THE OPTICALLY UNBIASED GRB HOST (TOUGH) SURVEY. IV. Lyα EMITTERS*

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ABSTRACT

We report the results of a spectroscopic search for Lyα emission from gamma-ray burst (GRB) host galaxies. Based on a well-defined parent sample (the TOUGH sample) of 69 x-ray-selected Swift GRBs, we have targeted the hosts of a subsample of 20 GRBs known from afterglow spectroscopy to be in the redshift range $z = 1.8–4.5$. We have obtained spectroscopy using the FORS1 instrument at the ESO Very Large Telescope to search for the presence of Lyα emission from the host galaxies. We detect Lyα emission from 7 out of the 20 hosts, with the typical limiting 3σ line flux being $8 \times 10^{-18} \text{erg cm}^{-2} \text{s}^{-1}$, corresponding to an Lyα luminosity of $6 \times 10^{41} \text{erg s}^{-1}$ at $z = 3$. The Lyα luminosities for the seven hosts in which we detect Lyα emission are in the range $(0.6–2.3) \times 10^{42} \text{erg s}^{-1}$, corresponding to star formation rates of $0.6–2.1 M_{\odot} \text{yr}^{-1}$ (not corrected for extinction). The rest-frame Lyα equivalent widths (EWs) for the seven hosts are in the range 9–40 Å. For 6 of the 13 hosts for which Lyα is not detected, we place fairly strong 3σ upper limits on the EW ($<20$ Å), while for others the EW is either unconstrained or has a less constraining upper limit. We find that the distribution of Lyα EWs is inconsistent with being drawn from the Lyα EW distribution of bright Lyman break galaxies (LBGs) at the 98.3% level, in the sense that the TOUGH hosts on average have higher EWs than bright LBGs. We can exclude an early indication, based on a smaller, heterogeneous sample of pre-Swift GRB hosts, that all GRB hosts are Lyα emitters. We find that the TOUGH hosts on average have lower EWs than the pre-Swift GRB hosts, but the two samples are only inconsistent at the 92% level. The velocity centroid of the Lyα line (where detected) is redshifted by 200–700 km s$^{-1}$ with respect to the systemic velocity (taken to be the afterglow redshift), similar to what is seen for LBGs, possibly indicating star-formation-driven outflows from the host galaxies. There seems to be a trend between the Lyα EW and the optical to x-ray spectral index of the afterglow ($\beta_{OX}$), hinting that dust plays a role in the observed strength and even presence of Lyα emission.

Key words: dust, extinction – galaxies: fundamental parameters – galaxies: high-redshift – galaxies: star formation – gamma-ray burst: general – surveys

Online-only material: color figures

1. INTRODUCTION

Due to their potential brightness at wavelengths ranging from radio to gamma rays, gamma-ray bursts (GRBs) and their afterglows can be used as powerful astrophysical probes. They are momentarily bright enough to be observed anywhere in the universe, even if located in the most dusty environments or at the highest redshifts (e.g., Wijers et al. 1998), but later fade away and allow a detailed study of their environment. It is now established that long-duration GRBs are associated with core-collapse supernovae (e.g., Stanek et al. 2003; Hjorth et al. 2003; Woosley & Bloom 2006; Hjorth & Bloom 2012) and hence sensitive to both the star formation rate (SFR) and the dust content of GRB host galaxies. In addition, geometrical effects and the kinematical state of the interstellar medium seem to be important for the escape of Lyα photons (e.g., Giavalisco et al. 1996; Hayes et al. 2005; Verhamme et al. 2006; Laursen et al. 2009).

The first studies of Lyα emission from (pre-Swift) GRB host galaxies indicated that Lyα emission seemed to be ubiquitous, with five detections out of five possible (Fynbo et al. 2003). This would be intriguing as only about 25% of Lyman-break-selected galaxies (LBGs) at similar redshifts have Lyα emission with rest-frame equivalent width (EW) larger than 20 Å (Shapley et al. 2003); this is also the case at higher redshifts (Douglas et al. 2010, but see also Stark et al. 2011). Another six GRB host Lyα emitters (all from Swift GRBs) have been reported in the literature since then (excluding the hosts reported in this work), but there still has not been a systematic examination of

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4 GRB 971214 (Kulkarni et al. 1998), GRB 000926 (Fynbo et al. 2002), GRB 011211 (Fynbo et al. 2003), GRB 021004 (Møller et al. 2002, and references therein), and GRB 030323 (Vreeswijk et al. 2004).
5 GRB 060714 (Jakobsson et al. 2006a), GRB 060926 (Fynbo et al. 2009), GRB 061222A (Perley et al. 2009), GRB 070110 (Fynbo et al. 2009), GRB 071031 (Fynbo et al. 2009), and GRB 090205 (D’Avanzo et al. 2010).
6 This work reports the detection of Lyα emission from seven host galaxies, of which one (GRB 070110) was already identified as an Lyα emitter in the literature.
the frequency of Lyα emitters among GRB host galaxies. This is the aim of the present work.

Given the effect of dust on Lyα photons, possible explanations for an excess of Lyα emitters among GRB host galaxies include (Fynbo et al. 2003): (1) a preference for GRB progenitors to be metal poor as expected in the collapsar model (Woosley & Heger 2006; Yoon & Langer 2005; see also Niino et al. 2009); (2) an optical afterglow selection bias against dusty hosts; (3) a higher fraction of Lyα emitters at the faint end of the high-redshift luminosity function, where most GRB hosts are found; and (4) small-number statistics. Using a well selected and more complete Swift sample, we shall here address these issues.

The paper is structured in the following way. The parent sample (The Optically Unbiased GRB Host, TOUGH), the target selection, the spectroscopic observations, and the data reduction are described in Section 2. The Lyα detections and upper limits are presented in Section 3.1. The velocity offset of the Lyα emission with respect to the systemic velocity as given by the afterglow redshift is discussed in Section 3.2. A comparison of the Lyα fluxes from afterglow and host spectra is done in Section 3.3. In Section 4, we discuss the results, including how they relate to LBGs and to pre-Swift studies, and how the observed Lyα emission is related to the afterglow broadband spectral index βOX, and we summarize our findings. Finally, the Appendix presents observations targeting the hosts of three GRBs that are not part of the complete, well-defined TOUGH sample discussed in the main part of the paper.

We assume $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$. This only affects the Lyα luminosities and the derived SFRs. The reported magnitudes are on the Vega system, with the exception of Figure 9.

The reduced data from this work will be available from ESO and from the TOUGH Web site.

2. TARGET SELECTION, OBSERVATIONS, AND DATA REDUCTION

2.1. The TOUGH Sample

This work is based on a parent sample named TOUGH sample. This sample of 69 Swift GRBs has several important features: (1) The selection criteria (see below) are designed to provide an optically unbiased (x-ray selected) sample of long-duration GRBs; (2) the selection criteria are also designed to increase the prospects of prompt follow-up observations being successful; (3) the sample has been the focus of an extensive prompt follow-up campaign by our group (e.g., Fynbo et al. 2009); and (4) the sample has been the focus of an extensive late-time follow-up campaign targeting the host galaxies, as reported in this series of papers (Hjorth et al. 2012; D. Malesani et al. 2012, in preparation; Jakobsson et al. 2012; this paper; Krühler et al. 2012; Michalowski et al. 2012).

The sample selection criteria and their rationale are given in detail in Hjorth et al. (2012). They can be summarized as follows: (1) the burst should trigger the γ-ray imager BAT onboard Swift; (2) only long-duration bursts are considered; (3) an x-ray afterglow should be detected and the Swift X-Ray Telescope (XRT) x-ray position should be made available within 12 hr from the trigger; (4) Milky Way extinction $A_V \lesssim 0.5$ mag; (5) Sun distance at the time of the GRB detection $> 55^\circ$; (6) no nearby bright stars (would complicate host galaxy observations); (7) only bursts in the period 2005 March 1–2007 August 10 are considered; (8) declination in the range $-70^\circ$ to $+27^\circ$ (suitable for Very Large Telescope, VLT, observations); and (9) the localization of the burst from the x-ray afterglow should be better than 2′ ($90\%$ error radius).\footnote{This includes using the revised UVOT-enhanced Swift–XRT positions (Evans 2011; Evans & Osborne 2011), which has had the effect of increasing the sample size from 68 (e.g., Jakobsson et al. 2011) to 69, with the additional burst being GRB 060923B.}

Furthermore, observations targeting the host as part of the TOUGH large program should be carried out at least 50 days after the GRB.

2.2. Target Selection

The GRBs for the Lyα host galaxy spectroscopy studied here were selected from the TOUGH sample by applying the criterion that the (spectroscopic) redshift should be known and in the range 1.8–4.5. The lower limit comes from the atmospheric cutoff and the sensitivity curve of the used CCDs, while the upper limit comes from fringing in the CCDs used in some of the observing runs.

