to only a few arcsec accuracy chance projection needs to be considered.

3. Conclusions based on pre-Swift samples

Despite the complications mentioned above, the previous decade of LGRB host galaxy studies has after all taught us a lot about LGRBs and their link to massive star formation (see van Paradijs *et al.* 2000 and Djorgovski *et al.* 2003 for early reviews). LGRB hosts were early on found to be predominantly faint, blue star-forming galaxies (Hogg et al. 1999). The early studies found that these properties of LGRB hosts were consistent with the expectation if LGRBs are unbiased tracers of star-formation (Mao *et al.* 1998; Hogg *et al.* 1999). It was also realized early on that LGRBs offer a unique possibility to locate and study star-formation activity in dwarf galaxies at $z > 2$ (Jensen *et al.* 2001). This is basically impossible with any other currently existing method. The star-formation rates were found to be modest, but the specific star-formation rates among the highest ever found (Christensen *et al.* 2004). LGRB hosts are hence often in a starburst state.

Later evidence indicated that LGRBs maybe related only to massive stars with metallicity below a certain threshold. The first evidence for this came with the realization the LGRB hosts were fainter and bluer than expected according to certain models about the nature of the galaxies dominating the integrated star-formation activity (Le Floc'h *et al.* 2003, 2006; Tanvir *et al.* 2004). Nevertheless, it has recently been pointed out by Priddey *et al.* (2006) that "there is sufficient uncertainty in models and underlying assumptions, as yet poorly constrained by observation (e.g., the adopted dust temperature) that a correlation between massive, dust-enshrouded star formation and GRB production cannot be firmly ruled out." (see also Michałowski *et al.* 2008 concerning the issue of dust temperature). Further circumstantial evidence for a preference towards low metallicity came from the observation that Lyman-α emission seemed to be ubiquitous for LGRBs hosts (Fynbo *et al.* 2003; Jakobsson et al. 2005b).

Lately, evidence from hosts of more local LGRBs seems to point in the same direction. Several studies have found that local LGRBs hosts tend to be faint and metal poor although a caveat for some of these studies is the difficulty of using the strong line metallicity indicators like R_{23} to derive robust metallicities (Prochaska *et al.* 2004; Sollerman *et al.* 2005; Gorosabel et al. 2005; Stanek *et al.* 2006; Wiersema *et al.* 2007). However, nearly all of these studies targeted very incomplete pre-*Swift* samples and this raises the question whether the predominance of faint, metal poor hosts can be explained by, e.g., a bias against metal rich hosts and hence more dust obscured LGRB afterglows.

A very important result is that LGRBs and core-collapse SNe are found in different environments (Fruchter *et al.* 2006). The same study also found that LGRB host galaxies at $z < 1$ are fainter than the host galaxies of core-collapse SNe. This study is also based on incomplete pre-*Swift* samples, but as the SNe samples are if anything more biased against dusty regions than LGRBs this result does seem to be substantial evidence that LRBs are biased towards massive stars with relatively low metallicity. Wolf & Podsiadlowski (2007) however, find, based on an analysis of the Fruchter *et al.* (2006) data, that the metallicity threshold cannot be below half the solar metallicity. Concerning the different environments of core-collapse SNe and LGRBs it has recently been found that type Ic SNe have similar positions relative to their host galaxy light profiles as LGRBs, whereas all other SN types have a similar distribution, less centred on their host light than LGRBs and SN Ic's (Kelly *et al.* 2007). Larsson *et al.* (2007) find that the different distributions of different SN types relative to their host light can be naturally explained by assuming different mass ranges for the typical progenitor stars: $\gtrsim 8$ M$_\odot$ for typical core-collapse SNe and $\gtrsim 20$ M$_\odot$ for LGRB progenitors. The picture is complicated by the finding that type Ic SNe typically are found in substantially more metal rich environments than LGRBs (Modjaz *et al.* 2008, and in these proceedings). It is well established that WR-stars become more abundant with *increasing* metallicity - opposite to LGRBs that if anything are biased towards low metallicity. Taken together these findings suggest that progenitors of LGRBs and "normal" type Ic SNe are two different subsets of the $\gtrsim 20$ M$_\odot$ stars. For a thorough discussion of the relation between WR stars, SN Ic's and LGRBs we refer to Crowther (2007).

