H I column densities of $z > 2$ *Swift* gamma-ray bursts

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ABSTRACT

Context. Before the launch of the *Swift* satellite, the majority of the gamma-ray burst (GRB) afterglows for which Lyα was redshifted into the observable spectrum showed evidence for a damped Lyα absorber. This small sample indicated that GRBs explode either in galaxies, or regions within them, having high neutral hydrogen column densities.
Aims. To increase the spectroscopic sample of GRBs with $z > 2$ and hence establish the N(H I) distribution along GRB lines-of-sight.
Methods. We have obtained six $z > 2$ GRB afterglow spectra and fitted the Lyα absorption line in each case to determine N(H I). This has been complemented with 12 other *Swift* N(H I) values from the literature.
Results. We show that the peak of the GRB N(H I) distribution is qualitatively consistent with a model where GRBs originate in Galactic-like molecular clouds. However, a systematic difference, in particular an excess of low column-density systems compared to the predictions, indicates that selection effects and conditions within the cloud (e.g. strong ionization) influence the observed N(H I) range. We also report the discovery of Lyα emission from the GRB 060714 host, corresponding to a star-formation rate of approximately 0.8 $M_\odot$ yr^{-1}. Finally, we present accurate redshifts of the six bursts: $z = 3.240 \pm 0.001$ (GRB 050319), $z = 2.198 \pm 0.002$ (GRB 050922C), $z = 3.221 \pm 0.001$ (GRB 060526), $z = 3.425 \pm 0.002$ (GRB 060707), $z = 2.711 \pm 0.001$ (GRB 060714) and $z = 3.686 \pm 0.002$ (GRB 060906).

Key words. gamma rays: bursts – galaxies: high-redshift – galaxies: abundances – dust, extinction

1. Introduction

In just 18 months, the *Swift* satellite (Gehrels et al. 2004) has already contributed considerably to the progress of gamma-ray burst (GRB) science. It detects roughly two GRBs/week and transmits their accurate localizations (error radius frequently less than 5″) to the ground within minutes for rapid follow-up observations. The GRB redshift distribution found by *Swift* is very different from that of the pre-*Swift* sample, being skewed to much higher redshifts (Berger et al. 2005; Jakobsson et al. 2006a,b; Daigne et al. 2006; Le & Dermer 2006). Approximately 70% of the *Swift* bursts are found to be located at $z > 2$, while the corresponding fraction was only 20% for pre-*Swift* bursts.

It is thus much more common for the Lyα line in *Swift* bursts to be redshifted redward of the atmospheric cutoff in optical spectra. This provides us with the opportunity to investigate the GRB host neutral hydrogen column density distribution. In particular we can compare it to the damped Lyα absorbers (DLAs) seen in absorption against QSO spectra (see Wolfe et al. 2005 for a recent review), defined as displaying $N(\mathrm{H\,I}) \geq 2 \times 10^{20}$ cm^{-2} ($\log N(\mathrm{H\,I}) \geq 20.3$). Most of the neutral gas in the Universe in the redshift interval $0 < z < 5$ is in DLAs, providing the fuel for star formation at these epochs. Given that long-duration GRBs are known to have massive stellar progenitors (e.g. Hjorth et al. 2003b; Malesani et al. 2004; Fruchter et al. 2006), GRB-DLAs provide valuable information on the sites of active star formation in the high-redshift Universe. In the pre-*Swift* era, only seven GRB N(H I) column density measurements were obtained, with six being classified as DLAs (Vreeswijk et al. 2004 and references therein).

In this Letter we present optical spectroscopy of six GRBs, focusing on the measurement of the N(H I) column density. We also report the detection of Lyα emission from one of the bursts (GRB 060714). We then discuss how the observed N(H I) column density distribution from *Swift* bursts can be understood in terms of the GRB environment.