At the time of the target selection for the last run of the observing campaign for the Lyα spectroscopy (Section 2.3), the redshift status of the TOUGH sample was as follows: (1) 20 bursts met the $z = 1.8–4.5$ criterion, and these were the ones observed, as listed in Table 1; (2) 21 bursts had $z$ outside the range 1.8–4.5; and (3) 28 bursts did not have a secure, spectroscopic redshift determination. Note that group (2) included five redshifts obtained as part of the TOUGH redshift campaign (Jakobsson et al. 2012) which were available before the Lyα observing campaign ended.

For reference, the redshifts were subsequently revised for some bursts, and redshifts became available for other bursts. As of 2012 February, the split of the TOUGH sample into three groups based on redshift would be: (1′) 27 hosts have $z = 1.8–4.5$, of which 20 hosts are those observed with FORS1 in the Lyα campaign and presented in this paper (Table 1), while 7 hosts do not have such FORS1 spectroscopy;\footnote{These seven additional bursts have redshifts from recent X-shooter host spectroscopy (Krühler et al. 2012, see also Section 4.2.)} (2′) 22 hosts have $z$ outside 1.8–4.5; and (3′) 20 hosts do not have a (secure, spectroscopic) redshift.

The redshifts of two of the hosts included in our Lyα campaign warrant special mention. GRB 060604 was originally included because it had an afterglow redshift of $z = 2.68$ proposed by Castro-Tirado et al. (2006). A subsequent re-reduction and analysis of the same data by Fynbo et al. (2009) did not confirm that redshift. Instead, an upper limit of $z < 3$ was derived, and a possible redshift of $z = 2.124$ was suggested, based on a single absorption line interpreted as Al II. We recently obtained an X-shooter host spectrum (Krühler et al. 2012) that gives $z \approx 2.1359$ from Hβ, [O iii], and Hα. This prompted the discovery of a wavelength calibration error in the afterglow spectrum; the revised absorption-line redshift is $z \approx 2.1361$. We will adopt the value $z = 2.136$. GRB 060908 was originally included because it had an afterglow redshift of $z = 2.43$ from Rol et al. (2006). Our spectroscopy (Section 2.3) gave an Lyα host emission redshift of $z = 1.887$. This prompted a re-analysis of the afterglow spectrum which did not find evidence for $z = 2.43$ but which did find an afterglow redshift of $z = 1.8836$ reported by Fynbo et al. (2009), matching our Lyα host redshift.

For the target selection for the TOUGH Lyα campaign, there was no requirement that the hosts should be detected in the...
deep R-band imaging from the TOUGH imaging campaign (D. Malesani et al. 2012, in preparation) or elsewhere. The statistics for the R-band imaging of the 20 observed systems with a secure redshift in the range 1.8–4.5 (Table 1) are: 14 hosts are detected in the R band (with R-band magnitudes in the range 24.4–27.7) and 6 hosts are not detected down to a typical 3σ limit of R = 27.

All observed bursts have a detected optical afterglow. This was not required, but is a consequence of the requirement of a known redshift before the end of the observing campaign. In all cases, the redshift from the optical afterglow comes from interstellar absorption lines, both low-ionization metal lines (such as O I, Si II, and C II) and high-ionization lines (such as C IV and Si IV), providing a good estimate of the systemic redshift of the host galaxy. This is relevant for the interpretation of the velocity offset of the Lyα emission line with respect to the afterglow redshift (Section 3.2).

2.3. Observations

Spectroscopic observations were completed using the FORS1 spectrograph (cf. Appenzeller et al. 1998) on the VLT over the period 2006 May–2008 May in service mode.

The detector system of FORS1 was changed in 2007 April, i.e., during the observing campaign (cf. Table 1). The old system consisted of a single Tektronix CCD, providing a pixel scale of 0.′′20 pix−1. The new system consists of two blue-optimized E2V CCDs, providing a pixel scale of 0.′′25 pix−1 when read out using the default 2 × 2 binning as we did. The two CCDs are mounted so that the small gap between them is in the spatial direction; the gap has no practical consequences for our program. Compared to the old detector system, the new detector system provides a larger recorded wavelength range, a higher efficiency below 6000 Å, and suffers from fringing above 6500 Å.

All targets were observed using a 1′′ wide long slit. For most of the observing campaign, grisms 600B and 600V were used depending on the redshift of the target (see Table 1). Toward the end of the observing campaign, the lower resolution but higher throughput 300V grism was used instead of 600B for some targets. The achieved wavelength range and spectral resolution for the different grisms and detector systems are listed in Table 2.

The targets, which were generally too faint to be seen in an acquisition image, were put in the slit using one of two methods, both involving a nearby reference star. Either the position angle of the slit was set so that the slit would go through the reference star and the target, or the reference star was put in the slit, after which an offset was applied to the telescope to put the target in the slit. The required position angle or offset was computed based on the R-band detection of the host or, for the hosts that were undetected or only marginally detected in our R-band host imaging, based on the position of the afterglow.

Each target was observed for a total exposure time of 1.4–3.8 hr (see Table 1), split into 4–8 individual exposures. The individual exposures were dithered along the slit. GRB 060714 was observed twice, since the first observation was obtained in poor transparency conditions. In the first observation, the galaxy continuum was not detected, whereas in the second observation it was. The first observation was done using grism 600B, whereas the second observation was done using the more efficient grism 300V and with a slightly larger exposure time. In the analysis, we will only use the data from the second observation.

Table 1: GRB Sample and Log of FORS1 Lyα Host Galaxy Observations

| Name         | z     | Ref. | $R_{\text{host}}$ (mag) | Grism+Filter | CCD  | $r_{\text{exp}}^{\text{total}}$ (hr) | Seeing (arcsec) | $A_V$ (mag) |
|--------------|-------|------|-------------------------|--------------|------|-------------------------------------|----------------|------------|
| GRB 050315   | 1.950 | (1)  | 24.4                    | 600B         | New  | 1.5                                  | 0.84           | 0.159      |
| GRB 050401   | 2.893 | (2);(8)| 26.1                    | 600B         | Old  | 2.1                                  | 0.76           | 0.216      |
| GRB 050730   | 3.9685 | (3) | 27.2                    | 600B+GG435   | Old  | 1.8                                  | 0.77           | 0.168      |
| GRB 050820A  | 2.61469 | (4) | 24.8                    | 600B         | Old  | 2.6                                  | 0.86           | 0.147      |
| GRB 050908   | 3.3467 | (2)  | 27.7                    | 600B         | New  | 2.2                                  | <1.1           | 0.083      |
| GRB 050922C  | 2.1992 | (5)  | >26.3                   | 600B         | Old  | 2.2                                  | <1.3           | 0.332      |
| GRB 060115   | 3.5328 | (2)  | 27.1                    | 600B+GG435   | Old  | 2.1                                  | 1.23           | 0.447      |
| GRB 060526   | 3.2213 | (2);(9) | >27.0                   | 600B         | New  | 2.2                                  | 0.93           | 0.221      |
| GRB 060604   | 2.136 | (6)  | 25.5                    | 600B         | New  | 1.7                                  | <1.1           | 0.142      |
| GRB 060605   | 3.773 | (7)  | >26.5                   | 600B+GG435   | New  | 1.4                                  | <1.5           | 0.164      |
| GRB 060607A  | 3.0749 | (2);(10) | >27.9                   | 300V         | New  | 2.2                                  | <1.4           | 0.096      |
| GRB 060707   | 3.4240 | (2)  | 24.9                    | 600B+GG435   | New  | 1.4                                  | 1.02           | 0.071      |
| GRB 060714   | 2.7108 | (2)  | 26.4                    | 300V         | New  | 1.5                                  | 0.99           | 0.261      |
| GRB 060908   | 1.8836 | (11) | 25.5                    | 600B         | New  | 1.5                                  | <0.9           | 0.099      |
| GRB 061110B  | 3.4344 | (2)  | 26.0                    | 600B         | New  | 2.2                                  | <1.0           | 0.127      |
| GRB 070110   | 2.3521 | (2)  | 25.0                    | 600B         | New  | 1.5                                  | <1.3           | 0.048      |
| GRB 070506   | 2.3090 | (2)  | 26.1                    | 600B         | New  | 1.5                                  | <1.2           | 0.130      |
| GRB 070611   | 2.0394 | (2)  | >27.0                   | 600B         | New  | 3.0                                  | 0.88           | 0.042      |
| GRB 070721B  | 3.6298 | (2)  | 27.5                    | 300V         | New  | 3.8                                  | <0.8           | 0.105      |
| GRB 070802   | 2.4541 | (2);(12)| 25.1                    | 600B         | New  | 1.5                                  | 0.78           | 0.090      |

Notes. $R_{\text{host}}$ is the R-band total magnitude (or 3σ upper limit) of the host galaxy (before correcting for Galactic extinction) from D. Malesani et al. (2012, in preparation). CCD indicates which FORS1 CCD was used (cf. Section 2.3). The seeing was measured using a Gaussian fit to stars that happened to be in the slit in the combined spectrum. If no stars were available, then an upper limit on the seeing was set as the size of the smallest galaxy in the slit. $A_V$ is the Galactic extinction in the V-band (from Schlegel et al. 1998), as obtained from the NASA/IPAC Extragalactic Database. The corresponding reddening is $E(B-V) = A_V / 3.15$ and the Galactic extinction in the R band is $A_R = 2.673 E(B-V)$.