4. Building a complete sample of *Swift* LGRBs

The following is to a large extent based on Fynbo *et al.* (2007). The *Swift* satellite has been operating for about three years and is far superior to previous GRB missions. The reason for this is the combination of several factors: *i)* it detects LGRBs at a rate of about two bursts per week about an order of magnitude larger than the previous successful BeppoSAX and HETE-2 missions; *ii)* with its X-Ray Telescope (XRT) it localizes the

bursts with a precision of about 5 arcsec also orders of magnitude better than previous missions; *iii)* it has a much shorter reaction time, allowing the study of the evolution of the afterglows literally seconds after the burst, sometimes during the prompt γ-ray emission itself. The *Swift* mission is funded at least until 2010. A crucial objective is to secure a large sample, as complete as possible, of LGRB afterglows while *Swift* is still operating. More concretely, rather than including all *Swift* detected GRBs, it is more optimal to concentrate on those LGRB afterglows with favourable observing conditions. Our group uses the following sample criteria:

(*a*) XRT afterglow detected within 12 hr
(*b*) Small foreground Galactic extinction: $A_V < 0.5$ mag
(*c*) Favourable declination: $-70 < \mathrm{Dec} < 70$
(*d*) Sun distance larger than 55°

By introducing these constraints, we are not biasing the sample towards optically bright afterglows, but we select a sample for which useful follow-up observations are likely to be secured.

About 50% of all *Swift* LGRBs do not fulfill these criteria, primarily because *Swift*, for technical reasons, has to point close to the Sun a significant fraction of the time. For bursts fulfilling the above criteria, we make every possible effort to detect optical and near-infrared afterglows and to measure their redshifts. As shown below, we have been very successful in this effort, using mainly the ESO VLT. Redshifts, or more generally spectroscopic observations, are crucial for almost all LGRB-related science. The most important science cases for which spectroscopy is critical are listed below:

• Determining the luminosity function for LGRBs (prompt emission as well as afterglows).

• Determining the redshift distribution of LGRBs and using LGRBs as tracers for the cosmic star-formation history (Jakobsson *et al.* 2006a; Fiore *et al.* 2007).

• Studying the host galaxies, in particular those faint, high-redshift galaxies that are unlikely to be found and studied with other methods (e.g., Vreeswijk *et al.* 2004).

• Studying LGRB-selected absorption-line systems (e.g., Jakobsson *et al.* 2004b; Prochter *et al.* 2006).

• Characterizing the dust extinction curves of high-z galaxies (e.g., Jensen *et al.* 2001; see also Fig. 4).

• Determining the Lyman continuum escape fraction from high-z galaxies (Chen *et al.* 2007, see also Fig. 5).

• Spotting very high redshift LGRBs (e.g., Kawai *et al.* 2006; Ruiz-Velasco *et al.* 2007).

• Probing cosmic chemical evolution with LGRBs (e.g., Savaglio 2006; Fynbo *et al.* 2006b; Prochaska *et al.* 2007).

• Studying if LGRBs can be used for cosmography (e.g., Ghirlanda *et al.* 2004).

Since the launch of *Swift*, we have had programmes running at the VLT with the aim of securing redshifts for *Swift* LGRBs. The status at the time of writing is that 109 *Swift* LGRBs fulfilled our selection criteria. For 57 of these a redshift measurement has been secured (see Fig. 6). The VLT has been the dominant single contributor in all LGRB redshift measurements, providing around 40% of the secure redshifts to date. The redshift of the most distant known GRB 050904 at $z = 6.295$ was measured with the Subaru telescope (Kawai *et al.* 2006). Most of the other redshifts have been measured using other 6–10 m telescopes (Keck, Gemini, Subaru, Magellan). This is contrary to the expectations prior to the launch of *Swift*, where it was suspected that *Swift* itself, or at least 2–4-m telescopes, would be able to measure most of the redshifts. However, optical afterglows turned out to be much fainter at early times than anticipated. As we show in Fig. 3, the majority of the afterglows are fainter than $R = 20$ when a slit can be placed
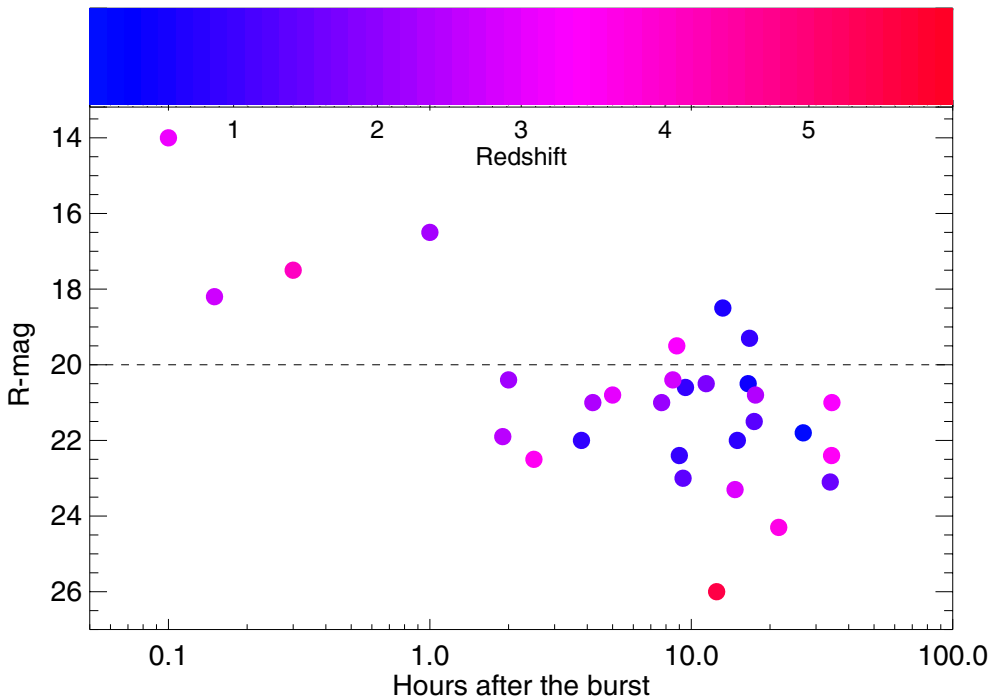
Figure 3. The R-band magnitude of the optical afterglows as a function of the time after the burst at which the spectroscopic observations were obtained. Only included are Swift bursts for which we have measured the redshift (using primarily the VLT, but also NOT, WHT and Gemini). The bar at the top indicates the code for the measured redshifts. The dashed line marks a magnitude of $R = 20$ which is roughly the spectroscopic limit for 2–4-m telescopes for detecting absorption lines. As seen, most afterglows are fainter than this limit when observable.

