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The host of GRB 030323 at z = 3.372: A very high column density DLA system with a low metallicity*

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Abstract. We present photometry and spectroscopy of the afterglow of GRB 030323. VLT spectra of the afterglow show damped Lyα (DLA) absorption and lowand high-ionization lines at a redshift z = 3.3718 ± 0.0005. The inferred neutral hydrogen column density, log N(HI) = 21.90 ± 0.07, is larger than any (GRB- or QSO-) DLA H I column density inferred directly from Lyα in absorption. From the afterglow photometry, we derive a conservative upper limit to the host-galaxy extinction: Av < 0.5 mag. The iron abundance is [Fe/H] = −1.47 ± 0.11, while the metallicity of the gas as measured from sulphur is [S/H] = −1.26 ± 0.20. We derive an upper limit on the H2 molecular fraction of 2N(H2)/[2N(H2) + N(H)] ≤ 10−6. In the Lyα trough, a Lyα emission line is detected, which corresponds to a star-formation rate (not corrected for dust extinction) of roughly 1 M⊙ yr−1. All these results are consistent with the host galaxy of GRB 030323 consisting of a low metallicity gas with a low dust content. We find fine-structure lines of silicon, Si II, which have never been clearly detected in QSO-DLAs; this suggests that these lines are produced in the vicinity of the GRB explosion site. Under the assumption that these fine-structure levels are populated by particle collisions, we estimate the H I volume density to be nH I = 10−2–10−4 cm−3. HST/ACS imaging 4 months after the burst shows an extended AB(F606W) = 28.0 ± 0.3 mag object at a distance of 0.14 (1 kpc) from the early afterglow location, which presumably is the host galaxy of GRB 030323.

Key words. gamma rays: bursts – galaxies: distances and redshifts – galaxies: quasars: absorption lines – ISM: dust, extinction

1. Introduction

Damped Lyα (DLA) absorbers, conventionally detected in Quasi-Stellar Object (QSO) spectra, are absorption-line systems that have a column density of N(HI) ≥ 2 × 1020 atoms cm−2, as determined from the damping wings of the Lyα line (e.g. Wolfe et al. 1986; Turnshek et al. 1989).

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DLA systems are believed to contain the bulk of the neutral hydrogen at high redshift and to be the gas reservoir from which the stars at the present epoch are produced (e.g. Wolfe 1987; Lanzetta et al. 1991). Numerous high-resolution spectroscopic studies have extracted detailed information about the metallicity (e.g. Prochaska et al. 2003a), the kinematics (Prochaska & Wolfe 1997; Ledoux et al. 1998), and the dust and H$_2$ contents (Petitjean et al. 2000; Ledoux et al. 2003) of DLA systems as a function of redshift. Despite intensive searches, only a handful of DLA counterparts have been detected so far (see Möller et al. 2002b); linking DLA systems with galaxy types has therefore proven difficult: some advocate large, disk-forming galaxies (e.g. Wolfe et al. 1995; Prochaska & Wolfe 1997), others suggest they are faint, gas-rich dwarfs (Haehnelt et al. 1998).

Gamma-ray burst (GRB) afterglows are, just as QSOs, bright and distant sources. For instance, the spectacular GRB 990123 was detected at the 9th visual magnitude (Akerlof et al. 1999) while it was located at $z = 1.6$ (Kulkarni et al. 1999; Andersen et al. 1999). However, the afterglow brightness in general fades very rapidly in time (roughly flux $\propto$ time$^{-1}$). The current afterglow redshifts range from $z = 0.169$ (Greiner et al. 2003) to $z = 4.5$ (Andersen et al. 2000). Moreover, GRBs are associated with massive-star formation: the discovery of a supernova (SN) spectrum similar to that of SN1998bw (Galama et al. 1998b) superimposed on the GRB 030329 afterglow spectrum (Stanek et al. 2003; Hjorth et al. 2003b) provided strong evidence that at least some of the long-duration ($> 2\text{s}$) GRBs are caused by the core collapse of massive stars (Woosley 1993; MacFadyen & Woosley 1999).

The discovery of a damped Ly$\alpha$ (DLA) absorption line at the burst redshift in the spectra of several GRB afterglows (Jensen et al. 2001; Fynbo et al. 2001; Hjorth et al. 2003a) is consistent with the massive-star progenitor scenario: they indicate a high neutral hydrogen column density origin in the host galaxy, presumably a star-forming region. However, the signal-to-noise ratio at the location of the DLA absorption line in the spectra is fairly low in these cases, much lower than for typical QSO-DLAs. We here present afterglow spectra of the high-redshift GRB 030323, which unambiguously demonstrate a GRB-DLA, with a column density exceeding that of any (QSO- or GRB-) DLA measured so far using Ly$\alpha$ in absorption. These spectra allow us to measure the metallicity of the host environment and obtain an upper limit on the molecular hydrogen ($H_2$) fraction. The detection of Ly$\alpha$ in emission is presented in Sect. 7, and we report on the detection of the probable host galaxy of GRB 030323 in HST/ACS imaging data in Sect. 8. In the final section, we close with a general discussion of all these results.

### Table 1. Log of UT4/FORS2 spectroscopic observations.

| UT date | Grism(filter) | Coverage | $\lambda/\Delta\lambda$ | Exptime | Seeing |
|---------|---------------|----------|------------------------|---------|--------|
| March 03 | 300V          | 330–660  | 440                    | 3 × 10  | 1.1    |
| 25.050  | 300(OG590)    | 600–1100 | 660                    | 3 × 10  | 0.7    |
| 26.213  | 1400V         | 456–586  | 2100                   | 4 × 30  | 0.8    |
| 26.306  | 1200R(GG435)  | 575–731  | 2140                   | 4 × 30  | 0.9    |

This paper is organized as follows: in Sect. 2, we describe the data reduction of both the spectroscopic and imaging observations. In Sect. 3, we present the light curves and infer an upper limit on the rest-frame optical extinction. We measure the equivalent widths of the absorption lines and determine the burst redshift in Sect. 4. An H$\alpha$ column density model is fitted to the damped Ly$\alpha$ line in Sect. 5, and we analyze the spectra in more detail in Sect. 6 to derive the metallicity and an upper limit on the molecular hydrogen ($H_2$) fraction. The detection of Ly$\alpha$ in emission is presented in Sect. 7, and we report on the detection of the probable host galaxy of GRB 030323 in HST/ACS imaging data in Sect. 8. In the final section, we close with a general discussion of all these results.

### 2. Observations and data reduction

The spectroscopic observations of GRB 030323 were performed with the Focal Reducer Low Dispersion Spectrograph 2 (FORS2) at unit 4 (Yepun) of the Very Large Telescope (VLT) at the European Southern Observatory (ESO) at Paranal, Chile. The imaging observations were performed with a variety of telescopes and instruments. Tables 1 and 2 show the spectroscopy and imaging observation logs.