References. (1) Berger et al. 2005; (2) Fynbo et al. 2009; (3) Chen et al. 2005; (4) Prochaska et al. 2007; (5) Piranomonte et al. 2008; (6) Fynbo et al. 2009, but corrected for error (see the text); (7) Ferrero et al. 2009; (8) Watson et al. 2006; (9) Thöne et al. 2010; (10) Fox et al. 2008; (11) Fynbo et al. 2009, but prompted by the Lyα redshift from this work (see the text); (12) Elíasdóttir et al. 2009.
The obtained spectrum will have a better spectral resolution (i.e., smaller FWHM and larger the central wavelength of the available wavelength range. Note that the listed values of FWHM and R only correspond to the spectral resolution of the obtained host galaxy spectrum if the observed spatial profile of the galaxy (i.e., the intrinsic profile convolved with the seeing) was flat over the slit. For a peaked spatial profile, the obtained spectrum will have a better spectral resolution (i.e., smaller FWHM and larger R).

Data reduction was performed mainly using IRAF. The individual frames were bias subtracted and flat fielded. Cosmic-ray hits and readout noise. The error (in ADU) in the given pixel is given by

$$\sigma = \sqrt{\frac{f}{g \cdot n} + \left(\frac{\text{RON}}{\sqrt{n}}\right)^2}$$  \hspace{1cm} (1)

where $f$ are the counts in ADU in the given pixel in the 2D science spectrum before sky subtraction, $g$ is the gain (conversion factor) in $e^-$/ADU for a single image, $n$ is the number of single images that were averaged in the combination, and RON is the readout noise (in ADU) for a single image.

The spectra and sigma spectra were flux calibrated based on sensitivity functions derived from 30 standard star observations and reference data from Hamuy et al. (1992, 1994) and Oke (1990). The spectra and sigma spectra were corrected for atmospheric extinction. The extinction curve for La Silla was used (Tüg 1977; Schwarz & Melnick 1993), since no extinction curve was available for Paranal at the time of the reduction. A comparison between the La Silla curve and the Paranal FORS1 broadband extinction coefficients (Patat 2003) shows a very good agreement (Milvang-Jensen et al. 2008).

The spectra and sigma spectra were finally corrected for Galactic extinction (Cardelli et al. 1989; O'Donnell 1994) using $R_V = 3.1$, with $E(B - V)$ taken from Schlegel et al. (1998). Table 1 lists the used values.

It should be noted that the requested observing conditions were to have a transparency that was better than or equal to thin cirrus. This means that the spectra were not necessarily obtained under photometric conditions, and thus that some of the derived fluxes may be affected by thin cirrus. Any such effect is mitigated by the rescaling of the spectra based on the photometry (Section 3.1).

2.5. Subtraction of Neighboring Objects in the Spectra

The spectra of two of the hosts were substantially contaminated by a neighboring object, which we fitted and subtracted in the 2D spectra. For GRB 070721B ($z = 3.6$), a foreground galaxy ($z = 3.1$) 1″ away was fitted as a Gaussian in the spatial direction and a polynomial in the wavelength direction. For GRB 070802, the wings of a bright star in the slit 18″ away was fitted as a polynomial in both directions. The fits were performed using MPFIT (Markwardt 2009; Moré 1978). Figure 1 shows the spatial profiles before and after the subtraction of the neighboring objects. The subtraction makes the derived continuum flux densities of the hosts be 3.2 times (GRB 070721B) and 2.6 times (GRB 070802) smaller and much more in line with what the photometry predicts (cf. below). The EWs of Lyα (or upper limits thereof) become larger by the same factors. The Lyα fluxes, which are continuum-subtracted (cf. Section 3.1), are practically unaffected.

3. RESULTS

3.1. Lyα Detections and Upper Limits

We first describe the measurement of continuum flux densities in the spectra. We then compare these with the photometry and

| Grism+Filter | Slit Width (arcsec) | Wavelength Range | FWHM (Å) | $R$ | $c/R$ | Dispersion |
|-------------|---------------------|------------------|----------|-----|-------|------------|
| 600B        | 1.3                 | 3300–5680        | 6.5      | 690 | 430   | 1.17       |
| 600V+GG435  | 1.3                 | 4510–7190        | 6.2      | 920 | 330   | 1.15       |
| 300V        | 1.3                 | ...              | 14.1     | 420 | 710   | 3.15       |
| 600R+GG435^b| 1.3                 | 5090–7220        | 6.5      | 950 | 320   | 1.05       |

Notes. The FWHM values were measured from the [O i]5578 skyline in the combined science frames. The resolving power $R = \lambda$/FWHM values were computed at the central wavelength of the available wavelength range. Note that the listed values of FWHM and $R$ only correspond to the spectral resolution of the obtained host galaxy spectrum if the observed spatial profile of the galaxy (i.e., the intrinsic profile convolved with the seeing) was flat over the slit. For a peaked spatial profile, the obtained spectrum will have a better spectral resolution (i.e., smaller FWHM and larger $R$).

^b Grism 600R is not relevant for the main part of this paper, only for the Appendix.

Additionally, three bursts not in the TOUGH sample were observed. These are discussed separately in the Appendix.
derive an average correction for slit loss and extraction aperture loss. We finally describe the measurement of Lyα fluxes and EWs from the spectra.

To measure the continuum flux density in the spectra, apertures on the blue and red side of Lyα were defined as follows. In rest-frame wavelength, the apertures were 175 Å wide and located such that a guard interval of ±6 Å (corresponding to ±1500 km s\(^{-1}\)) centered on Lyα placed at the afterglow redshift was excluded. In the spatial direction, the continuum apertures coincided with the Lyα apertures (see below). The width of 175 Å was the maximum value that was covered by all spectra, and this value also allowed an accurate measurement of the continuum flux density. Uncertainties on all measured fluxes and flux densities were calculated by propagating the individual uncertainties from the 2D sigma spectra (Section 2.4).

In Figure 2(a), we compare the spectroscopy-based blue and red continuum flux densities. Of the 20 hosts in the sample, the red continuum is detected for 14 hosts, while the blue continuum is only detected for 9 hosts, all at \( \geq 3\sigma \) confidence; note that two of the blue non-detections are outside the plotted range in Figure 2(a). One host (GRB 050908, \( z = 3.3 \), the magenta lower limit) is just above the 3σ detection limit in the blue (3.5σ) but just below it in the red (2.2σ), which is plausible given the redshift and the sensitivity curve of the used grism (600B). The seemingly discrepant point at \( z = 2.3 \) (GRB 070506) is due to a time-variable pattern in the bias which we were unable to fully remove or quantify in terms of the error bars. This only has a noteworthy effect in the far blue where the sensitivity is very low and where the flux calibration therefore corresponds to a large amplification. This issue has no effect on the reported Lyα line properties, as we have adopted the continuum flux densities measured in the red window in the spectra as those used to subtract the (small) continuum contribution from the measured flux in the Lyα aperture and to calculate the EWs.

In order to investigate the absolute flux scale of the fluxes and flux densities extracted from the spectra, we use our FORS2 R-band host imaging (D. Malesani et al. 2012, in preparation). The imaging was obtained largely under photometric conditions, and the photometry was calibrated using Landolt (1992). The derived magnitudes are total magnitudes, obtained either from using a large aperture, or from using a smaller aperture combined with an aperture correction. The correction was computed by analyzing the brighter host galaxies, and adopting as uncertainty the observed scatter.