on them. $R = 20$ is, in our experience, the limit for spectroscopic redshift determination using 2–4-m telescopes (typically, no more than 1–2 hr exposure time is available for observing LGRB afterglows). Several optical afterglows are already fainter than $R = 22$ a few hours after the bursts. Hence, 6–10 m telescopes are crucial for securing redshifts for the majority of *Swift* LGRBs.

The fact that in particular the VLT, but also other 6-10 m telescopes, have made tremendous efforts to secure redshifts means that we now have a much higher redshift completion than for pre-*Swift* samples. But it is clear that we will not get redshifts for all bursts from spectroscopy of the afterglows for multiple reasons. In about 20-30% of the triggers we are not able to measure the redshift either due to lack of lines (probably bursts at redshifts between 1 and 2, see Fig. 6), bad weather or because the afterglow has faded too much before it is observable from Paranal. For these bursts our only chance of measuring the redshift is via spectroscopy of the host galaxy. We have also pursued this route extensively in an ESO large program (PI Hjorth). This is a challenging task due to the faintness of these systems, and the analysis of these data is still ongoing, but we have already determined a number of redshifts (included in Fig. 6).

4.1. *The redshift distribution of Swift LGRBs: current status*

The first conclusion from Fig. 6 is that *Swift* LGRBs are very distant. *Swift* LGRBs are more distant than LGRBs from previous missions due to the higher sensitivity of the satellite to the lower energies prevalent in the more distant events (Fiore *et al.* 2007).
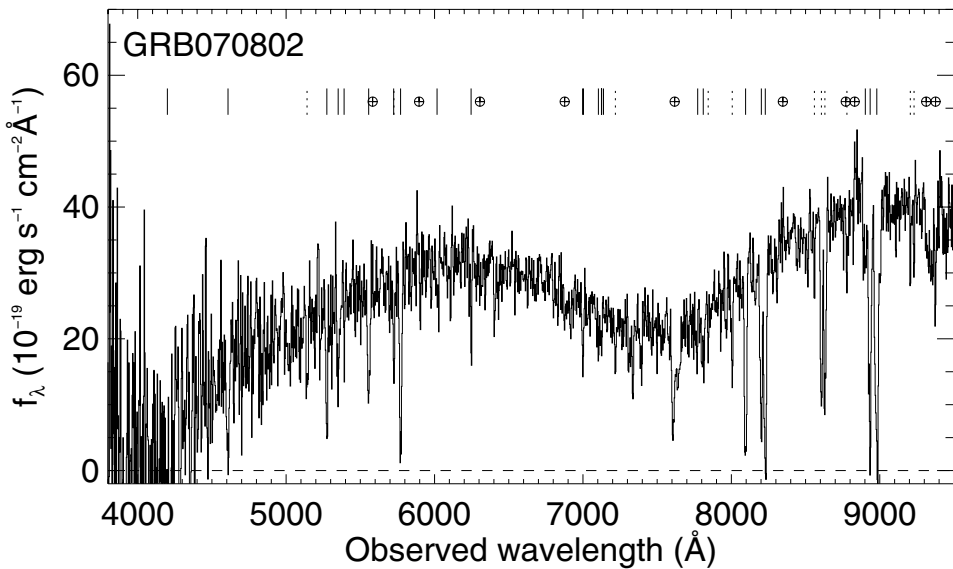
Figure 4. The VLT/FORS2 spectrum of the afterglow of GRB 070802 (Elíasdóttir *et al.*, in preparation). Plotted is the flux-calibrated spectrum against observed wavelength. Metal lines at the host redshift are marked with full-drawn lines whereas the lines from two intervening systems are marked with dotted lines. The broad depression centred around 7500 Å is caused by the 2175 Å extinction bump in the host system at $z_{abs} = 2.4549$.