The images and 2-D spectra were bias-subtracted and flat-fielded in the usual manner, mostly within IRAF\(^1\). Following this, the spectra were cosmic-ray cleaned using the LA Cosmic program written by Van Dokkum (2001). Each spectrum was extracted separately, and wavelength-calibrated using an HeNeAr lamp. The error in the wavelength solution was of the order of 0.1 Å for the low resolution 300V and 300I grisms (with $\lambda/\Delta\lambda$ of 440 and 660, respectively), and 0.03 Å for the intermediate resolution grisms 1400V and 1200R (with $\lambda/\Delta\lambda \sim 2100$).

Flux calibration was performed using the standard LTT3864, and the slit losses were determined for each grism by fitting a Gaussian along the spatial direction of the summed 2-D spectra, every 4 pixels across the entire dispersion axis (i.e. summing 4 columns before performing the fit). The resulting Gaussian full width at half maximum (FWHM) was then compared to the slit width to obtain the slit loss (i.e. the fraction of the surface underneath the Gaussian fit that is outside the slit

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\(^1\) IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
The magnitudes have been determined from an overlapping region free of lines, and a standard field was observed. For the near-infrared filters we calibrated on two different nights provided by Henden (2003). This was found to be consistent with our own calibration on two different nights, but during which only one standard field was observed. For the infrared filters we used the calibration provided by the 2MASS archive, as none of the nights on which the near-infrared data were taken were photometric.

The magnitude errors listed in Table 2 are a combination of the Poisson error of the afterglow measurement and the scatter in the reference star magnitudes; they do not include the error in the absolute calibration. For the optical bandpasses, we determined this absolute error by calculating the average difference of two calibrations on two different nights provided by Henden (2003) for several stars; we find the following magnitude errors: 0.02 (B), 0.03 (V), 0.02 (R), and 0.12 (I). For the infrared filters the absolute calibration error is provided by Cohen et al. (2003), which amount to 0.02 mag for J, H, and K. No correction has been attempted for the fact that the observations were taken with filters from different systems. The magnitudes listed in Table 2 have not yet been corrected for the Galactic foreground absorption.

(a) The magnitudes have not been corrected for Galactic extinction, and the errors do not include the uncertainty in the absolute calibration (see text).

(b) Combinations of telescopes and instruments: USNO Flagstaff Station 1.0 m with 2k × 2k Tek CCD, 0.68/pixel; Calar Alto 2.2 m and CAOFS with 1k × 1k STeC CCD, 0.29/pixel; ESO/Danish 1.54 m and DFOSSC with 2k × 4k EEV CCD, binned to 0.78/pixel; Yepun and FORS2 with two MIT CCDs of 4k × 2k, binned to 0.25/pixel; Yepun and NACO with the Aladdin InSb 1k × 1k detector and S54 camera, 0.054/pixel; SARA 0.9 m and Apogee Ap7 CCD camera with 512 × 512 array, 0.7/pixel; UKIRT and UFTI with a 1k × 1k HgCdTe array, 0.091/pixel; Gemini South and acquisition camera with 1k × 1k EEC CCD, binned to 0.23/pixel; HST/ACS and WFC detector with two 2k × 4k STiTE CCDs, 0.05/pixel.

### Table 2. Imaging observations.

| UT date       | Magnitude $^a$ | Filter | Exposure time | Seeing | Tel./Instr.$^b$ |
|---------------|---------------|--------|---------------|--------|----------------|
| Mar. 24.302   | 20.39 ± 0.06  | B      | 12            | 2.4    | USNO 1 m       |
| Mar. 24.310   | 19.68 ± 0.05  | V      | 8             | 2.5    | USNO 1 m       |
| Mar. 24.316   | 18.75 ± 0.03  | R      | 8             | 2.6    | USNO 1 m       |
| Mar. 24.323   | 18.20 ± 0.04  | I      | 8             | 2.4    | USNO 1 m       |
| Mar. 24.392   | 20.64 ± 0.26  | R      | 8.33          | 1.1    | CAHA 2.2 m     |
| Mar. 25.027   | 20.56 ± 0.08  | R      | 54            | 2.0    | Danish         |
| Mar. 25.030   | 21.44 ± 0.03  | V      | 1             | 1.1    | FORS2          |
| Mar. 25.033   | 21.45 ± 0.03  | V      | 1             | 1.0    | FORS2          |
| Mar. 25.091   | 22.29 ± 0.04  | R      | 1             | 0.9    | FORS2          |
| Mar. 25.092   | 21.42 ± 0.02  | V      | 1             | 0.8    | FORS2          |
| Mar. 25.094   | 20.51 ± 0.02  | R      | 1             | 0.8    | FORS2          |
| Mar. 25.095   | 20.02 ± 0.02  | I      | 1             | 0.8    | FORS2          |
| Mar. 25.099   | 20.04 ± 0.10  | I      | 15            | 2.0    | Danish         |
| Mar. 25.129   | 20.57 ± 0.03  | R      | 25            | 2.0    | Danish         |
| Mar. 25.150   | 21.55 ± 0.12  | V      | 15            | 1.8    | Danish         |
| Mar. 25.250   | 20.83 ± 0.13  | R      | 130           | 3.0    | SARA           |
| Mar. 26.023   | 22.17 ± 0.08  | V      | 25            | 1.2    | Danish         |
| Mar. 26.041   | 21.27 ± 0.05  | R      | 25            | 1.0    | Danish         |
| Mar. 26.064   | 20.82 ± 0.08  | I      | 25            | 1.0    | Danish         |
| Mar. 26.107   | 19.86 ± 0.04  | J      | 6             | 0.7    | NACO           |
| Mar. 26.120   | 17.93 ± 0.07  | K      | 2.25          | 0.7    | NACO           |
| Mar. 26.162   | 22.12 ± 0.02  | V      | 1             | 0.6    | FORS2          |
| Mar. 26.164   | 22.09 ± 0.03  | V      | 1             | 0.6    | FORS2          |
| Mar. 26.257   | 22.22 ± 0.03  | V      | 1             | 0.7    | FORS2          |
| Mar. 26.259   | 22.18 ± 0.04  | V      | 1             | 0.8    | FORS2          |
| Mar. 26.267   | 21.50 ± 0.07  | R      | 160           | 2.2    | USNO 1 m       |
| Mar. 26.306   | 18.13 ± 0.18  | K      | 3.35          | 0.5    | UKIRT          |
| Mar. 26.351   | 22.32 ± 0.04  | V      | 3             | 0.8    | FORS2          |
| Mar. 26.351   | 19.38 ± 0.05  | H      | 3.35          | 0.6    | UKIRT          |
| Mar. 26.353   | 21.43 ± 0.02  | R      | 3             | 0.8    | FORS2          |
| Mar. 26.356   | 20.90 ± 0.03  | I      | 3             | 0.8    | FORS2          |
| Mar. 26.379   | 20.09 ± 0.03  | J      | 3.35          | 0.7    | UKIRT          |
| Mar. 27.041   | 22.01 ± 0.14  | R      | 30            | 1.0    | Danish         |
| Mar. 27.156   | 22.94 ± 0.09  | V      | 24            | 0.7    | Gemini S       |
| Mar. 27.176   | 22.15 ± 0.15  | R      | 22.5          | 0.6    | Gemini S       |
| Mar. 27.196   | 21.57 ± 0.09  | I      | 22.5          | 0.6    | Gemini S       |
| Mar. 28.159   | 22.36 ± 0.09  | R      | 36            | 1.2    | Danish         |
| Mar. 28.398   | 19.06 ± 0.20  | K      | 7             | 0.5    | UKIRT          |
| Mar. 28.455   | 20.34 ± 0.08  | H      | 7             | 0.7    | UKIRT          |
| Apr. 3.282    | 24.30 ± 0.13  | R      | 88            | 1.3    | Gemini S       |
| Jul. 5.979    | >25.0 ± (3 r)  | I      | 15            | 0.7    | FORS2          |
| Jul. 5.993    | >25.6 ± (3 r)  | R      | 15            | 0.8    | FORS2          |
| Jul. 20.958   | 28.0 ± 0.3    | V      | 32            |        | HST            |