2. Observations

GRBs 050319, 050922C, 060526, 060707, 060714 and 060906 are all long-duration bursts detected by the *Swift* satellite. Each

Table 1. A log of the follow-up spectroscopic observations for the six bursts presented in the paper. Δt is the time from the onset of the burst.

GRB	Tel/instrument/grism	Exposure time [s]	Δt [days]	Spectral res. [Å]
050319	NOT/ALFOSC/#4	3 × 2400	1.50	7
050922C	NOT/ALFOSC/#4	2400	0.05	5
060526	VLT/FORS1/600V	900 + 1800	0.44	5
060707	VLT/FORS1/300V	3 × 1800	1.44	10
060714	VLT/FORS1/300V	3 × 1800	0.50	8
060906	VLT/FORS1/300V	600	0.05	8

burst was localized by the Burst Alert Telescope, each position refined by the X-Ray Telescope and a subsequent optical afterglow (OA) was detected in every case (Rykoff et al. 2005a,b; Campana et al. 2006; de Ugarte Postigo 2006; Krimm et al. 2006; Cenko et al. 2006b).

Using the Nordic Optical Telescope (NOT), we obtained spectra of the OA of GRBs 050319 and 050922C (Fynbo et al. 2005; Jakobsson et al. 2005b). The data were acquired with the ALFOSC instrument with a 1.″3 wide slit and a grism with a wavelength coverage from 3700−9100 Å. The FORS1 instrument on the Very Large Telescope (VLT) was used to obtain OA spectra of GRBs 060526, 060707, 060714 and 060906 (Thöne et al. in prep.; Jakobsson et al. 2006c,d; Vreeswijk et al. 2006). A 1.″0 wide slit was used and grisms with a wavelength coverage from 4700−7100 Å (GRB 060526) and 3600−9000 Å. The details of our observations are given in Table 1.

3. Results

The spectrum of each OA displays a strong absorption line with usually clear damped wings. Blueward of this line, the flux drops substantially and exhibits the signature of the Lyα forest. Associating the line with Lyα, the rest of each spectrum was searched for additional features (>3σ) at the corresponding approximate redshift. The results are presented in Table 2.

There is additional strong absorption in GRB 050922C, corresponding to Lyα at $z \approx 2.07$. At this redshift we identify four other features (O I 1302/Si II 1304, C II 1334/C II* 1335, Si II 1526 and C IV 1548,1550) with an average redshift of $z = 2.075 \pm 0.003$.

In Fig. 1 we plot the normalized OA spectral region around Lyα for each burst. Overplotted is a fit to the Lyα absorption line yielding values reported in Table 2. Apart from GRB 060526, these values are well above the DLA definition. The redshifts deduced from the metal lines were found to be perfectly consistent with the DLA line fits for GRBs 050922C and 060714. For the other four spectra, we note that slightly lower redshifts were used in order to provide the best fit to both the core and the red damped wing of the Lyα profiles. However, adopting the metal line redshifts would make the N(H I) only slightly smaller and within the reported 1σ uncertainties.

There is clearly a Lyα emission in the centre of the GRB 060714 trough (Fig. 2, see also Fig. 1), with an approximate flux of 1.3×10^{-17} erg s^{-1} cm^{-2}. In our assumed cosmology, $(\Omega_m, \Omega_\Lambda, h) = (0.3, 0.7, 0.7)$, this corresponds to a luminosity of 7.9×10^{41} erg s^{-1}. We can use this result to derive the star-formation rate (SFR), assuming that a Lyα luminosity of 10^{42} erg s^{-1} corresponds to a SFR of 1 $M_\odot$ yr^{-1} (Kennicutt 1998; Cowie & Hu 1998). The Lyα SFR in the GRB 060714 host is thus ∼0.8 $M_\odot$ yr^{-1}, which is within the range of values found for other GRB hosts (e.g. Fynbo et al. 2002, 2003; Jakobsson et al. 2005a). We note that this value has not been corrected for host extinction, and is therefore a strict lower limit to the