The median and mean redshift are now both 2.3, while for previous missions it was closer to 1 (Jakobsson *et al.* 2006a). The record holder is $z = 6.295$ (Kawai *et al.* 2006). It is striking how events at redshifts as large as 6 can be detected within such a small sample. For comparison, only a few QSOs are detected at similar distances out of a sample of hundred thousand QSOs. Remarkably, the redshift distribution, measured for just over 50% of all bursts, is consistent with the redshift distribution predicted if LGRBs are unbiased tracers of star formation (see, e.g., Jakobsson *et al.* 2006a and http://www.dark-cosmology.dk/~pallja/GRBsample.html for a regularly updated analysis).

4.2. *HI column densities*

The HI column density distribution for LGRB sightlines is extremely broad. It covers a range of about 5 orders of magnitude from $\sim 10^{17}$ cm^{-2} (Fig. 5, Chen *et al.* 2007) to nearly 10^{23} cm^{-2} (Jakobsson *et al.* 2006b). I still remain to be understood if this distribution is representative of the intrinsic distribution of HI column densities towards massive stars in galaxies or if the distribution is rather controlled by the ionizing emission from the afterglows themselves. In any case, as pointed out by Chen *et al.* (2007) the HI column density distribution provides an upper limit to the escape fraction of Lyman continuum emission from star-forming galaxies.

4.3. *Metallicities*

Afterglow spectroscopy often allows us to measure the metallicity of the line-of-sight in the host galaxy. In Fig. 7 we plot the metallicities along LGRB sightlines together with metallicities derived from QSO damped Lyman-α absorbers (QSO-DLAs). Here it can be seen that LGRBs are more metal rich than QSO-DLAs at similar redshifts. Some of the LGRB sightlines are almost as metal rich as the Lyman-break galaxies at similar redshifts (Pettini *et al.* 2001). The shift in metallicity relative to QSO-DLAs
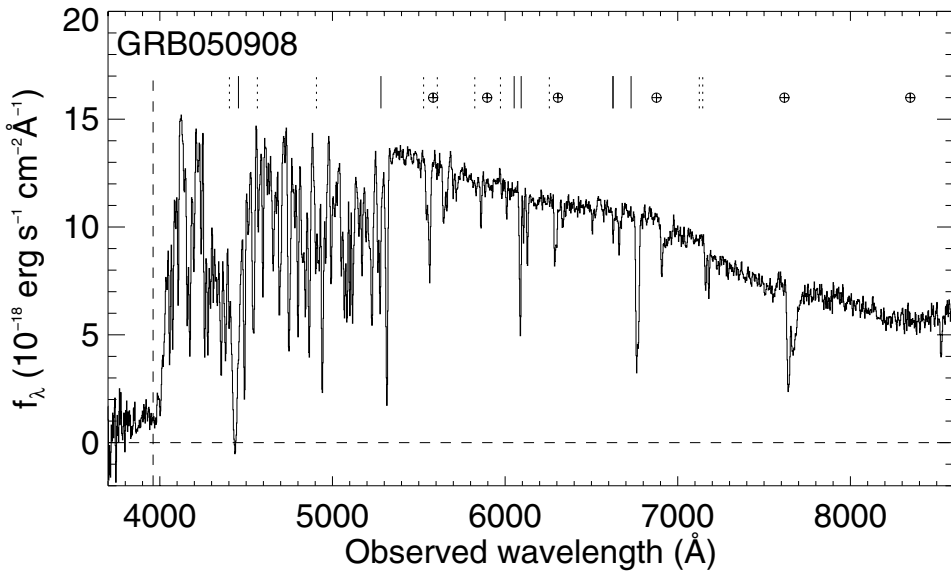
Figure 5. The VLT/FORS2 spectrum of the afterglow of GRB 050908 (Smette *et al.*, in preparation). Plotted is the flux-calibrated 1-dimensional spectrum against observed wavelength. The vertical dashed line shows the position of the Lyman limit at the redshift of the GRB ($z = 3.343$). As seen, there is clear excess flux below the Lyman limit.

can be understood from the different selection functions of the (star-formation selected) LGRB-DLAs and the (HI cross-section selected) QSO-DLAs combined most likely with metallicity gradients in high-z galaxies (Fynbo *et al.* 2008). Hence, most likely LGRBs will give a reasonably unbiased census of where the massive stars are located, at least at $z > 2$ (Fynbo *et al.* 2006b).