Starting from the total R-band host magnitude \( M_{\text{host}} \), we correct for Galactic extinction (\( A_R \)) to obtain a flux density at the observed-frame wavelength of the R band of

\[
F_{\lambda,R} = f_{\lambda,\text{eff,R}} \times 10^{-0.4(\lambda_{\text{host}}-\lambda_R)}
\]

(2)

where

\[
f_{\lambda,\text{eff,R}} = 2.15 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}
\]

(3)

is the conversion factor for Cousins R from Fukugita et al. (1995); practically the same factor would be obtained from Blanton & Roweis (2007).\(^{12}\) We then extrapolate this flux

\(^{12}\) For Bessel R, Blanton & Roweis (2007) find \( m_{AB} - m_{\text{Vega}} = 0.21 \) mag and \( \lambda_{\text{eff}} = 6442 \text{ Å}, \) which corresponds to a conversion factor (Equation (3)) of \( 2.16 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \).
density from the effective wavelength of the R band (6410 Å; Fukugita et al. 1995) to the observed-frame center wavelength of our red window, (1 + z) 1309 Å, by assuming an \( F_\lambda \propto \lambda^{\beta} \) spectrum, giving

\[
F_\lambda(\text{phot, red}) = F_{\lambda,R} \times \left( \frac{(1 + z) 1309 \, \text{Å}}{6410 \, \text{Å}} \right)^\beta,
\]

where \( \beta \) is the rest-frame UV spectral slope. We will use \( \beta = -1.5 \) as a representative value (e.g., Shapley et al. 2003; Douglas et al. 2010; Finkelstein et al. 2011). Figure 2(c) shows the effect of \( \beta \) as function of redshift, since in addition to the adopted value of \( \beta = -1.5 \) (filled points), the case of \( \beta = -1.0 \) is illustrated (open points).

The spectroscopic flux densities show a good correlation with those from the photometry. This is shown in Figure 2(b), where the two are plotted against each other, and in Figure 2(c) where their ratio is plotted against redshift. Twelve hosts have both a continuum detection (at 3 \( \sigma \)) in the spectra on the red side of Ly\( \alpha \) and a detection in the R-band host imaging (at 2 \( \sigma \)). These hosts are shown as red points in Figure 2(c). Two hosts have a continuum detection in the spectra but not in the imaging; these are GRB 060526 and GRB 060605 and are shown as magenta lower limits in Figure 2(c). Two hosts conversely do not have a continuum detection in the spectra but have a detection in the imaging; these are GRB 050908 and GRB 060115 and are shown as blue upper limits in Figure 2(c).

The ratio of spectroscopic to photometric flux density shown in Figure 2(c) has a median value of 0.50 for the photometry extrapolated using \( \beta = -1.5 \). We attribute the fact that this median ratio is lower than one to slit losses (i.e., flux falling outside the slit) and extraction aperture losses (i.e., flux falling outside the used extraction apertures, as defined below), as well as possibly a small amount of thin cirrus affecting the observations (Section 2.4). We use this result to derive an approximate global scaling factor of 1/0.50 = 2.0 that we apply to all the flux-calibrated science and sigma spectra (Section 2.4). This has the effect of making the derived Ly\( \alpha \) fluxes (or upper limits) and their uncertainties a factor of 2.0 larger, while the EWs are unaffected by this procedure.\(^{13}\) This factor is used throughout the paper, except in Figures 2 and 8.

The Ly\( \alpha \) fluxes were measured from the 2D spectra using a rectangular aperture defined in terms of \( v \), the rest-frame velocity with respect to the afterglow redshift (cf. Table 1), and \( s \), the spatial offset along the slit with respect to the afterglow position. If Ly\( \alpha \) was detected, the aperture was centered on the line and the width of the aperture was adjusted accordingly (as illustrated in the last seven panels of Figures 4–6). If Ly\( \alpha \) was not detected, an aperture of width 900 km s\(^{-1} \) \times 1\( \prime\prime \) was used, centered at 300 km s\(^{-1} \) in \( v \) (a value typical for the detected lines, cf. Section 3.2) and at \( s = 0\prime\prime.0 \). The aperture was defined in terms of integer pixels for simplicity. The centers and widths of the apertures are listed in Table 3. The width in \( v \) can be compared to the spectral resolution expressed as a rest-frame velocity, \( c/R \), which is \( \lesssim 700 \) km s\(^{-1} \), cf. Table 2.

The fluxes within the Ly\( \alpha \) apertures in the 2D spectra were integrated by summing the flux densities (in erg s\(^{-1} \) cm\(^{-2} \) Å\(^{-1} \)) and multiplying by the spectral pixel size (in Å). Uncertainties were calculated by propagating the individual uncertainties from the 2D sigma spectra (Section 2.4). The continuum contribution was subtracted (if positive) and the errors propagated, to give the continuum-subtracted Ly\( \alpha \) fluxes listed in Table 3. If the Ly\( \alpha \) emission was not detected at 3\( \sigma \) (with the \( \sigma \) being the uncertainty on the continuum-subtracted Ly\( \alpha \) flux), we give the 3\( \sigma \) upper limit in the table. Ly\( \alpha \) emission was detected in 7 hosts out of 20: GRB 050315, GRB 060605, GRB 060707, GRB 060908, GRB 070110, GRB 070506, and GRB 070721B. Of these, only one was known to be an Ly\( \alpha \) emitter from the literature (GRB 070110; Fynbo et al. 2009). Ly\( \alpha \) emission was not detected at 3\( \sigma \) for GRB 060714, only at 2.5\( \sigma \), but Ly\( \alpha \) emission was convincingly detected in the afterglow spectrum, cf. Section 3.3 below. Note that the 20 hosts in Figures 4–6 are sorted by Ly\( \alpha \) detection significance, as listed on the panels.

Rest-frame EWs of Ly\( \alpha \) were calculated from the Ly\( \alpha \) fluxes and from the continuum flux densities measured in the spectra in a 175 Å [rest-frame] wide window on the red side of Ly\( \alpha \) centered at 1309 Å (cf. above) and the errors propagated. Throughout the remainder of this paper, it is implicit that the EWs are rest-frame values. The results are summarized in Figure 3 which shows the Ly\( \alpha \) fluxes, luminosities, and EWs (or upper limits in case of non-detections) versus redshift.

The spectra of the 20 systems are illustrated in three figures: (1) smoothed 2D spectra centered on the Ly\( \alpha \) lines are shown in Figure 4 with the used aperture indicated, (2) 1D spectra (not smoothed) are shown in Figure 5, and (3) spatial profiles (also not smoothed) are shown in Figure 6.

3.2. Velocity Offset Between Ly\( \alpha \) Emission and Low-ionization Absorption Lines in the Afterglow Spectra

For the seven hosts with a \( \geq 3\sigma \) detection of Ly\( \alpha \) emission, the centroid in \( v \) within the Ly\( \alpha \) aperture was measured

---

\(^{13}\) In reality, the Ly\( \alpha \) EWs may in some cases be affected by slit loss, namely, if the Ly\( \alpha \) and continuum emission differ in term of spatial distribution. We do not have the required Ly\( \alpha \) narrowband imaging to investigate this issue.
Figure 4. Obtained 2D spectra, centered on where Lyα is expected. The zero point for the rest-frame velocity is defined by the afterglow redshift listed in Table 1. The zero point for the spatial (angular) position corresponds to the afterglow position. The shown sections have size 3800 km s$^{-1} \times 7.5$. The spectra have been smoothed by a Gaussian with FWHM = 3 px. The intensity cuts are the same for all the panels, in units of the noise in the given spectrum, allowing a visual comparison of the significance of the features in the different panels. The green rectangle marks the aperture within which the Lyα flux and its uncertainty are measured; the aperture centers and widths are listed in Table 3. It is stated in the panels how many sigma the Lyα are detected by; the panels are sorted by this. The red horizontal lines indicate where the continuum (if detected at $\geq 3\sigma$) is located, as defined by the spatial centroid in the aperture in which the continuum is measured, cf. Figure 6.

(A color version of this figure is available in the online journal.)

(see Table 3). Since the afterglow redshift defines the zero point of $v$, this velocity measurement is the velocity offset between the Lyα emission centroid and low-ionization interstellar absorption in the GRB afterglow spectrum. A histogram of this offset for the seven hosts is given in Figure 7. The range is 200–700 km s$^{-1}$, consistent with the few values for GRB hosts reported in the literature (cf. Table 5). The histogram resembles the distribution of velocity offsets between Lyα emission and low-ionization interstellar absorption in LBGs (Adelberger et al. 2003; Shapley et al. 2003; see also Pettini et al. 2000). The distribution is also in agreement with the velocity offsets for two Lyα-selected galaxies reported by McLinden et al. (2011) using the [O iii] emission line to define the systemic velocity. It should be noted that the assumption that the afterglow redshift provides the systemic velocity is only valid on average (over a sample of hosts). For individual hosts, the GRB sightline may probe a region of the host that has a non-zero velocity due to the internal kinematics of the galaxy (e.g., rotation). This cannot be a large effect, since otherwise the measured velocity offsets of Lyα (Figure 7) would not all have the same sign.