See http://www.ipac.caltech.edu/2mass/
Figure 1 shows the light curves of GRB 030323 in several wavelengths. The light curves can be fit neither with a single power law, nor with a broken power law. This is clear from performing simple power law fits to the early epochs in the optical bands, and extrapolating these to later times. These fits are shown by the dashed lines in Fig. 1. The $V$ band light curve shows the clearest deviation in between day 2 and 3 after the burst. However, after day 3 the observations are fairly well described again by the extrapolation of the early slope, even the $R$ band measurement around day 10. The $V$ band extrapolation underestimates the late-time HST point by roughly a magnitude, which suggests that the afterglow has become fainter than its host galaxy at this epoch.

Several afterglows have displayed deviations from the common smooth power law decay, such as GRB 970508 (e.g. Galama et al. 1998a), GRB 000301C (e.g. Masetti et al. 2000), GRB 021004 (e.g. Holland et al. 2003), and GRB 030329 (e.g. Price et al. 2003). Garnavich et al. (2000) have suggested that a microlensing event caused the deviations in GRB 000301C. In the context of the fireball model, the deviations in the case of GRB 021004 are interpreted as due to a variable external density (Lazzati et al. 2002b), and for GRB 030329 they are interpreted as due to refreshed shocks from the inner engine (Granot et al. 2003). We note that the cannonball model offers an alternative explanation for these observations (Dado et al. 2002, 2003a,b). For GRB 030323, we only study the global properties of the light curve, and compare them to the light curve decay and spectral slope values as predicted by the fireball model (e.g. Sari et al. 1998, 1999), with the aim of constraining the host-galaxy extinction.

As the late-time afterglow behaviour is not clear, we only use the simple power law fits to the early optical data. The inferred optical temporal decay indices are consistent with one another, with an average decay of $\alpha_{\text{opt}} = -1.56 \pm 0.03$ (using the convention: $F_\nu(t) \propto t^{-\alpha_{\text{opt}}}$). The near-infrared slopes have similar values as the optical ones: $\alpha_J = -1.81 \pm 0.39$, $\alpha_H = -1.42 \pm 0.14$ and $\alpha_K = -1.46 \pm 0.31$. However, these may be affected by the “bump” in between day 2 and 3, if it is achromatic.

At several epochs after the burst, observations in at least two filters were performed around the same epoch. This allows us to construct broad-band spectral energy distributions (SEDs) and fit them to obtain the optical to near-infrared spectral slopes at these epochs. Note that we discard the $B$ and $V$ bands, as these are attenuated by the Ly$\alpha$ line and forest absorption. For day after burst 0.40, 1.18, 2.17, 2.44, 3.27, and 4.50, we obtain: $\beta(0.40) = -1.05 \pm 0.64 (\chi^2_{\text{red}} = 0)$, $\beta(1.18) = -0.83 \pm 0.61 (\chi^2_{\text{red}} = 0)$, $\beta(2.17) = -1.09 \pm 0.07 (\chi^2_{\text{red}} = 4.5)$, $\beta(2.44) = -0.80 \pm 0.05 (\chi^2_{\text{red}} = 1.7)$, $\beta(3.27) = -1.2 \pm 1.0 (\chi^2_{\text{red}} = 0)$, and $\beta(4.50) = -0.82 \pm 0.12 (\chi^2_{\text{red}} = 4.5)$. For the epochs with $\chi^2_{\text{red}} = 0$, observations in only two filters are available. Except for the fit value at day 2.17, these values are consistent with being constant, and the weighted mean and its error is $\beta_{\text{obs}} = -0.89 \pm 0.04$.

We now compare these observed spectral slopes with the ones predicted by the fireball model to obtain an estimate of the host-galaxy extinction. An important assumption that we make in estimating the optical extinction is that the intrinsic afterglow spectrum is a power law, which is a consequence of the fireball theory for GRB afterglows. The fireball theory has been quite successful in explaining the observations (but see Dado et al. 2002). The predicted spectral slope depends on the assumed circumburst density profile being either constant or that of a stellar wind (see Li & Chevalier 2001), whether the...
light curve is in the jet regime or not (see Sari et al. 1999), and whether the cooling break (see Sari et al. 1998) has already passed the optical wavebands (cooling regime) or not. Considering all these possibilities, the predicted spectral slope ranges from $\beta_{\exp} = (\alpha + 1)/2 = -0.28 \pm 0.01$ (wind or constant density medium, post jet-break and non-cooling regime) to $\beta_{\exp} = (2\alpha - 1)/3 = -1.37 \pm 0.01$ (wind or constant density, pre jet-break and cooling regime), with $\alpha = -1.56 \pm 0.03$. We have assumed that these relations between $\alpha$ and $\beta$ are also valid for a power law index of the electron energy distribution, $p < 2$ (but see Dai & Cheng 2001).