4.4. *Extinction*

In addition to HI column densities, metal and molecular abundances and kinematics, the afterglow spectra also provide information of the extinction curves. The intrinsic spectrum of the afterglow is from theory predicted to be a power-law and therefore any curvature or other broad features in the spectrum can be interpreted as being due to features in the extinction curve. So far, almost all the extinction curves derived for LGRB host galaxy sightlines have been consistent with an extinction curve similar to that of the SMC. Recently, we obtained the clearest yet detection of the 2175 Å bump known from the Milky Way in a $z=2.45$ LGRB (Eliasdottir *et al.*, in preparation and Fig. 4). This LGRB absorber also has unusually strong metal lines suggesting that the presence of the 2175 Å extinction bump is related to a high metallicity. However, we have examples of LGRBs with nearly solar metallicity for which the bump is not seen so it seems that metallicity is not the only parameter controlling the presence of the 2175 Å extinction bump. Concerning the amount of extinction the LGRB sightlines vary from no extinction (e.g., GRB050908, Fig. 5) to $A_V > 5$ mag (e.g., GRB070306, Jaunsen et al. 2008).

5. Conclusions and outlook

Spectroscopy of LGRB afterglows provides redshifts and information on the ISM properties for the population of galaxies containing the bulk of the high-redshift massive stars.
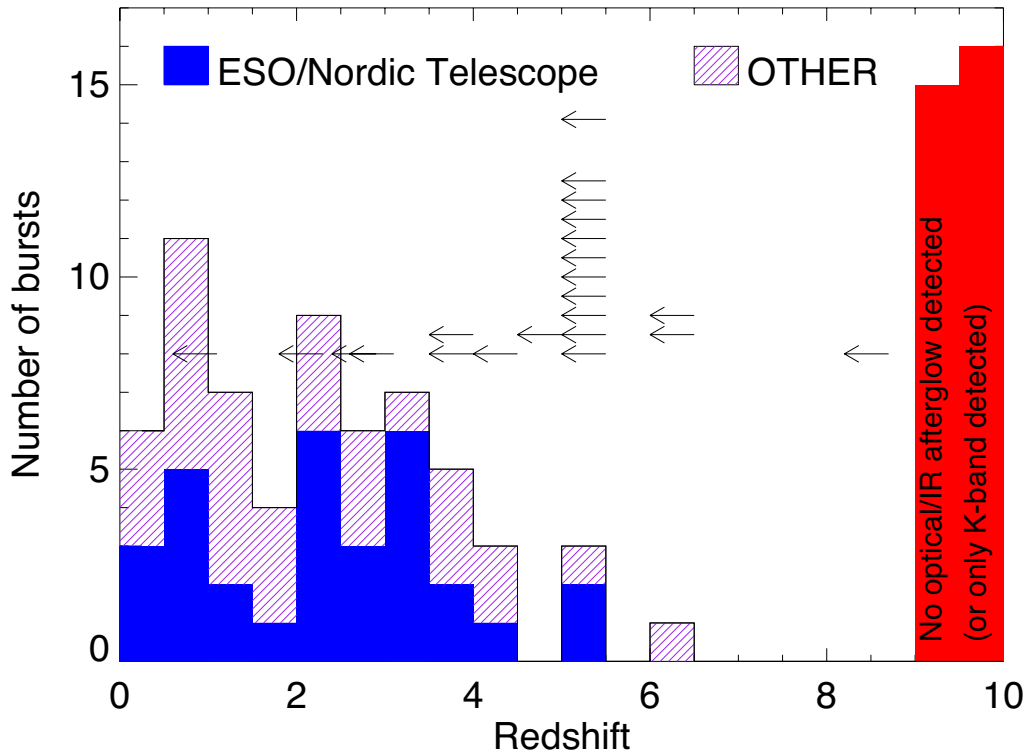
Figure 6. Redshift distribution (up to October 2007) of 109 *Swift* LGRBs localized with the X-ray telescope and with low foreground extinction $A_V < 0.5$. Of the 58 measured redshifts, our group has measured nearly half (25, shown in black). As shown, the VLT is the dominant source of redshifts in the *Swift* era (four of the black bursts in the histogram are also from the Nordic Optical Telescope). Bursts, for which only an upper limit on the redshift could be established so far, are indicated by arrows. Note that it is also difficult to secure redshifts for GRBs in the desert between $z = 1$ and $z = 2$. The grey histogram at the right indicates the 27 bursts for which no optical/J/H afterglow was detected and hence no redshift constraint could be inferred (see Ruiz-Velasco *et al.* 2007 for a full discussion).

We are currently working on securing this information for a complete sample of *Swift* LGRBs. Already now we can conclude that the environments of LGRB progenitors are very diverse with metallicities ranging from solar to a hundredth solar and extinction ranging from none to $A_V > 5$ mag. We have also identified a sightline with significant escape of Lyman continuum photons and another with a clear 2175 Å extinction bump.