It should be noted that what we measure is simply the centroid of the Lyα emission line in our GRB host spectra, which may not be identical to the peak of the line if the line is asymmetrical. Our spectra (Figure 5) do not have sufficient spectral resolution or signal-to-noise ratio to investigate this issue.

The origin of the offset is most likely a combination of radiative transfer of the resonantly scattered Lyα photons and a star-formation-driven outflow from the host galaxy (for a full discussion of these effects we refer to Fynbo et al. 2010, their Section 4.3). It should be emphasized that the velocities presented in Table 3 and Figure 7 simply represent the centroid of the Lyα line in the spectrum (with respect to the afterglow redshift); they do not directly translate into outflow velocities. In the outflow scenario, several factors affect the observed redward shift of the Lyα velocity centroid with respect to the systemic velocity. High column densities and (to a lesser extent) low temperatures push the Lyα peak further from the systemic velocity (Harrington 1973). The velocity shift also increases with increasing outflow velocities, up to $\sim 10^3$ km s$^{-1}$, where the peak starts to drift back toward the systemic velocity (e.g., Verhamme et al. 2006). On the other hand, if dust is present, preferentially the wings of the line are removed, effectively reducing the shift (Laursen et al. 2009). The more homogeneous the medium is the stronger this effect is, since clumpiness of the gas and dust facilitates the escape of Lyα photons (Neufeld 1991; Hansen & Oh 2006).

3.3. Lyα Emission Comparison: Host and Afterglow Spectra

For three of the hosts in the sample, Lyα emission was detected directly in the afterglow spectra: GRB 060714 (Jakobsson et al. 2006a), GRB 070110 (Fynbo et al. 2009), and also marginally in GRB 070721B (Fynbo et al. 2009). Figure 8 compares the spectra. For GRB 070110 and GRB 070721B, the Lyα flux measured from the afterglow and host spectroscopy is consistent within the errors (at 2σ). However, for GRB 060714, there is a significant difference, with the Lyα flux from the afterglow spectrum being almost a factor of four larger than in the host spectrum reported here. In the afterglow spectrum,
the Lyα emission appears to be very extended both spatially and in velocity space. In addition, the position angles of the two observations are nearly perpendicular (0° east of north for the afterglow spectrum and 116° for the host galaxy spectrum). Hence, we suspect the cause of the difference is a higher slit loss in the host galaxy spectrum. It is possible that additional hosts among the 12 hosts where we do not detect Lyα emission at \( \geq 3\sigma \) actually would have been detected as Lyα emitters had we used a slit at a different position angle or a wider slit.

### 4. DISCUSSION AND SUMMARY

In this work, we have carried out a systematic search for Lyα photons from GRB host galaxies selected from the larger well-defined TOUGH sample of such galaxies presented in Hjorth et al. (2012). Unlike previous studies (cf. Fynbo et al. 2003), we find that Lyα emission is not ubiquitous among GRB host galaxies. Of the 20 host galaxies studied here, we detect (at 3\( \sigma \)) Lyα emission from 7 of them (with the Lyα rest-frame EW in the range 9–40 Å), derive 3\( \sigma \) upper limits on the Lyα EW for 7 of them (in the range 8–26 Å), while we obtain no constraints on the Lyα EW for the last 6 hosts (due to neither detecting the continuum nor Lyα emission in the spectra, both at 3\( \sigma \)), cf. Table 3. Out of the 14 hosts with either an Lyα EW or an upper limit on the EW, 8 hosts have Lyα EW less than 20 Å (rest frame), which is the typical limit in narrowband surveys for Lyα emitters. For the seven detections, the measured EWs in the range 9–40 Å are low compared to the distribution of EWs found for narrowband-selected galaxies at similar redshifts (Gronwall et al. 2007; Grove et al. 2009; Nilsson et al. 2009).

The Lyα luminosities for the seven GRB hosts with detected Lyα emission are in the range \((0.6–2.3) \times 10^{42} \text{ erg s}^{-1}\). Such fairly low Lyα luminosities are only probed by a few studies of Lyα-emitting galaxies, e.g., Rauch et al. (2008), Grove et al. (2009), and Cassata et al. (2011). The Lyα luminosity can be translated into a SFR, assuming no dust extinction, as

\[
SFR = \frac{L(\text{Ly}\alpha)}{1.1 \times 10^{42} \text{ erg s}^{-1}} M_\odot \text{ yr}^{-1},
\]

using the relation between SFR and \( L(\text{H}\alpha) \) from Kennicutt (1998) and the case B recombination ratio \( L(\text{Ly}\alpha)/L(\text{H}\alpha) = 8.7 \) (Brocklehurst 1971). The observed range in Lyα luminosity for the seven detections would translate into a range in SFR of \((0.6–2.1) M_\odot \text{ yr}^{-1}\), but the assumption of no dust extinction is likely not always correct, as illustrated by the trends of Lyα luminosity and EW with afterglow spectral index discussed in Section 4.2. If dust is present, then Equation (5) provides a lower limit of the SFR.

### 4.1. Comparison with LBGs

Lyman break selection and GRB selection are complementary methods to identify samples of galaxies at high redshift. In this section and in Figure 9, we carry out a comparison of the LBGs from Shapley et al. (2003) with the GRB host galaxies from this work.
The 20 GRB host galaxies from this work fall into three categories. For six galaxies, we detected neither the continuum nor Lyα emission in the spectra, and these galaxies are omitted from the analysis. For seven galaxies, we detected both the continuum and Lyα emission in the spectra, and for these we use the Lyα EWs reported in Table 3. For another seven galaxies, we detected the continuum but not Lyα emission in the spectra. In Table 3 and the rest of the paper, we have reported the 3σ upper limits on the Lyα EWs. An example is GRB 061110B where the measured [rest-frame] EW is 5.0 ± 3.6 Å, which we replaced by the 3σ upper limit of EW < 10.7 Å. This procedure implicitly assumes that Lyα can only be in emission. However, the LBGs from Shapley et al. (2003) often show significant Lyα absorption (negative EWs), so in order to make a fair comparison with that sample, we use the measured EWs also for the seven GRB host galaxies without detected Lyα emission.14

Figure 9(a) shows apparent $R$-band magnitude15 versus Lyα EW. The 803 LBGs are shown as small black open squares. The seven GRB host galaxies with Lyα emission detected at 3σ are shown as red filled circles, and the seven GRB host galaxies without such detected Lyα emission are shown as blue open circles. The plot shows that the GRB hosts from this work typically are fainter than the LBGs from Shapley et al. (2003). This is also the case for the luminosities, since the redshift distributions of the two samples are fairly similar—LBGs: ⟨z⟩ = 3.0, σ = 0.3 and GRB host galaxies: ⟨z⟩ = 2.8, σ = 0.6 (with σ being the standard deviation). It is tempting to define a faint subset of the LBG sample that is better matched to our sample, but Shapley et al. (2003) conclude that the redshift incompleteness at fainter magnitudes (say fainter than $R \approx 24.5$, cf. Figure 7 in Shapley et al. 2003) is likely such that, preferentially, galaxies without (strong) Lyα emission are missing. This might argue for only comparing our GRB hosts with a bright LBG subsample, but then the luminosity difference would be substantial. We will therefore simply use the full Shapley et al. (2003) for comparison with our GRB host sample.

Figure 9(b) shows histograms of the EWs—gray filled histogram: LBGs; jagged magenta curve: the 14 GRB host galaxies. A Kolmogorov–Smirnov (K-S) test (e.g., Press et al. 1992) gives a 1.7% probability that the two samples are drawn from the same parent distribution. In other words, we detect a difference at 98.3% confidence between the two samples. This result is driven by the lack of GRB host galaxies with substantial Lyα absorption (i.e., with EWs below −5 Å).