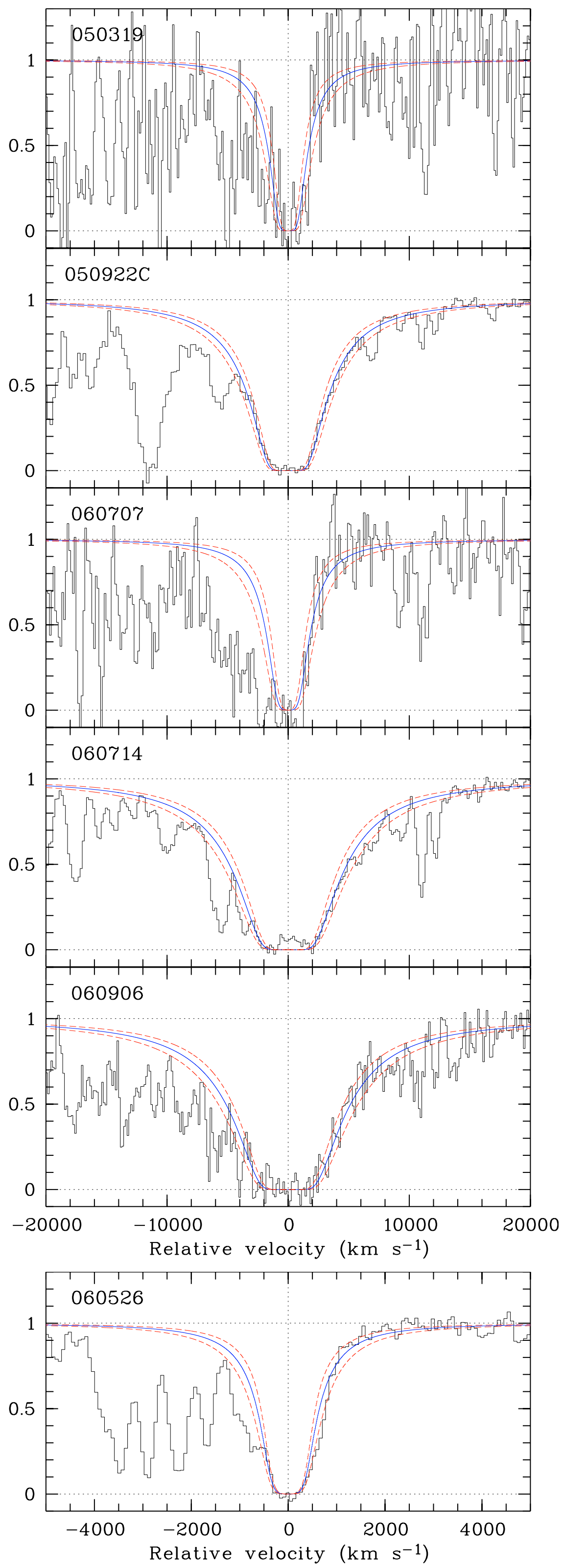

Fig. 1. The normalized OA spectra centred on the Lyα absorption lines at the GRB host galaxy redshifts. A neutral hydrogen column density fit to the damped Lyα line is shown with a solid line in each panel, while the 1σ errors are shown with dashed lines.

Table 2. The redshift, neutral hydrogen column density and absorption lines identified for each afterglow spectrum. The number in square brackets after the redshift indicates the number of lines used to calculate it.