Even though the completeness of the current *Swift* sample in terms of detections of optical afterglows ($\sim$75%), redshift determinations ($\sim$50%) and host galaxy detections ($\sim$80%) is much higher than for LGRBs from previous missions we still need to do better - preferably all three fractions should be $\gtrsim 80$%. We also need to improve the understanding of the link between LGRBs and massive stars. The SN-less GRBs GRB 060505 and GRB 060614 show that either some LGRBs are unrelated to massive stellar death or some massive stars die without causing SNe. The currently unfolding SN2008D/XRF080109 shows that there may be much more frequent bursts with softer prompt emission bridging the gap (in terms of both burst, SN and host properties) between GRBs and normal Ic SNe (e.g., Soderberg *et al.* 2008; Malesani *et al.*, 2008).
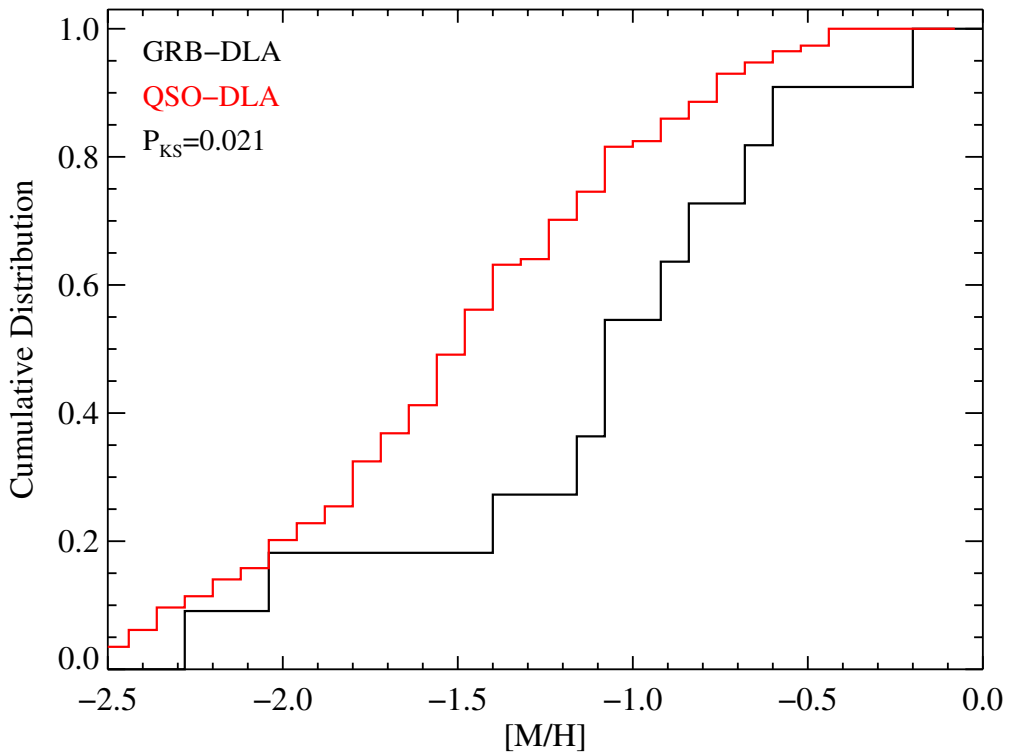
Figure 7. The histograms show the cumulative distribution of QSO-DLA and LGRB-DLA metallicities in the statistical samples compiled by Prochaska *et al.* (2003) and Prochaska *et al.* (2007). As seen, the LGRB-DLA metallicities are systematically higher than the QSO-DLA metallicities. See also Fynbo *et al.* (2008) for a simple model of these two distributions.

References

Band, D. L. & Hartmann, D. H. 1998 *ApJ*, 493, 555
Bloom, J. S., Kulkarni, S. R., & Djorgovski, S. G. 2002 *AJ*, 123, 1111
Chen, H.-W., Prochaska, J. X., & Gnedin, N. Y. 2007 *ApJ*, 667, L125
Christensen, L., Hjorth, J., & Gorosabel, J. 2004 *A&A*, 425, 913
Costa, E., Frontera, F., Heise, J., *et al.* 1997 *Nat*, 387, 783
Crowther, P. A. 2007 *ARA&A*, 45, 177
Della Valle, M., Chincarini, G., Panagia, N., *et al.* 2006 *Nat*, 444, 1050
Djorgovski, S. G., Kulkarni, S. R., Frail, D. A., *et al.* 2003, in: P. Guhathakurta (ed.), *Discoveries and Research Prospects from 6-10m Class Telescopes* (Bellingham: SPIE) *Proc. SPIE*, Vol. 4834, 238
Fiore, F., Guette, D., Piranomonte, S., *et al.* 2007 *A&A*, 470, 515
Fishman, G. J. & Meegan, C. A. 1995 *ARA&A*, 33, 415
Frail, D. A., Kulkarni, S. R., Nicastro, L., *et al.* 1997 *Nat*, 389, 261
Fruchter, A. S., Levan, A., Strolger, L., *et al.* 2006 *Nat*, 441, 463
Fynbo, J. P. U., Holland, S. T., Andersen, M. I., *et al.* 2000a *ApJ*, 542, L89
Fynbo, J. P. U., Freudling, W., & Møller, P. 2000b *A&A*, 355, 37