Fynbo et al. (2003) also found a significant difference (99.8% confidence) between the EWs of five pre-Swift GRB host galaxies and an approximation of the Shapley et al. (2003) distribution. If we use our updated compilation of the EWs for these five pre-Swift hosts and carry out a K-S test against

\[ \text{Table 3 and the rest of the paper, we have reported the 3σ upper limits on the Lyα EWs. An example is GRB 061110B where the measured [rest-frame] EW is 5.0 ± 3.6 Å, which we replaced by the 3σ upper limit of EW < 10.7 Å. This procedure implicitly assumes that Lyα can only be in emission. However, the LBGs from Shapley et al. (2003) often show significant Lyα absorption (negative EWs), so in order to make a fair comparison with that sample, we use the measured EWs also for the seven GRB host galaxies without detected Lyα emission.14} \]

\[ \text{Figure 9(a) shows apparent $R$-band magnitude15 versus Lyα EW. The 803 LBGs are shown as small black open squares. The seven GRB host galaxies with Lyα emission detected at 3σ are shown as red filled circles, and the seven GRB host galaxies without such detected Lyα emission are shown as blue open circles. The plot shows that the GRB hosts from this work typically are fainter than the LBGs from Shapley et al. (2003). This is also the case for the luminosities, since the redshift distributions of the two samples are fairly similar—LBGs: ⟨z⟩ = 3.0, σ = 0.3 and GRB host galaxies: ⟨z⟩ = 2.8, σ = 0.6 (with σ being the standard deviation). It is tempting to define a faint subset of the LBG sample that is better matched to our sample, but Shapley et al. (2003) conclude that the redshift incompleteness at fainter magnitudes (say fainter than $R \approx 24.5$, cf. Figure 7 in Shapley et al. 2003) is likely such that, preferentially, galaxies without (strong) Lyα emission are missing. This might argue for only comparing our GRB hosts with a bright LBG subsample, but then the luminosity difference would be substantial. We will therefore simply use the full Shapley et al. (2003) for comparison with our GRB host sample.} \]

\[ \text{Figure 9(b) shows histograms of the EWs—gray filled histogram: LBGs; jagged magenta curve: the 14 GRB host galaxies. A Kolmogorov–Smirnov (K-S) test (e.g., Press et al. 1992) gives a 1.7% probability that the two samples are drawn from the same parent distribution. In other words, we detect a difference at 98.3% confidence between the two samples. This result is driven by the lack of GRB host galaxies with substantial Lyα absorption (i.e., with EWs below −5 Å).} \]

\[ \text{Fynbo et al. (2003) also found a significant difference (99.8% confidence) between the EWs of five pre-Swift GRB host galaxies and an approximation of the Shapley et al. (2003) distribution. If we use our updated compilation of the EWs for these five pre-Swift hosts and carry out a K-S test against}

\[ \text{Figure 9(c) shows the cumulative EW distributions—smooth black curve: LBGs; jagged magenta curve: the 14 GRB host galaxies. A Kolmogorov–Smirnov (K-S) test (e.g., Press et al. 1992) gives a 1.7% probability that the two samples are drawn from the same parent distribution. In other words, we detect a difference at 98.3% confidence between the two samples. This result is driven by the lack of GRB host galaxies with substantial Lyα absorption (i.e., with EWs below −5 Å).} \]

\[ \text{Fynbo et al. (2003) also found a significant difference (99.8% confidence) between the EWs of five pre-Swift GRB host galaxies and an approximation of the Shapley et al. (2003) distribution. If we use our updated compilation of the EWs for these five pre-Swift hosts and carry out a K-S test against} \]
Figure 6. Spatial profiles, i.e., the flux densities averaged over a given wavelength range vs. spatial coordinate in the 2D spectrum. Red thick curve: \( \langle F_\lambda \rangle \) calculated over the 175 Å rest-frame wide continuum window on the red side of Ly\(^\alpha\), in units of \( 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1} \). Green curve: \( \langle F_\lambda \rangle \) calculated over the wavelength range of the Ly\(^\alpha\) aperture, in units of \( 10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1} \). No smoothing has been applied. The detection significance of the continuum in the above-mentioned red window is given on the right-hand side of the panel in red, and the detection significance of the Ly\(^\alpha\) emission line is given on the left-hand side of the panel in green. The vertical dotted lines mark the spatial limits of the Ly\(^\alpha\) aperture, cf. Table 3. The plotted range in spatial coordinate corresponds to the range of the 2D spectra shown in Figure 4. The panels are sorted by Ly\(^\alpha\) detection significance. (A color version of this figure is available in the online journal.)

Figure 7. Distribution of velocity offsets between the centroid of the Ly\(^\alpha\) emission in the GRB host spectrum and low-ionization interstellar absorption lines in the GRB afterglow spectrum.

the Shapley et al. (2003) sample, then we get a similar result, namely, a difference that is significant at 99.2% confidence. We compare the pre-Swift sample with the sample from this work in Section 4.2.

4.2. The Relation Between Afterglow Spectral Index and Host Ly\(^\alpha\) Emission, and Comparison with Pre-Swift Studies

Remarkably, substantially larger EWs were found in the previous, pre-Swift studies of Ly\(^\alpha\) emission from GRB hosts despite the fact that these studies targeted a much smaller sample (Fynbo et al. 2003 and references therein). Our updated compilation of the EWs for the five pre-Swift hosts studied by Fynbo et al. (2003) is given in the first five rows of Table 5; the three large values around 70–100 Å are noteworthy. A K-S test comparing the EWs of the pre-Swift sample (\( N = 5 \)) with the sample from this work (\( N = 14 \), cf. Section 4.1) gives an 8% probability that the two samples are drawn from the same parent distribution. This is marginal evidence for a difference. This difference could therefore be a chance effect, but another plausible explanation is different biases in the two samples. The present sample is based on an underlying x-ray-selected sample of 69 bursts (the TOUGH sample, see Section 2.1 and Hjorth et al. 2012) which is nearly unbiased. The sample of 20 bursts followed up for Ly\(^\alpha\) spectroscopy in this work (i.e., those with a known afterglow redshift in the range 1.8–4.5) is biased since an optical afterglow was de facto required, and since some bursts in the TOUGH sample were without a determined redshift at the time of the target selection for the Ly\(^\alpha\) spectroscopy and thus could be in the targeted redshift range of 1.8–4.5 (indeed, seven of these bursts were recently found to be at \( z = 1.8–4.5 \)) from X-shooter host spectroscopy, see Krühler et al. 2012 and below, while 20 of the TOUGH bursts still do not have a determined redshift, cf. Section 2.2). The pre-Swift sample of five bursts (Fynbo et al. 2003 and references therein) is even more biased toward relatively bright optical afterglows due to the larger times to localize the burst and larger localization uncertainties (see also Kann et al. 2010). This is shown in Figure 10(a), where we plot the afterglow R-band magnitude at 12 hr after the burst (see Table 4) versus redshift for the pre-Swift
Table 4

| Name        | EW | $R$           | Ref. | Comment                      |
|-------------|----|---------------|------|------------------------------|
| GRB 971214  | yes| 22.06 ± 0.06  | (1)  | Extrapolated from $R = 19.33$ at 20.7 hr using $\alpha = 1.69$ |
| GRB 000926  | yes| 18.33 ± 0.10  | (2)  |                              |
| GRB 011211  | yes| 20.23 ± 0.04  | (3)  |                              |
| GRB 021004  | yes| 18.60 ± 0.03  | (4)  |                              |
| GRB 030323  | yes| 19.00 ± 0.1   | (5)  |                              |
| GRB 050315  | yes| 20.90 ± 0.20  | (6)  |                              |
| GRB 050401  | UL | 23.00 ± 0.10  | (7)  |                              |
| GRB 050730  | ...| 20.20 ± 0.1   | (8)  |                              |
| GRB 050820A| UL | 18.78 ± 0.14  | (6)  |                              |
| GRB 050908  | ...| 22.38 ± 0.10  | (9)  |                              |
| GRB 050922C| ...| 19.98 ± 0.03  | (6)  |                              |
| GRB 060115  | ...| 21.77 ± 0.12  | (10) |                              |
| GRB 060526  | UL | 19.82 ± 0.05  | (11) |                              |
| GRB 060604  | UL | 21.40 ± 0.30  | (12) |                              |
| GRB 060605  | yes| 20.45 ± 0.1   | (13) |                              |
| GRB 060607A| ...| ...           | ...  | Unusual light curve—unable to interpolate |
| GRB 060707  | yes| 21.30 ± 0.30  | (14) | Interpolation between two data points |
| GRB 060714  | UL | 21.10 ± 0.1   | (15) |                              |
| GRB 060908  | yes| 21.90 ± 0.1   | (16) |                              |
| GRB 061110B| UL | >23.30        | (17) | Limit assuming $\alpha = 0.5$ from the VLT observation at 2.3 hr |
| GRB 070110  | yes| 20.00 ± 0.1   | (18) | Converted from V band         |
| GRB 070506  | yes| >20.14        | (19) | Limit assuming $\alpha = 0.5$ from the VLT observation at 3.6 hr |
| GRB 070611  | ...| 21.50 ± 0.30  | (17) | Extrapolated from $R = 21.0$ at 7.7 hr adopting $\alpha = 1.0 ± 0.5$ |
| GRB 070721B| yes| 22.50 ± 0.30  | (20) | Extrapolated from $R = 23.0 ± 0.1$ at 17.6 hr adopting $\alpha = 1.0 ± 0.5$ |
| GRB 070802  | UL | 23.50 ± 0.1   | (21) |                              |

Notes. The first 5 bursts are from the pre-Swift sample (Fynbo et al. 2003 and references therein), and the remaining 20 bursts are from the Swift-based sample studied in this work. The EW column indicates what type of information is available about the Lyα EW of the host (detection, upper limit, or no constraint); the actual values are given in Tables 3 and 5. $R$ is the afterglow R-band magnitude at 12 hr after the burst. In the cases where we directly read the afterglow magnitude at 12 hr after the burst from a plot in the stated reference, we have assigned a magnitude error of 0.1. The parameter $\alpha$ is the slope of the light curve: $F(t) \propto t^{-\alpha}$.