GRB	z	log N(H I)	Absorption features
050319	3.240 ± 0.001 [3]	20.90 ± 0.20	Lyα, Si II 1260, O I 1302, C II 1334/C II* 1335, C IV 1548,1550
050922C	2.198 ± 0.002 [8]	21.55 ± 0.10	Lyα, Si II 1260, Si II* 1264, O I 1302/Si II 1304, C II 1334/C II* 1335, Si IV 1393,1402, Si II 1526, Si II* 1533, C IV 1548,1550, Fe II 1608, Al II 1670
060526	3.221 ± 0.001 [12]	20.00 ± 0.15	Si II 1190,1193, Si III 1206, Lyα, Si II 1260, O I 1302, Si II 1304, C II 1334, C II* 1335, Si II 1526, Si II* 1533, Fe II 1608, Al II 1670
060707	3.425 ± 0.002 [8]	21.00 ± 0.20	Lyβ, C II 1036/C II* 1037, N II 1083, Si III 1206, Lyα, Si II 1260, O I 1302/Si II 1304, C II 1334/C II* 1335, Si II 1526, C IV 1548,1550, Al II 1670
060714	2.711 ± 0.001 [36]	21.80 ± 0.10	Lyγ, C III 977, Si II 989, Lyβ, O VI 1031,1037, C II 1036, C II* 1037, N II 1083, Fe II 1144, Si II 1190,1193, Lyα, S II 1250,1253, Si II 1260, Si II* 1264, O I 1302/Si II 1304, Si II* 1309, C II 1334/C II* 1335, Ni II 1317,1370, Si IV 1393,1402, Si II 1526, Si II* 1533, C IV 1548,1550, Fe II 1608, Al II 1670, Ni II 1709,1741, Si II 1808, Al III 1854,1862, Zn II 2026,2062, Fe II 2260,2344,2374,2382, Fe II** 2328,2349, Fe II*** 2359, Fe II* 2365
060906	3.686 ± 0.002 [5]	21.85 ± 0.10	Lyβ, C II 1036/C II* 1037, Lyα, Si II 1260, O I 1302/Si II 1304, C II 1334/C II* 1335, Si IV 1393,1402, Si II 1526

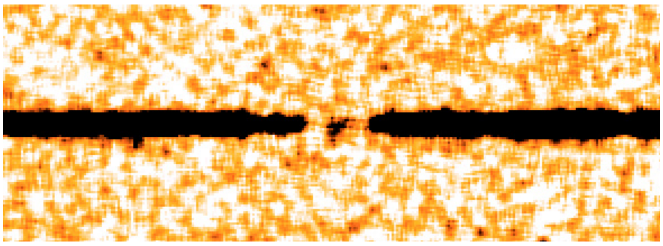

Fig. 2. The two-dimensional GRB 060714 OA spectrum centred on the Lyα absorption line. Lyα in emission is clearly extended and centred in the trough.

actual SFR. Fynbo et al. (2003) find that Lyα emission is much more frequent among pre-*Swift* GRB host galaxies than among the Lyman-break galaxies at similar redshifts and that a low metallicity preference for GRBs could be the explanation (see also Vink & de Koter 2005; Fruchter et al. 2006; Priddey et al. 2006). We are currently undertaking a survey of GRB host galaxies that will constrain the fraction of Lyα emitters among *Swift* GRB hosts.

Although there are many metal lines observed in the GRB spectra, most of them are saturated. However, we have identified a couple of lines, corresponding to elements that are known to deplete negligibly on dust. They fall well outside the Lyα forest and are thus probably unblended. In addition, these transition lines are very weak, implying they are the least saturated ones: Si II 1808 and Zn II 2026 in GRB 060714. In the optically thin limit approximation, their equivalent widths correspond to the following metallicity limits: [Si/H] ≥ -1.35 and [Zn/H] ≥ -1.0.