All intrinsic spectral slopes shallower than the observed slope of $-0.89 \pm 0.04$ leave some room for host-galaxy extinction (see Ramaprakash et al. 1998), as any host-galaxy extinction results in a steepening of the intrinsic slope. We conservatively take $-0.28 \pm 0.01$ to be the actual slope, to obtain an upper limit on the host-galaxy extinction. Using the extinction-curve fits of Pei (1992) for the Milky Way (MW), and the Large- and Small Magellanic Clouds (LMC and SMC), we iteratively find $A_V$ that fits best with the expected spectral slope of $-0.28$ (held fixed in the fit) for the energy distribution at 2.44 days after the burst. We find $A_V(MW) = 0.50$ mag ($\chi^2_{\text{red}} = 1.5$), $A_V(LMC) = 0.25$ mag ($\chi^2_{\text{red}} = 1.8$) and $A_V(SMC) = 0.16$ mag ($\chi^2_{\text{red}} = 2.3$). These fits are shown in Fig. 2. We note that if we would have assumed that the light-curve break occurred after day 1.4, which is likely, then the expected spectral slope would be $\beta_{\exp} = (2\alpha + 1)/3 = -0.71$, and the extinction values would decrease to $A_V(MW) = 0.09$ mag ($\chi^2_{\text{red}} = 1.3$), $A_V(LMC) = 0.04$ mag ($\chi^2_{\text{red}} = 1.4$) and $A_V(SMC) = 0.02$ mag ($\chi^2_{\text{red}} = 1.4$). When we do not fix the intrinsic slope at a particular value (but still assume that the intrinsic spectrum is a power law), we find spectral slopes ranging from $-0.80$ to $-0.67$, and $A_V$ from 0 to 0.12 mag. Therefore, a very conservative upper limit on the host galaxy extinction is: $A_V < 0.50$ mag.

4. Absorption-line measurements and redshift

The combined 1400$\rm{\nu}$ + 1200$\nu$ spectrum of GRB 030323, corrected for Galactic extinction, is shown in Fig. 3. The most obvious feature is the very broad absorption line around 5300 Å, which can be identified as Ly$\alpha$. Redward of Ly$\alpha$ several metal absorption lines are detected, and to the blue the intervening Ly$\alpha$ forest is present. We also show the 1$\sigma$ Poisson error spectrum.

After normalization of the spectrum with a high-order (25) polynomial, we measured all possible lines with splot in IRAF, summing the equivalent width (EW) of the individual pixels, and determined the line center. In case two lines were clearly blended, we used splot to deblend, using Gaussian line shapes, and forcing a single FWHM for both lines. The EWs and centers of the lines above $5\sigma$ significance are tabulated in Table 3 for both the low- (lr) and high-resolution (hr) spectrum, along with the error in the EW, the line identification and the line redshift.

These line redshifts are determined from the high-resolution spectrum, unless the line is not covered by this spectrum (i.e. above 7310 Å and below 4560 Å – see Table 1). The error in the EW is determined by: $\Delta EW = \Delta \lambda \sqrt{\Sigma \sigma^2}$, where the error spectrum ($\sigma$) is normalized by the high-order polynomial continuum fit of the object spectrum, and is summed over the same pixels ($\lambda$) that were used to measure the line EW. $\Delta \lambda$ is the number of Å per pixel, which is 3.2 and 0.64 Å/pixel for the combined 300$\nu$ + I and 1400$\nu$ + 1200$\nu$ spectra, respectively.

Using all lines that are detected above 5$\sigma$ significance and that could be identified, we find $z(\text{lr}) = 3.3728 \pm 0.0011$ and $z(\text{hr}) = 3.3716 \pm 0.0005$, for the low- (lr) and high-resolution (hr) spectrum, respectively. We adopt the weighted mean of these values as the redshift of GRB 030323: $z = 3.3718 \pm 0.0005$. There is no doubt that this is the redshift of GRB 030323 and not that of a chance foreground galaxy, since otherwise Ly$\alpha$ forest lines redward of the DLA line would have been detected. We find that the strongest lines in the red part of the high-resolution spectrum, CIV$\lambda$1548, 1550, are split into separate components (see the inset of Fig. 3) with a velocity difference of $130 \pm 60 \text{ km s}^{-1}$ (where the error on the wavelength determination of the lines in the blend is 1 Å). Such a velocity spread is consistent with the absorption taking place in separate regions in the host galaxy.

Several lines that are detected above 5$\sigma$ can not be identified, some of which correspond to significant lines in the standard star spectra. Most of these are imprinted on the spectrum by the Earth’s atmosphere. Several lines not belonging to the GRB host galaxy can in principle be identified with Fe$\II\lambda$2344.2, 2600.1 (although an atmospheric line is detected at the latter wavelength) and Mg$\II\lambda$2796.3, 2803.5, all around $z = 1.41$. However, the oscillator strength of Fe$\II\lambda$2382 is three times larger than that of the detected Fe$\II\lambda$2344, but this line is not detected. Moreover, both Fe$\II$ lines are stronger than Mg$\II$, which is usually not observed (e.g. Boissé & Bergeron 1985; Steidel & Sargent 1992). Therefore,
Fig. 3. Combined 1400V + 1200R spectrum of GRB 030323, including the Poisson error spectrum. The inset on the left shows the normalized spectrum with the hydrogen column fit to the damped Ly\(\alpha\) line, including the 1\(\sigma\) errors. This column density is currently the highest for any DLA system measured using Ly\(\alpha\) in absorption (see Fig. 4). Redward of Ly\(\alpha\) we detect numerous metal-absorption lines (see Table 3), whose average redshift (in this high-resolution spectrum) is \(z = 3.3716 \pm 0.0005\). In the inset on the right, we zoom in on the C\(IV\) doublet, which is split into separate components. In the Ly\(\alpha\) trough, Ly\(\alpha\) is detected in emission. Lines that could not be identified, atmospheric absorption lines (indicated with an \(\oplus\)), and lines belonging to the tentative absorber at \(z = 1.41\), are indicated with a dashed line instead of a solid one.
Table 3. Lines detected above 5σ in the low- (hr) and high-resolution (hr) spectra.