References. (1) Diercks et al. 1998; (2) Fynbo et al. 2001; (3) Jakobsson et al. 2004; (4) Holland et al. 2003; (5) Vreeswijk et al. 2004; (6) Kann et al. 2010; (7) Watson et al. 2006; (8) Pandey et al. 2006; (9) our measurement using archival data from ESO program 275.D-5022 (PI: Chincarini); (10) our measurement using archival data from ESO program 076.A-0392 (PI: Tagliaferri); (11) Thöne et al. 2010; (12) Tanvir et al. 2006; (13) Ferrero et al. 2009; (14) de Ugarte Postigo et al. 2006; Jakobsson et al. 2006b; (15) Krimm et al. 2007; (16) Covino et al. 2010; (17) Fynbo et al. 2009; (18) Troja et al. 2007; (19) Fynbo et al. 2009 but corrected for typo: correct value is $R = 19.5$ at 3.6 hr; (20) our measurement using data from our own ESO program 079.D-0429 (PI: Vreeswijk); (21) Krühler et al. 2008.

sample (open green stars) and the Swift sample from this work (other symbols). In panel (b), we plot EW(Lyα) (detections, and for our sample also upper limits) versus afterglow magnitude. Comparing the two samples suggests that the larger Lyα EWs for the pre-Swift sample is related to brighter afterglows, which in turn could be related to galaxies having less dust. On the other hand, within the sample from this work, there is no evidence for a correlation between Lyα EW and afterglow magnitude.

To further examine the role of dust, we turn to the afterglow spectral index $\beta_{OX}$, defined by

$$\beta_{OX} = \frac{\log[F_{\nu}(v_{\text{opt}})/F_{\nu}(v_X)]}{\log[v_X/v_{\text{opt}}]},$$

where $F_{\nu}$ is the flux density of the afterglow and where $v_{\text{opt}}$ and $v_X$ are representative center frequencies (pivotal frequencies) of the optical and x-ray bands, respectively. If $F_{\nu}$ were a single power law between $v_{\text{opt}}$ and $v_X$, then it would have the form $F_{\nu} \propto v^{-\beta_{OX}}$. A low value of $\beta_{OX}$ indicates suppression of the optical emission compared to the x-ray flux. For low-redshift events (e.g., for $z \lesssim 4.5$ as considered here) where the optical is not cutoff by intergalactic medium absorption, $\beta_{OX}$ is thus connected to dust extinction along the GRB sightline (e.g., Fynbo et al. 2009). In particular, assuming standard synchrotron theory, $\beta_{OX}$ cannot be intrinsically smaller than 0.5, and therefore bursts with $\beta_{OX} < 0.5$ are referred to as “dark bursts” (Jakobsson et al. 2004a), although moderate extinction can present also in bursts with larger values of $\beta_{OX}$.

We have compiled a list of all known GRB hosts with Lyα emission, both from this work and from the literature, including both pre-Swift and Swift bursts, see Table 5. The table lists both the afterglow $\beta_{OX}$ and the host Lyα emission properties. We have corrected the literature Lyα fluxes for Galactic extinction where needed. The table only contains hosts with an Lyα detection. The Lyα upper limits from this work are in Table 3 (with $\beta_{OX}$ available for all bursts from Fynbo et al. 2009).

In Figure 11, we plot host EW(Lyα) and host $L$(Lyα) versus afterglow $\beta_{OX}$, both for the hosts from this work and for the additional hosts with Lyα detections from the literature. The plots show a lack of hosts with high EW(Lyα) and large $L$(Lyα) at the low end of the $\beta_{OX}$ range. This indicates that dust extinction is important in reducing the strength of the Lyα line. GRB 061222A goes against the trend, with a very low $\beta_{OX}$ (namely, an upper limit of $\beta_{OX} < 0.22$) and detected Lyα emission. This can be explained by the fact that $\beta_{OX}$ only probes the afterglow sightline, whereas the host Lyα emission is a quantity that is global for the galaxy. There are indeed several

16 The upper limit comes from the afterglow only having an R-band upper limit. The afterglow has a Ks-band detection (Cenko & Fox 2006), which gives $\beta_{OX} = 0.10$ (with “O” now signifying $K_{S}$-band rather than optical/R band), which is even more constraining.
Figure 8. Comparison of host spectra (red solid lines) with afterglow spectra (blue dotted-solid lines). The three GRBs shown are those for which Ly$\alpha$ emission was detected in the afterglow spectrum superimposed on the damped Ly$\alpha$ absorption trough. The position angle (P.A.) of the slit is given on the panels; note the large P.A. difference between host and afterglow spectroscopy for GRB 060714. The spectra have been corrected for Galactic extinction. $F_\lambda$ is given in units of $10^{-18}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. In the comparison for GRB 070721B, it should be noted that only the host spectrum has had a neighboring galaxy subtracted (cf. Section 3.1), a procedure that decreases the overall flux level by about 0.1 in the plotted units. The afterglow spectra were taken from Jakobsson et al. (2006a; GRB 060714) and Fynbo et al. (2009; GRB 070110 and GRB 070721B). None of the spectra in this figure have been corrected for slit losses or aperture losses.

(A color version of this figure is available in the online journal.)

cases where a dark GRB exploded in an overall blue galaxy, e.g., GRB 070306 (Jaunsen et al. 2008) and GRB 100621A (Krühler et al. 2011). It is also seen from Figure 11 that the hosts of the pre-Swift GRBs with high EW(Ly$\alpha$) and large $L$(Ly$\alpha$) are preferentially found at the high end of the $b_{OX}$ range. This suggests that the pre-Swift sample (shown as open green stars in Figure 11) discussed by Fynbo et al. (2003) is more biased against dusty sightlines.

Our finding that Ly$\alpha$ emission is not ubiquitous among GRB host galaxies has implications on how well GRBs trace the overall massive star formation activity and on the nature of GRB progenitors. Given that Ly$\alpha$ photons are more easily destroyed by dust than other UV photons due to resonant scattering, it has been argued that GRB hosts have low dust content. This could be due, among other reasons, to low metallicity, in agreement with the prediction of the collapsar model (MacFadyen & Woosley 1999; Yoon & Langer 2005; Woosley & Heger 2006). Our analysis of a larger sample of GRB hosts shows that Ly$\alpha$ emission is less ubiquitous than previously found based on a much smaller sample (Fynbo et al. 2003; Jakobsson et al. 2005), so that the above argument is not valid. Whereas other mechanisms than dust can reduce the strength of the Ly$\alpha$ line (e.g., the geometry of the interstellar medium), the trend visible in Figure 11 suggests that the strength of the Ly$\alpha$ line is related to the presence of dust. We note that the objects in the sample studied in this work all have a redshift measured from the optical afterglow, hence they are biased against very dusty systems. If the connection between the presence of dust and the weakness of the Ly$\alpha$ line holds, then we expect that the hosts of optically obscured (i.e., dark) GRBs should have even less prominent Ly$\alpha$ emission.

The recent work of Krühler et al. (2012) provides additional insight. VLT/X-shooter was used to target several TOUGH hosts that lacked redshifts. For seven of the TOUGH hosts, the found redshift was in the range $z = 1.8–4.5$, and these are thus hosts missed by the target selection for this work (cf. Section 2.2). The redshifts were based on detecting one or more of the following emission lines: [O ii], H$\beta$, [O iii], and H$\alpha$. In no cases was Ly$\alpha$ detected. These seven bursts mostly have...
low $\beta_{\text{OX}}$ values.\footnote{The $\beta_{\text{OX}}$ values are: GRB 050819: $< 0.90$, GRB 050915A: $< 0.44$, GRB 051001: $< 0.56$, GRB 060814: $< 0.08$, GRB 070103: $< 0.48$, GRB 070129: 0.62, and GRB 070419B: 0.25 (Fynbo et al. 2009 and references therein).} While the lack of Ly$\alpha$ emission still has to be quantified in terms of upper limits on the EWs, the Krühler et al. (2012) result supports the picture that weak or absent Ly$\alpha$ emission is at least in part caused by dust.