4. Discussion

In Table 3 we have compiled all available H I column density measurements for $z > 2$ *Swift* bursts (currently displaying a median redshift of 3.4). The bottom panel of Fig. 3 shows a comparison between these H I column densities and those of the pre-*Swift* sample (Vreeswijk et al. 2004). The former currently has a median log N(H I) of 21.6, a bit higher than the latter (21.3). However, the small size of the pre-*Swift* sample does not allow us to reject, with any degree of confidence, the null hypothesis that the two samples are drawn from the same distribution, i.e. a two-sample Kolmogorov-Smirnov (KS) test results in a 90% significance. The fraction of DLAs is also similar in both

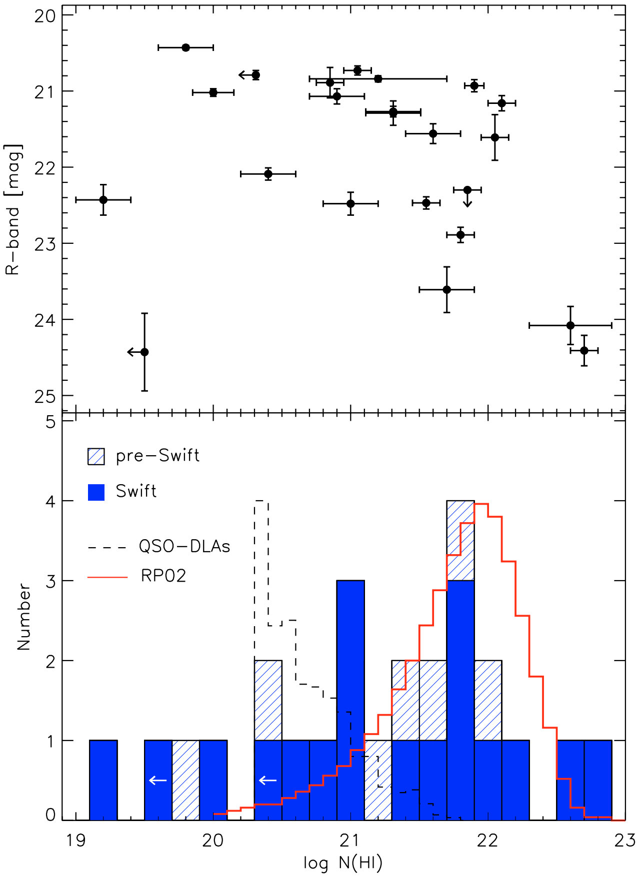

Fig. 3. *Bottom*: histogram of the H I column density measured in GRBs for which the redshift was large enough to detect Lyα. Bursts detected by *Swift* are filled while the pre-*Swift* sample is hashed (Vreeswijk et al. 2004). The current range of known GRB H I systems is $19.2 \leq \log N(\mathrm{H\,I}) \leq 22.7$. For comparison, the QSO-DLAs (Prochaska et al. 2005) are overplotted as the dashed histogram (normalized with respect to the GRB observations). The solid, non-filled histogram shows the GRB N(H I) prediction by RP02. *Top*: the corresponding afterglow *R*-band magnitudes, corrected for Galactic extinction (Schlegel et al. 1998), interpolated to a common epoch of 12 hr (in the source rest-frame) and redshifted to $z = 3$. GRBs 060210 and 060522 are omitted due to the lack of information on their spectral energy distribution; hence corrections could not be made to account for Lyα absorption. Where the uncertainty on the H I column is not reported in the literature, a value of 0.2 has been plotted.

Table 3. A list of all *Swift* GRBs with $z > 2$ known to date (1 October 2006). N(H I) is derived from optical spectroscopy. References are given in order for the redshift and the H I column density (information is not currently available for bursts marked with −). (1) This work; (2) Watson et al. (2006a); (3) Berger et al. (2006b); (4) Berger et al. (2005); (5) Starling et al. (2005); (6) Ledoux et al. (2005); (7) Ledoux et al. (in prep); (8) Kawai et al. (2006); (9) Foley et al. (2005); (10) Quimby et al. (2005); (11) Piranomonte et al. (2006); (12) Prochaska et al. (2006b); (13) J. X. Prochaska (private communication); (14) Fynbo et al. (2006b); (15) Cucchiara et al. (2006a); (16) Cucchiara et al. (2006b); (17) Berger et al. (2006a); (18) Price (2006); (19) Cenko et al. (2006a); (20) Ferrero et al. (2006); (21) Ledoux et al. (2006); (22) Smette et al. (in prep); (23) Rol et al. (2006); (24) D'Elia et al. (2006); (25) Fugazza et al. (in prep); (26) Fynbo et al. (2006a).