| λ(Å) | EW_{hr} (Å) | λ(Å) | EW_{hr} (Å) | ID**c | z |
|------|-------------|------|-------------|-------|---|
| 4484 | 9 (1)a      | 5317 | 5316.9      | Lyβ,1025.7 | 3.3715 |
| 5415.8 | 0.31 (3)   | Nv,1238.8 | 3.3717 |
| 5435.3 | 0.20 (2)   | Nv,1242.8 | 3.3720 |
| 5465.4 | 0.15 (2)   | Siτ,1250.5 | 3.3719 |
| 5476.4 | 0.21 (3)   | Siτ,1253.8 | 3.3716 |
| 5483 | 0.44 (6)   | Siτ,1255.9 | 3.3707 |
| 5511 | 1.07 (5)   | Siτ,1260.4 | 3.3713 |
| 5550 | 0.76 (5)   | Siτ,1260.5 | 3.3709 |
| 5530 | 0.76 (5)   | Siτ,1264.7 | 3.3718 |
| 5591.5 | 0.11 (2)   | C1,1280.1 | 3.3679 |
| 5595.7 | 0.10 (2)   | 6244.4 | 0.11 (2) |
| 5637 | 0.33 (5)   | 5634.7 | 0.16 (2) |
| 5649.2 | 0.16 (1)   | 5652.0 | 0.15 (1) |
| 5692 | 0.75 (6)   | 5692.5 | 0.69 (2) |
| 5706 | 1.08 (6)   | 5702.4 | 0.70 (2) |
| 5706 | 1.08 (6)   | 5709.7 | 0.32 (2) |
| 5727 | 0.26 (5)   | 5723.9 | 0.29 (2) |
| 5838 | 1.71 (7)   | 5833.7 | 0.84 (3) |
| 5838.9 | 0.79 (2)   | C1**,1309.2 | 3.3718 |
| 6095 | 1.19 (6)   | 6092.9 | 1.08 (4) |
| 6135 | 0.98 (6)   | 6132.4 | 1.15 (4) |
| 6280 | 0.51 (3)   | 6278.0 | 0.42 (3) |
| 6269.2 | 0.14 (2)   | 6278.0 | 0.42 (3) |
| 6676 | 0.69 (4)   | 6673.8 | 0.75 (3) |
| 6706 | 0.54 (4)   | 6703.7 | 0.34 (3) |
| 6743.0 | 0.14 (2)   | Mgτ,12796.3 | 1.4114 |
| 6754.2 | 0.13 (2)   | Mgτ,12803.5 | 1.4092 |
| 6760.6 | 0.14 (3)   | 6776.9 | 0.51 (3) |
| 6778.2 | 0.84 (3)   | 6778.2 | 0.84 (3) |
| 6810.1 | 0.53 (3)   | 6810.1 | 0.53 (3) |
| 6875 | 6870.4      | 6867.5 | 6891.9 |
| 7004 | 0.65 (4)   | 7004.0 | 0.65 (4) |
| 7034 | 0.51 (4)   | 7031.7 | 0.48 (3) |
| 7043.6 | 0.17 (3)   | Feτ,16612.2 | 3.3716 |
| 7082.0 | 0.15 (3)   | 7106.0 | 0.20 (3) |
| 7202.7 | 0.17 (3)   | 7307.0 | 1.08 (5) |
| 7303.5 | 0.99 (7)   | Alτ,16707.0 | 3.3713 |
| 7907 | 0.58 (5)   | Siτ,18080.0 | 3.3734 |
| 8112 | 0.45 (5)   | Alτ,18547.0 | 3.3738 |
| 8143 | 0.24 (3)   | Alτ,18612.7 | 3.3724 |
| 8237 | 0.34 (4)   | 8237.4 | 0.34 (4) |
| 8802 | 0.55 (6)   | 8802.5 | 0.55 (6) |
| 8859 | 0.82 (9)   | Znτ,12026.1 | 3.3725 |
| 8970 | 0.73 (11)  | 8970.3 | 0.73 (11) |
| 9019 | 0.77 (5)   | Znτ,12062.6 | 3.3726 |

**a** Lyβ is located in the Lyα forest, which causes it to be blended with forest lines, and the continuum placement is highly uncertain, resulting in a large EW error.

**b** The lines at λ15652.0, 6278.0, 6743.0, and 6754.2 can in principle be identified with Feτ and Mgτ at z = 1.41; however, strong absorption is then expected from Feτ,12382, which is not detected.

**c** The lines for which significant absorption was also detected in the standard star spectrum are marked with a @.

Fig. 4. Histogram of the column densities of DLA systems measured through the damping wings of Lyα discovered in the spectrum of a background QSO (compilation taken from Curran et al. 2002). The shaded histogram shows measurements in GRBs for which the redshift was large enough to detect Lyα. Out of 7 GRBs, 5 show neutral hydrogen column densities above the DLA definition of 2×10^{20} cm^{-2} (log N(HI) = 20.3). The host of GRB 030323 contains a column density larger than in any observed (GRB- or QSO-) DLA system.

we consider the existence of this foreground absorption system to be highly uncertain.

The optical/UV flash of the GRB is expected to alter its immediate environment, possibly leading to a change in absorption-line strengths as a function of time (see Perna & Loeb 1998; Vreeswijk et al. 2001; Perna et al. 2003). Comparing the low- and high-resolution equivalent widths in Table 3 shows that none of the lines detected in both spectra are significantly varying (3σ).

5. HI column density

We have fitted a power law continuum to the high-resolution spectrum over the wavelength range 5870–7000 Å and determined a power law slope (in F_{ν}) of −0.76 ± 0.09 (fitting only the first 1200R spectrum, as the other 1200R spectra suffer from colour-dependent slit losses). This value is in agreement with the red slope of the 300R spectrum and with the slope of the photometry measurements (see Sect. 3). We used an extrapolation of this power law to blue wavelengths in order to normalize the entire spectrum. The resulting average flux decrement in the Lyo forest between Lyδ and Lyα: D_{A} = \frac{F_{\nu} (obsvd)}{F_{\nu} (intrinsic)} (Oke & Korycansky 1982), that we obtain is D_{A} = 0.44 ± 0.04. This decrement, which is due to intervening hydrogen systems, is consistent with that observed in QSO lines of sight at the redshift of GRB 030323 (Cristiani et al. 1993).

A fit to the strong Lyα absorption (using the DIPOS package within Starlink) yields log N(HI) = 21.90 ± 0.07. This fit is shown in the inset of Fig. 3. This is the 7th GRB for which a neutral hydrogen column has been determined from the afterglow spectrum, and GRB 030323 happens to have the highest HI column density measured so far. Figure 4 shows a comparison of the HI column density distribution of QSO-DLAs (taken
from the compilation of Curran et al. 2002) and GRB-DLAs (Jensen et al. 2001; Fynbo et al. 2001; Hjorth et al. 2003a; Jakobsson et al. 2004, in prep., and this paper). For completeness, we also show the two GRBs for which Lyα was detected but which do not qualify as a DLA system: GRB 011211 (Vreeswijk et al. 2004, in prep.) and GRB 021004 (Møller et al. 2002a). It is quite striking that out of 7 GRB afterglows for which Lyα was red-shifted into the observable spectrum, 5 show evidence for a high column density DLA system. This clearly demonstrates that GRBs explode in either galaxies, or regions within galaxies with high neutral hydrogen column densities. The H I gas responsible for these large columns could be related to the site of the GRB explosion, e.g. part of the massive-star forming region in which the GRB occurred, but could also be gas that is not associated with the GRB, further away in the host galaxy. We performed a Kolgomorov-Smirnov (KS) test (e.g. Press et al. 1992) to estimate that the probability that both samples are drawn from the same parent distribution is 0.0006. Moreover, in this comparison with QSO-DLAs, the GRB-DLA H I column densities are in fact lower limits as the GRB itself occurs within the galaxy that is associated with the DLA system; if the GRB sightlines would have been probed with background QSOs, their column densities would have been on average a factor of two larger, which would shift the GRB column densities in Fig. 4 by 0.3 dex upward. However, GRB 011211 would then move into the GRB-DLA sample resulting in a only a slight decrease in the above-mentioned KS probability.