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Table 5
Known GRB Host Lyα Emitters: Afterglow Spectral Slope and Host Lyα Properties

| Name      | z   | T  | βOX | Ref. | EW(Lyα) | F(Lyα) | L(Lyα) | v(Lyα) | Ref. |
|-----------|-----|----|-----|------|---------|--------|--------|--------|------|
| GRB 071214| 3.42| no | 0.64| (1)  | 13      | (6)    | 6.2 ± 0.7 | (13)    | 0.66 ± 0.07 | ... |
| GRB 000926| 2.04| no | 0.87| (1)  | 71 ± 18 | (7)    | 149 ± 111b | (7)     | 4.51 ± 0.33 | ... |
| GRB 011211| 2.14| no | 0.98| (1)  | 21 ± 10 | (8)    | 33.6 ± 9.6b | (8)     | 1.14 ± 0.33 | ... |
| GRB 021004| 2.33| no | 0.93| (1)  | 68 ± 11.5 | (9)   | 313 ± 64d | (14)    | 13.14 ± 2.67 | 530 |
| GRB 030223| 3.37| no | ... | ...  | 108 ± 38 | (10)   | 12 ± 1 | (15)    | 1.23 ± 0.10 | 151 ± 46 |
| GRB 050315| 1.95| yes| 0.63| (2)  | 9.2 ± 2.8 | (11)   | 23.4 ± 6.8 | (11)    | 0.64 ± 0.19 | 283 ± 62 |
| GRB 060605| 3.77| yes| 1.00| (2)  | 33.7 ± 10.5 | (11) | 17.0 ± 2.7 | (11)    | 2.28 ± 0.36 | 620 ± 26 |
| GRB 060707| 3.42| yes| 0.73| (2)  | 11.2 ± 2.3 | (11)   | 16.5 ± 3.1 | (11)    | 1.75 ± 0.33 | 742 ± 38 |
| GRB 060714| 2.71| yes| 0.77| (2)  | ...   | ...   | ...   | ...   | 17.3b  | (16)  | 1.05  | ... |
| GRB 060908| 1.88| yes| 0.80| (3)  | 40.4 ± 6.7 | (11)   | 77.8 ± 9.5 | (11)    | 1.94 ± 0.24 | 347 ± 31 |
| GRB 060926| 3.21| no | 0.87| (4)  | ...   | ...   | 62.1 ± 4.9b | (17)    | 5.65 ± 0.45 | 311 (17) |
| GRB 061222A| 2.09| no | <0.22| (2)  | 31    | (12)   | 168b  | (18)    | 5.39  | ... |
| GRB 070110| 2.35| yes| 0.77| (2)  | 31.8 ± 4.3 | (11)   | 40.2 ± 4.0 | (11)    | 1.73 ± 0.17 | 358 ± 26 |
| GRB 070506| 2.31| yes| 0.93| (2)  | 32.3 ± 11.8 | (11)   | 13.9 ± 3.5 | (11)    | 0.57 ± 0.14 | 360 ± 62 |
| GRB 070721B| 3.63| no | 0.72| (2)  | 32.5 ± 8.0a | (11)   | 11.2 ± 1.6 | (11)    | 1.37 ± 0.19 | 212 ± 31 |
| GRB 071031| 2.69| no | 0.97| (2)  | ...   | ...   | 23.6 ± 2.7b | (17)    | 1.41 ± 0.16 | 254 (17) |
| GRB 090205| 4.65| no | 0.98| (5)  | ...   | ...   | ...   | ...   | 23.6 ± 4.9b | (19)  | 5.17 ± 1.08 | 180 ± 153 |

Notes. T indicates whether the host is part of the TOUGH sample (Section 2.1; Hjorth et al. 2012) studied in this work. βOX is the afterglow optical-to-x-ray spectral slope (see Equation (6)), where optical means R band (unless otherwise stated) and x-ray means 3 keV. EW(Lyα) is the rest-frame Lyα emission line luminosity, in units of 10^{42} erg s^{-1}. L(Lyα) is the Lyα line luminosity, in units of 10^{42} erg s^{-1}. v(Lyα) is the rest-frame velocity centroid of the Lyα emission line with respect to the afterglow redshift, in km s^{-1}. “Ref.” gives the reference for the preceding column. The bursts up to and including GRB 030323 are pre-Swift, while the remaining bursts are from Swift. All Lyα fluxes and luminosities are corrected for Galactic extinction. Note that GRB 030323 is not included, since even though its spectrum showed an indication of Lyα emission, it was not statistically significant (≤2σ) (Jakobsson et al. 2004b).

a The published Lyα flux or the provided spectrum was not corrected for Galactic extinction, but we have applied the correction.

b The data were also observed, see Table 6. The reason for these three systems not being in the TOUGH sample is as follows: GRB 050603 and GRB 060223A did not have an XRT position distributed within 12 hr (although an XRT observation had been made within 12 hr), and GRB 070810A did not have a Sun distance greater than 55° (its Sun distance was 49°). The TOUGH sample criteria are described in Hjorth et al. (2012) and are summarized in Section 2.1.

The spectra are shown in Figure 12 (2D spectra), Figure 13 (1D spectra), and Figure 14 (spatial profiles). For none of these systems were the continuum or the Lyα emission line detected, see Table 7.

For GRB 050603, the afterglow redshift of z = 2.821 from Berger & Becker (2005) is likely wrong: it was derived based on a reported bright emission line interpreted as Lyα in the afterglow spectrum (0.75 hr exposure with Magellan/IMACS), but in our deep host spectrum (2.2 hr exposure with VLT/FORS1) we do not detect any emission; we derive a 3σ upper limit on the Lyα flux at z = 2.821 of 4.7 × 10^{-19} erg cm^{-2} s^{-1}.

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Facility: VLT:Kueyen (FORS1)

APPENDIX A

OBSERVATIONS OBTAINED OF SYSTEMS NOT IN THE TOUGH SAMPLE

Three systems which were not in the final TOUGH sample were also observed, see Table 6. The reason for these three systems not being in the TOUGH sample are as follows: GRB 050603 and GRB 060223A did not have an XRT position distributed within 12 hr (although an XRT observation had been made within 12 hr), and GRB 070810A did not have a
Table 6
Observed Systems Not in the TOUGH Sample

| Name            | z          | Ref. | $R_{lim}$ (mag) | Grism+Filter | CCD | $T_{Exp}$ (hr) | Seeing (arcsec) | $A_V$ (mag) |
|-----------------|------------|------|----------------|--------------|-----|---------------|----------------|-------------|
| GRB 050603      | N/A*       | (1)  | >26.6          | 600B         | old | 2.2           | <1.1           | 0.092       |
| GRB 060223A     | 4.406      | (2)  | >26.3          | 600R+GG435   | old | 2.1           | 0.7            | 0.389       |
| GRB 070810A     | 2.17       | (3)  | >26.7          | 600B         | new | 1.5           | 0.7            | 0.072       |

Notes. See Table 1 for further information.

* The redshift $z = 2.821$ for GRB 050603 from Berger & Becker (2005) is likely wrong; it was derived based on a reported very bright emission line interpreted as Ly$\alpha$ in the afterglow spectrum, but in our deep host spectrum we do not detect any Ly$\alpha$ emission; we derive a 3$\sigma$ upper limit on the Ly$\alpha$ flux at $z = 2.821$ of $4.7 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ (cf. Table 7).

References. (1) Berger & Becker 2005; (2) Chary et al. 2007; (3) Thöne et al. 2007.

Table 7
Ly$\alpha$ Measurements from the Spectra

| Name            | Ly$\alpha$ Aperture | $F(Ly\alpha)$ | $L(Ly\alpha)$ | $F_\nu$ (cont.) | EW(Ly$\alpha$) | $\epsilon(Ly\alpha)$ |
|-----------------|---------------------|---------------|---------------|-----------------|----------------|--------------------|
| (1)             | $c(u)$ | $c(s)$ | $w(u)$ | $w(s)$ | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| GRB 050603      | 281    | 0.02   | 906    | 1.20   | <9.3           | <0.62           | <9.0             | ...           | ...           | ...           | ...           | ...           | ...           |
| GRB 060223A     | 297    | 0.00   | 862    | 1.20   | <14.5          | <2.80           | <12.6            | ...           | ...           | ...           | ...           | ...           | ...           |
| GRB 070810A     | 264    | -0.05  | 912    | 1.25   | <8.7           | <0.31           | <9.5             | ...           | ...           | ...           | ...           | ...           | ...           |

Note. See Table 3 for further information.

10$^{-18}$ erg s$^{-1}$ cm$^{-2}$ (cf. Table 7). We do not find an emission line at any other redshift.

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