Fynbo, J. P. U., Jensen, B. L., Gorosabel, J., *et al.* 2001 *A&A*, 369, 373

Fynbo, J. P. U., Jakobsson, P., Møller, P., *et al.* 2003 *A&A*, 406, L63

Fynbo, J. P. U., Gorosabel, J., Smette, A., *et al.* 2005 *ApJ*, 633, 317

Fynbo, J. P. U., Starling, R. L. C., Ledoux, C., *et al.* 2006 *A&A*, 451, L47

Fynbo, J. P. U., Watson, D., Thöne, C. C., *et al.* 2006 *Nat*, 444, 1047

Fynbo, J. P. U., Vreeswijk, P., Jakobsson, P., *et al.* 2007 *ESO-Messenger*, 130, 43

Fynbo, J. P. U., Prochaska, J. X., Sommer-Larsen, J., *et al.* 2008 *ApJ*, submitted (arXiv:0801.3273)

Galama, T. J., Vreeswijk, P. M., van Paradijs, J., *et al.* 1998 *Nat*, 395, 670

Gal-Yam, A., Fox, D. B., Price, P. A., *et al.* 2006 *Nat*, 444, 1053

Gehrels, N., Chincarini, G., Giommi, P., *et al.* 2004 *ApJ*, 611, 1005

Gehrels, N., Norris, J. P., Barthelmy, S. D., *et al.* 2006 *Nat*, 444, 1044

Ghirlanda, G., Ghisellini, G., Lazzati, D., & Firmani, C. 2004 *ApJ*, 613, L13

Gorosabel, J., Pérez-Ramírez, D., Sollerman, J., *et al.* 2006 *A&A*, 444, 711

Groot, P., Galama, T. J., van Paradijs, J., *et al.* 1998 *ApJ*, 493, L27

Hjorth, J., Sollerman, J., Møller, P., *et al.* 2003 *Nat*, 423, 847

Hogg, D. W. & Fruchter, A. S. 1999 *ApJ*, 520, 54

Jakobsson, P., Hjorth, J., Fynbo, J. P. U., *et al.* 2004a *ApJ*, 617, L21

Jakobsson, P., Hjorth, J., Fynbo, J. P. U., *et al.* 2004b *A&A*, 427, 785

Jakobsson, P., Frail, D. A., Fox, D. B., *et al.* 2005a *ApJ*, 629, 45

Jakobsson, P., Björnsson, G., Fynbo, J. P. U., *et al.* 2005b *MNRAS*, 362, 245

Jakobsson, Levan, A., Fynbo, J. P. U., *et al.* 2006a *A&A*, 447, 897

Jakobsson, Fynbo, J. P. U., Ledoux, C., *et al.* 2006b *A&A*, 460, L13

Jaunsen, A. O., Rol, E., Watson, D. J., *et al.* 2008 *ApJ*, in press (arXiv:0803.4017)

Jensen, B. L., Fynbo, J. P. U., Gorosabel, J., *et al.* 2001 *A&A*, 370, 909

Kawai, N., Kosugi, G., Aoki, K., *et al.* 2006 *Nat*, 440, 184

Kelly, P. L., Kirshner, R. P., & Pahre, M. 2008, submitted (arXiv:0712.0430)

Klebesadel, R. W., Strong, I. B., & Olson, R. A. 1973, *ApJ*, 182, L85

Kouveliotou, C., Meegan. C. A., Fishman, G. J., *et al.* 1993, *ApJ*, 413, L101

Larsson, J., Levan, A. J., Davies, M. D., & Fruchter, A. S. 2007 *MNRAS*, 376, 1285

Lazzati, D., Covino, S., & Chisellini, G. 2002 *MNRAS*, 330, 583

Le Floc'h, E., Duc, P.-A., Mirabel, I. F., *et al.* 2002 *ApJ*, 581, L81

Le Floc'h, E., Duc, P.-A., Mirabel, I. F., *et al.* 2003 *A&A*, 400, 499

Le Floc'h, E., Charmandaris, V., Forrest, W. J., *et al.* 2006 *ApJ*, 642, L636

Mao, S. & Mo, H. J. 1998 *ApJ*, 339, L1

Malesani, D., Tagliaferri, G., Chincarrini, G., *et al.* 2004 *A&A*, 609, L5

Malaseni, D., Fynbo, J. P. U., Hjorth, J., *et al.* 2008, *ApJL*, submitted (arXiv:0805.1188)

McBreen, S., Foley S., Watson D., *et al.* 2008 *ApJL*, *ApJ*, 667, L85

Michałowski, M., Hjorth, J., Castro-Cerón, & J. M., Watson, D. 2008 *ApJ*, 672, 817

Modjaz, M., Kewley, L., Kirshner, R. P., *et al.* 2008 *AJ*, 135, 1136

Nemiroff, R. J. 1994, *Comments on Astrophysics*, 17, 189 (astro-ph/9402012)