6. Metallicity and H2 content

Although there are many metal lines observed in the spectrum of this GRB, most of them are saturated in the intermediate resolution spectrum. We have identified only 2 sets of lines as potentially unsaturated, based on their small (<0.4 Å) rest-frame equivalent widths (EWs). These are the Si II λ1250, 1253, 1259 triplet and Fe II λ1611. Two of the Si II lines (λ = 1250, 1259) show signs of blending, evidenced by a weak component that broadens the λ1250 line in its blue wing, and a strong interloper redward of the λ1259 line. Si II λ1253 appears as an unresolved single component. We measured the observed EWs of Si II λ1253 and Fe II λ1611 to be 1.25 Å and 0.72 Å (EWrest = 0.29 Å and 0.16 Å), respectively. In the optically thin limit, these correspond to the column densities: log N(S ii) = 15.3 and log N(Fe ii) = 15.7, and abundances [S/H] = –1.8 and [Fe/H] = –1.7. In this conversion from column density to abundance, we assumed the Solar values from Grevesse & Sauval (1998), and no correction for ionization; i.e. we assumed that the column densities of Si II and Fe II are equal to the total column densities of S and Fe, as the singly ionized state of both of these elements should be the dominant one in a region with such a high H I column density. This has been motivated theoretically for QSO-DLAs (Viegas 1995; Vladilo et al. 2001); we here assume that ionization corrections are also negligible in GRB-DLAs.

In a second step, we performed a simultaneous one-component fit to the lines Si II λ1250, 1253, 1259 and Fe II λ1611, taking into account line blending and a range of broadening parameters. Figure 5 shows the resulting fits. We find log N(S ii) = 15.84 ± 0.19 and log N(Fe ii) = 15.93 ± 0.08, together with a (turbulent) broadening parameter b = 35 ± 10 km s\(^{-1}\). Comparing these column densities with those from the optically thin limit approximation shows that the Si II λ1253 and Fe II λ1611 lines are slightly saturated. These measured column densities correspond to the abundances: [S/H] = –1.26 ± 0.20 and [Fe/H] = –1.47 ± 0.11. Therefore, although the N(Fe ii) is large (see also Savaglio et al. 2003), the [Fe/H] is only marginally higher than that of QSO-DLAs at this redshift: the mean [Fe/H] of 26 QSO-DLAs with 3 < z < 3.5 from Prochaska et al. (2003a) is –1.83, with a scatter of 0.35.

Since essentially all DLA systems observed toward QSOs have [S/Fe] greater than zero (see Lopez & Ellison 2003, for a recent compilation and discussion), our measurement of [S/Fe] = 0.21 ± 0.23 in GRB 030323 does not represent a very stringent constraint on a possible α-element overabundance. Moreover, as iron is a known dust-depleted element, there could be a small correction to this ratio due to dust depletion. Interestingly, a tendency toward high values of [Si/Fe] has been found in other GRBs (Savaglio et al. 2003), as expected in cases where massive-star formation has recently deposited metals into the ISM.

We have examined the GRB 030323 spectra for presence of H2 absorption lines, but these are not detected (for a list of lines and their oscillator strengths, see Morton & Dinerstein 1976). The location of possible H2 lines at z\(_{red}\) = 3.3716 is actually observed for the L = 0 to 3 Lyman bands of H2. Of these, only the expected location of the L = 2 band is clear of blending with Lyα forest lines. Because of the low resolution of the spectra, two ranges of possible broadening

\[3\] Observationally, [Si/Si] = 0 in gaseous absorbers when there is neither dust depletion nor ionization effects.
parameters $b_{\text{H}_2}$ (with $b_{\text{H}_2} \leq b_{\text{metals}}$) were considered to perform trials of Voigt-profile fitting of both the $J = 0$ and 1 lines (namely: $\text{H}_2$ L$2$–$0$ R$(0)$, L$2$–$0$ R$(1)$ and L$2$–$0$ P$(1)$). We find the following upper limits: (1) for the range $10 \text{ km s}^{-1} < b_{\text{H}_2} \leq 50 \text{ km s}^{-1}$: $\log N(J = 0) < 14.5$ and $\log N(J = 1) < 15.5$, and (2) for the range $1 \text{ km s}^{-1} \leq b_{\text{H}_2} < 10 \text{ km s}^{-1}$: $\log N(J = 0) < 14$ and $\log N(J = 1) < 18$. Therefore, strictly speaking the derived upper limit on the mean molecular fraction of the system (i.e. GRB environment + host galaxy) is: $f \equiv 2N(\text{H}_2)/(2N(\text{H}_2) + N(\text{H}^+)) < 2 \times 10^{-18}/(2 \times 10^{-18} + 7.9 \times 10^{21}) = 2.5 \times 10^{-4}$ with $N(\text{H}^+) = 7.9 \times 10^{21} \text{ cm}^{-2}$ (i.e. the above case 2). However, under the assumption that $N(J = 1) \leq 10 \times N(J = 0)$, as observed in H$_2$-detected QSO-DLAs (Ledoux et al. 2003) and in the Magellanic Clouds (Tumlinson et al. 2002), i.e. taking $\log N(J = 0) = 14.5$ and $\log N(J = 1) = 15.5$ (which is actually the above case 1), $f$ should be less than or of the order of $10^{-6}$. Although our spectra have a lower spectral resolution than those normally used to study DLA systems along QSO lines of sight, the large H$_1$ column density in GRB 030323 allowed us to obtain an upper limit which is similar to the limits found in QSO-DLAs. We also examined the GRB 030323 spectra for presence of absorption lines from vibrationally excited molecular hydrogen predicted by Draine & Hao (2002), but these are also not detected.

As shown by Ledoux et al. (2003), the lack of H$_2$ molecules in DLA systems is mainly due to the low metallicity in the gas in addition to its particular physical conditions (density, temperature, UV flux). In particular, H$_2$ is usually not detected whenever the metallicity $\text{[X/H]} < -1$. In GRB 030323, the sulphur metallicity, $\text{[S/H]} = -1.26 \pm 0.20$, is low enough to explain the lack of H$_2$. An alternative explanation is that H$_2$ close to the GRB has been dissociated by the strong UV/X-ray emission; however such an emission would also ionize a large fraction of the gas with which H$_2$ molecules are associated (see Draine & Hao 2002).

A dust depletion factor (i.e. the abundance difference between a dust-depleted element such as Fe or Cr and a non-depleted element such as Zn or Si) of 0.2 dex at a metallicity of $-1.26$ (cf. $\text{[Fe/H]} = -1.47 \pm 0.11$) is also consistent with measurements in QSO-DLAs (see Fig. 12 of Ledoux et al. 2003). However, this result is different from the analysis of three GRB host galaxies by Savaglio et al. (2003), who find that the GRB host dust depletion is much larger than it is in QSO-DLAs.