GRB	z	$\log N$(H I)	References
050319	3.24	20.9 ± 0.2	(1) (1)
050401	2.90	22.6 ± 0.3	(2) (2)
050505	4.27	22.1 ± 0.1	(3) (3)
050603	2.82	–	(4)
050730	3.97	22.1 ± 0.1	(5) (5)
050820A	2.61	21.1 ± 0.1	(6) (7)
050904	6.30	21.3	(8) (8)
050908	3.34	19.2	(9) (9)
050922C	2.20	21.6 ± 0.1	(1) (1)
051109	2.35	–	(10)
060115	3.53	–	(11)
060124	2.30	<20.3	(12) (13)
060206	4.05	20.9 ± 0.1	(14) (14)
060210	3.91	21.7 ± 0.2	(15) (16)
060223	4.41	–	(17)
060510B	4.94	–	(18)
060522	5.11	20.5 ± 0.5	(19) (19)
060526	3.22	20.0 ± 0.2	(1) (1)
060605	3.71	–	(20)
060607	3.08	<19.5	(21) (22)
060707	3.43	21.0 ± 0.2	(1) (1)
060714	2.71	21.8 ± 0.1	(1) (1)
060906	3.69	21.9 ± 0.1	(1) (1)
060908	2.43	–	(23)
060926	3.21	22.7 ± 0.1	(24) (25)
060927	5.6	–	(26)

samples (~80%), supporting the conclusion that GRB absorption systems show exceptionally high column densities of gas when compared to DLA systems observed in the lines-of-sight to QSOs (Vreeswijk et al. 2004). Indeed, a two-sample KS test indicates there is a less than 10^{-7} probability that GRB-DLAs and QSO-DLAs (Prochaska et al. 2005) are drawn from the same population. This result presumably reflects the fact that GRBs occur in star-forming regions within their hosts, whilst QSOs select more random lines-of-sight through intervening galaxies.

In the bottom panel of Fig. 3 we also compare the observed GRB N(H I) distribution to the expected column density distribution for bursts in Galactic-like molecular clouds (Reichart & Price 2002, hereafter RP02). The model (solid, non-filled histogram) is mass-weighted and corrected for geometrical effects, i.e. the clouds being centrally condensed, and the GRB location within a cloud (not behind it). Qualitatively, especially in terms of the location of the peak of the distribution, the match is relatively good. However, a KS test shows that the model and observed N(H I) distributions are inconsistent with being drawn from the same population at the 3σ level, with a clear overabundance of low-N(H I) detections compared to the model. A possibility is that GRB host galaxies tend to have lower N(H I) clouds than the Milky Way (MW) and/or GRBs are more likely to occur in lower N(H I) clouds. Some evidence for the former exists (Rosolowsky 2005), with the mass distribution of clouds in the LMC (which is more similar to GRB hosts than the MW) having a marginally steeper distribution than the inner disk of the MW.

A few other effects can give rise to the excessive detections of $\log N(\text{H I}) \leq 21.0$. The GRB progenitor and nearby massive stars may (partially) ionize their local environments; there is clearly a trend for GRBs with the smallest N(H I) to exhibit very weak low-ionization lines (e.g. Si II and C II) while displaying strong absorption of e.g. Si IV and C IV (GRB 021004: Møller et al. 2002; GRB 050908: Prochaska et al. 2006a; GRB 060124: Prochaska et al. 2006b). This may support the high-ionization scenario for the low-N(H I) systems, although implicit is the assumption that low- and high-ionization species trace the same phase. An alternative scenario is that some GRBs are formed by massive runaway stars (e.g. Hammer et al. 2006); these would explode in regions of relatively low N(H I). Finally, it has been suggested (e.g. White et al. 1999; Sugitani et al. 2002; Miao et al. 2006) that a significant part of star formation in molecular clouds takes place at their outer edges. The triggering of this star formation also blows the cloud open, resulting in these stars having (largely) unimpeded view outside the cloud and presumably a low N(H I) column.