Norris, J. P. & Bonnell, J. T. 2006 *ApJ*, 643, 266

Ofek, E. O., Cenko, S. B., Gal-Yam, A., *et al.* 2006 *ApJ*, 662, 1129

Pettini, M., Shapley, A. E., Steidel, C. C., *et al.* 2001 *ApJ*, 554, 981

Pian, E., Mazzali, P. A., Masetti, N., *et al.* 2006 *Nat*, 442, 1010

Priddey, R. S., Tanvir, N. R., Levan, A. J., *et al.* 2006 *MNRAS*, 369, 1189

Prochaska, J. X., Gawiser, E., Wolfe, A. M., *et al.* 2003 *ApJ*, 595, L9

Prochaska, J. X., Bloom, J. S., Chen, H.-W., *et al.* 2004 *ApJ*, 611, 200

Prochaska, J. X., Chen, H.-W., Dessauges-Zavadsky, M., & Bloom, J. S. 2007 *ApJ*, 666, 267

Prochter, G. E., Prochaska, J. X., Chen, H.-W., *et al.* 2006 *ApJ*, 698, L93

Rol, E., Wijers, R. A. M. J., Kouveliotou, C., *et al.* 2005 *ApJ*, 624, 868

Rol, E., van der Horst, A., Wiersema, K., *et al.* 2007 *ApJ*, 669, 1098

Ruiz-Velasco, A. E., Swan, H., Troja, E., *et al.* 2007 *ApJ*, 669, 1

Savaglio, S. 2006 *New Journal of Phys.*, 8, 195

Soderberg, A. M., Berger, E., Page, K. L. 2008, in press (arXiv:0802.1712)

Sollerman, J., Holland, S. T., Challis, P., *et al.* 2002 *A&A*, 386, 944

Sollerman, J., Östlin, G. Fynbo, J. P. U., *et al.* 2005 *NewA*, 11, 103

Sollerman, J., Jaunsen, A. O., Fynbo, J. P. U., *et al.* 2006 *A&A*, 454, 503

Sollerman, J., Fynbo, J. P. U., Gorosabel, J., *et al.* 2007 *A&A*, 466, 839

Stanek, K. Z., Matheson, T., Garnavich, P. M., *et al.* 2003 *ApJ*, 591, L17

Stanek, K. Z., Gnedin, O. Y., Beacom, J. F., *et al.* 2006 *AcA*, 56, 333

Tanvir, N., Barnard, V. E., Blain, A. W., *et al.* 2004 *MNRAS*, 352, 1073

Thöne, C. C., Fynbo, J. P. U., Östlin, G., *et al.* 2008 *ApJ*, 676, 1151

van Paradijs, J., Groot, P., Galama, T. J., *et al.* 1997 *Nat*, 386, 686

van Paradijs, J., Kouveliotou, C., & Wijers, R. A. M. J. 2000 *ARA&A*, 38, 379

Vreeswijk, P. M., Ellison, S. L., Ledoux, C., *et al.* 2004 *A&A*, 419, 927

Wiersema, K., Savaglio, S., Vreeswijk, P. M., *et al.* 2007 *A&A*, 464, 529

Wijers, R. A. M. J., Bloom, J. S., Bagla, J. S., & Natarajan, P. 1998 *MNRAS*, 294, L13

Wolf, C. & Podsiadlowski, P. 2007 *MNRAS*, 375, 1049

Woosley, S. & Bloom, J. S. 2006 *ARA&A*, 44, 507

Discussion

BURBIDGE: Some closeby -low redshift- GRBs are clearly associated with supernovae-we see traces of the SN light curves. But for most of the GRBs either no optical or radio object has been identified or only very faint afterglows are found. Thus the connection with galaxies- even star forming galaxies is much weaker. On the other hand, many optical spectra of GRB afterglows show the absorption features of QSOs. Thus I think that some attention should be paid to the connection of GRBs with QSOs. Here the MgII absorption seen in all of the afterglows with absorption but only in a fraction of QSOs presents a real problem for those who believe that the QSOs all have cosmological redshifts.

FYNBO: I would describe the situation as follows. For $z < 2$ GRBs we almost always detect a host galaxy at the position of the afterglows. For more distant GRBs the fraction of hosts detected to a detection limit of about $R = 27$ drops. The properties of the GRB absorption systems are most similar to the DLAs seen in QSO spectra although GRB systems on average are more metal rich. In no case has a GRB been associated directly with a galaxy hosting an AGN.

RAUW: There have been suggestions to use nuclear resonance absorption lines in the γ-ray spectrum to determine the redshifts of GRBs beyound z=6. That would require very large column densities, well in excess of the values you have presented. Can you comment on this?

FYNBO: I am afraid I do not have much insight into this issue. I can add that in some cases substantially higher column densities are inferred from X-ray absorption than from Hydrogen Lyman-α (e.g., Watson *et al.* 2007, *ApJ*, 660, L101). This is most likely due to ionized material close to the GRB progenitor. Still, the column densities inferred from X-ray absorption are so far all below 10^{23} cm^{-2} equivalent HI.

Max Pettini.

Yoshi Taniguchi.