In Fig. 6, we compare the metallicities (from Zn, S or Si) of a sample of QSO-DLAs taken from Prochaska et al. (2003a), with the GRB-DLAS for which a metallicity has been determined: GRB 000926 and GRB 030323 (this paper). For GRB 000926, we have adopted the value $\text{[Zn/H]} = -0.25$ of Castro et al. (2003), which is consistent with the curve-of-growth analysis value – $\text{[Zn/H]} = -0.13$ – of Savaglio et al. (2003). Since the neutral hydrogen column density determination for GRB 000926 is not secure (Fynbo et al. 2001), we assume an error of 0.3 dex. Although only two GRBs have measured metallicities, Fig. 6 suggests that GRB host galaxies are more metal rich than QSO-DLAs. Savaglio et al. (2003) already pointed out large Zn column densities in three GRB host galaxies (for which only GRB 000926 has a measured H$_1$ column density) with respect to QSO-DLAs, while they found the Fe column densities to be similar to those of QSO-DLAs. Hence, $\text{[Zn/Fe]}$, a measure of the amount of dust depletion, is very large in their sample of GRB hosts with respect to QSO-DLAs, suggestive of a high dust content. Although we do not have an estimate of the Zn column density, the quantity $\text{[S/Fe]}$ is a similar measure. For GRB 030323, we find $\text{[S/Fe]} = 0.2$, while Prochaska et al. (2003b) find $\langle \text{[S/Fe]} \rangle = 0.4$ (based on three systems in their sample for which this quantity is not an upper or lower limit).

Using the measured metallicity and H$_1$ column density, we can check the low optical extinction that we inferred from the afterglow photometry. Following Prochaska & Wolfe (2002), we assume that $A_V = R_{V,i} \times N(\text{H}_1)^{\text{host}}/4.9 \times 10^{21}$, where $R_{V,i} = A_V/(E(B-V))$ is the total-to-selective extinction; $R_V(\text{MW}) = 3.1$, $R_V(\text{LMC}) = 3.2$, and $R_V(\text{SMC}) = 2.9$ (see Pei 1992). The dust-to-gas ratio, $\kappa = 10^{X(\text{H}_1)}/(1-10^{E(V,X)})$, corresponds to the dust-to-gas ratio of the dust responsible for the extinction. The value $(4.9 \pm 0.3) \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1}$ corresponds to the Galactic value for $N(\text{H}_1)/E(B-V)$ (Diplas & Savage 1994); for the LMC and SMC, we assume the values $(2.0 \pm 0.5) \times 10^{22} \text{ cm}^{-2} \text{ mag}^{-1}$ (Koornneef 1982) and $(4.4 \pm 0.7) \times 10^{22} \text{ cm}^{-2} \text{ mag}^{-1}$ (Bouchet et al. 1985), respectively. With $\text{[S/H]} = -1.26$ and $\text{[Fe/S]} = -0.21$, we find $\kappa = 0.02$, and $A_V(\text{MW}) = 0.08 \text{ mag}$, $A_V(\text{LMC}) = 0.02 \text{ mag}$, and $A_V(\text{SMC}) = 0.01 \text{ mag}$. These values are all consistent with the upper limits derived from the afterglow photometry (see Sect. 3).

As can be seen in Fig. 3, fine-structure lines of both CII$^*$ and SiII$^*$ are detected. The SiII$^*$ lines have never been clearly detected in QSO-DLAs, which suggests that their origin is associated with GRB 030323, or that they can be found only in regions with very high neutral gas densities. SiII$^*$ $\lambda 1264$ has also been observed along the GRB 010222 sightline (I. Salamanca, private communication). The population of the fine-structure levels is a function of the density of the absorbing medium and the ambient photon-flux intensity (Bahcall & Wolf 1968).
Using the calculations of Silva & Viegas (2002), we can make a rough estimate of the H1 volume density using the two unsaturated Si II lines λ1309, 1533 (the C II and Si II lines λ1264 lines are saturated), for which we measure log N(Si II) = 14.5. Assuming that [Si II]/H = [N(Si II)]/H, i.e. Si is undepicted onto dust grains, we obtain log N(Si II) ≈ 16.2 (as log N(Si II) ≈ 15.84 and the Solar abundance difference between S and Si is 0.34) and log (n e/n H) ≈ 1.7. This ratio corresponds to a volume density of n H1 ~ 100 cm~3 when the free electron density (n e) is assumed to be 10% of that of the H1 density (n H1). And n H1 ~ 10^6 cm~3 when n e ≈ 10~3 n H1 (see Fig. 8 of Silva & Viegas 2002). If these fine-structure lines originate in the same region as the neutral hydrogen, then the Si II medium is mostly neutral and the free electrons will mainly come from ionization of neutral atoms with an ionization potential lower than 13.6 eV, whose solar abundance relative to hydrogen is typically 10~4 (see Silva & Viegas 2002). This would result in an expected ratio n e/n H1. We have assumed that the fine-structure levels are populated by collisions between particles, and not through direct excitation by infra-red photons (although this mechanism is probably not important in the case of Si II), or fluorescence (Silva & Viegas 2002). Under this assumption, we can divide the column density by the volume density to obtain an order of magnitude estimate of the size (diameter) of the absorbing region: ~5 pc (taking n H1 = 10^3 cm~3). As a comparison, Galactic molecular cloud sizes range from roughly 0.5 pc to 50 pc (Solomon et al. 1987). Following Silva & Viegas (2002), we can also estimate the mass of the Si II absorbing cloud, M = m p N(H1)l^2/Si (where m p is the proton mass and l^2/Si is the diameter of the Si II absorbing region) to be M = 2 × 10^3 M⊙. However, the size and mass estimates would be upper limits if the Si II ions are only partly associated with the entire H1 column and/or Si II column. For instance, if half of the Si II absorption would not be related to the Si II absorbing region, the actual volume density would be roughly twice as large, the corresponding cloud size twice as small and the mass a factor of four smaller. If, on the other hand, fluorescence plays a non-negligible role, the size and mass estimates above would be lower limits.

7. Lyα in emission

As can be seen in Fig. 3, in the Lyα trough Lyα in emission is detected. Using splot within IRAF, we measured the center of the line at 3516.9±0.7 Å, corresponding to z = 3.3736±0.0006, with a FWHM of 237 km s~1. The velocity offset with respect to the metal-absorption lines is +151 ± 46 km s~1, i.e. the Lyα emitting region is red-shifted with respect to the material responsible for the absorption lines. We measured a Lyα flux of F = (1.2±0.1)×10~17 erg cm~2 s~1 in the 1400V spectrum. The emission line is also detected, albeit barely, in the lower resolution 300V spectrum with F = (1.0±0.3)×10~17 erg cm~2 s~1. Assuming H_0 = 70 km s~1 Mpc~1, Ω_M = 0.3 and Ω_L = 0.7, z = 3.372 corresponds to a luminosity distance of d_L = 9×10^28 cm. This transforms the observed flux into a Lyα luminosity of L_{Lyα} = (1.2±0.1)×10^22 erg s~1.