The drop-off in detections above $\log N(\text{H I}) \geq 22.0$ could be due to selection effects, i.e. the sample might be incomplete due to high extinction. GRBs most likely do not burn through all of the dust in their molecular clouds (e.g. Fig. 4 in RP02), so some high-N(H I) systems are likely dimmed by dust and consequently missed in the sample in Table 3 (see also Savaglio et al. 2003; Vergani et al. 2004). In the top panel of Fig. 3 we have plotted the corresponding afterglow R-band magnitudes (UV restframe) interpolated to a restframe epoch of 12 hr and redshifted to $z = 3$. The majority of the bursts have a well-sampled light curve, allowing us to determine the magnitudes via spline interpolation (see Appendix A in Kann et al. 2006 for a detailed description of the method used). For the most recent bursts with a relatively poor data sampling, we have applied extrapolation and adopted large conservative error bars. There is only a tentative evidence of an anti-correlation between the OA flux and higher N(H I) at the 2σ level as derived from Spearman's rank correlation. It should be noted that intrinsic GRB R-band afterglow light curves show evidence for a bimodal luminosity distribution (Kann et al. 2006; Liang & Zhang 2006; Nardini et al. 2006), that increases the scatter in the top panel of Fig. 3. Excluding the upper limits, there is indeed an indication of bimodality in the data.

The characteristics of the dust-to-gas ratio in the clouds are discernible from the range of more than three orders of magnitude in the H I column densities (lower panel of Fig. 3), suggesting a similar range in the dust column (e.g. Predehl & Schmitt 1995). If dust were entirely responsible for all of the observed variation in the R-band (about five magnitudes; upper panel of Fig. 3), the A_R range would, at most, be of that order, limiting it to a maximum of $A_R \approx 5$ mag. At the Galactic dust-to-gas ratio, the observed A_R (UV restframe) corresponding to the maximum N(H I) value is around 80 mag (e.g. Pei 1992; Diplas & Savage 1994), implying that the A_R/N(H I) ratio in these absorbers must be at most 7% of the Galactic value (see also Hjorth et al. 2003a). If some of the variation in the flux is due to other factors, the ratio drops even further.

Given that it is thought that most of the star formation in the Universe occurs in molecular clouds, it seems logical that long-duration GRBs originate in such regions (Fig. 3). However, there is a systematic difference between the model and observations that presumably can be clarified as a result of a combination of selection effects (dust extinction) and intense ionization in the GRB environment. Combining the N(H I) values derived from optical spectroscopy with the metal column densities from soft X-ray absorption would conceivably shed further light on these issues. A detailed analysis of this is presented in a subsequent paper (Watson et al. 2006b).

Acknowledgements. We thank the referee, Evert Rol, for excellent comments, and Jason X. Prochaska for providing us with the SDSS QSO-DLA data. PJ acknowledges PPARC for support, while NRT thanks PPARC for support through a Senior Research Fellowship. DAK and SK acknowledge support by DFG grant Kl 766/13-2. RSP and RC thank the University of Hertfordshire for a Research Fellowship and Studentship, respectively. The research of JG is supported by the Spanish Ministry of Science and Education through programmes ESP2002-04124-C03-01 and AYA2004-01515. GB acknowledges support from a special grant from the Icelandic Research Council. The Dark Cosmology Centre is funded by the Danish National Research Foundation. Based on observations made with the Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. Based on observations made with ESO Telescopes at the Paranal Observatory under programme ID 077.D-0661(A+C).

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