Adopting a relation between measured Lyα luminosity and star-formation rate of L/SFR = 10^55 erg s~1 per 1 M⊙ (Kennicutt 1998; Cowie & Hu 1998), the Lyα star-formation rate in the GRB 030323 host galaxy is roughly 1.2 M⊙ yr~1. This value has not been corrected for extinction and hence is a lower limit. The Lyα luminosity is roughly twice as large as the one obtained for the host of GRB 971214 at z = 3.42: (0.66±0.70)×10^42 erg s~1 (Kulkarni et al. 1998) but is at the low end of a sample of 10 Lyα emitters found at z ~ 3.4 by Cowie & Hu (1998) in and around the HDF and Hawaii deep field SSA 22 (with L_{Lyα} ranging from 1.2 to 8×10^42 erg s~1). However, a deeper survey by Fynbo et al. (2003b) has resulted in 42 confirmed Lyα emitting galaxies at z ~ 3, with most luminosities ranging from 0.4–2×10^42 erg s~1.

Lyα emission has also been observed in the troughs of half a dozen of QSO-DLAs (e.g. Møller & Warren 1993; Pettini et al. 1995; Djorgovski et al. 1996; Møller et al. 1998; Fynbo et al. 1999; Møller et al. 2002a). It is believed that this emission originates in the DLA host galaxy itself, and not in QSO photo-ionized regions when z_{abs} ~ QSO. In the GRB 030323 case, it is clear that the emission is produced by photo-ionization by massive stars (not necessarily related to the GRB) in the host galaxy. An origin in the immediate environment of the GRB is not possible, as this emission would be absorbed equally well as the afterglow continuum emission around Lyα by the high neutral hydrogen column density along this sightline.

8. HST imaging of the host galaxy

The field of GRB 030323 was observed for 4 × 480 s with HST/ACS in the F606W filter on July 20, 2003, starting at 23:00 UT. The dithered exposures were drizzled with the multidrizzle routine to produce an output image with a scale of 0′′033 per pixel. Figure 7 shows the 1′ × 1′ field of GRB 030323 on the left panel, and on the right panel the central 5″ × 5″ region. The close-up image has been convolved with a median filter of 3 by 3 pixels, excluding the central pixel of the kernel in the median calculation. The position of the early afterglow has been projected onto the HST image using the 3 min FORS2 V-band image of March 26.35 (see Table 2); 8 objects were used to perform the transformation, with a resulting positional accuracy of 0′′06. This error circle is shown on the zoomed image.

At 4.3 pixels, or 0′′14, an extended object is detected, which can be identified as the probable host of GRB 030323. The Gaussian FWHM of the point spread function of this object (5.0 pixels) is significantly greater than that of stars in the field (2.8 pixels), and SExtractor (Bertin & Arnouts 1996) classifies it as a galaxy, with the star-galaxy classification flag equal to 0.03 (which normally is 0 for a definite galaxy and 1 for a definite star). Adopting H_0 = 70 km s~1 Mpc~1, Ω_M = 0.3 and Ω_L = 0.7, 0′′14 at z = 3.372 corresponds to an angular diameter distance of 1 kpc (see Hogg 1999).

For the host galaxy, we measured a magnitude AB(F606W) = 28.15 ± 0.11 mag using SExtractor’s isophotal flux estimate (Bertin & Arnouts 1996), while we obtain AB(F606W) = 28.1 ± 0.2 mag with aperture photometry using an aperture radius of 5 pixels. With a 10-pixel aperture...
radius, the magnitude increases to \( AB(F606W) = 27.8 \) mag. We adopted a zeropoint of 26.51 mag for the conversion of counts to \( AB \) magnitudes. The error estimates given above only include the Poisson errors. Assuming that the host galaxy has a flat spectrum in \( AB \) (i.e. \( \beta = 0 \) in \( F_\lambda \propto \nu^\beta \)), the \( AB \) magnitude that we finally adopt: \( AB(F606W) = 28.0 \pm 0.3 \) mag, is the same when converting it to the Johnson \( V \) band.

From the UV continuum emission of the host galaxy we can obtain another crude estimate of the star-formation rate, independent of the \( SFR \) inferred from \( Ly\alpha \) in emission (see Sect. 7). The magnitude \( AB(F606W) = 28 \) mag corresponds to a flux \( F_\nu = 2.3 \times 10^{-11} \) erg s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\), which at the luminosity distance of GRB 030323, \( d_L = 9 \times 10^{28} \) cm, results in \( L_\nu = 5.4 \times 10^{27} \) erg s\(^{-1}\) Hz\(^{-1}\). Using the \( SFR-L_\nu(1500-2800 \text{\AA}) \) relation of Kennicutt (1998), this transforms to a \( SFR(\text{UV}) \) of \( 0.7 \, M_\odot \) yr\(^{-1}\). We note that we have neglected \( Ly\alpha \) forest absorption at the blue end of the \( F606W \) filter (4700–7200 \text{Å}, while \( Ly\alpha \) is at 5317 \text{Å}), which would increase the \( SFR \) estimate by roughly 25\% to around \( 0.9 \, M_\odot \) yr\(^{-1}\), which is very similar to the estimate from the \( Ly\alpha \) emission line (1.2 \, M_\odot \) yr\(^{-1}\)).

9. Discussion

Our observations show that GRB 030323 occurred behind a very high H\(I \) column density, in an environment (immediate and host-galaxy combined) having a low molecular hydrogen fraction \( (f \leq 10^{-6}) \), a low metallicity \( ([S/H] = -1.26 \pm 0.20) \) and a low dust content \( (\kappa = 0.02) \). For the DLA host of GRB 020124, Hjorth et al. (2003a) also find evidence for a large H\(I \) column density with a low reddening. The inferred low dust content may be interpreted as a selection bias: GRBs that would occur in a dusty host galaxy would be harder to detect because they would then be fainter. However, in this case one would expect to observe many GRB afterglows with considerable extinction in the optical, for which there is no clear evidence (Galama & Wijers 2001; Lazzati et al. 2002a). In apparent contradiction with this is the detection of several host galaxies in the radio and sub-mm (e.g. Frail et al. 2002; Barnard et al. 2003; Berger et al. 2003), suggesting that at least some GRB hosts are dusty, as expected when most of the star formation in the universe occurs in submm-bright galaxies (see Ramirez-Ruiz et al. 2002). Dust destruction (e.g. Fruchter et al. 2001; Draine & Hao 2002; Perna et al. 2003), which has been proposed to account for the apparent discrepancy between the low optical extinction and large (X-ray) gas column densities (Galama & Wijers 2001), could play a role, but is not required by our data: the reduced metallicity and hence the low dust-to-gas ratio in the host of GRB 030323 is sufficient to explain the combination of a large H\(I \) column density with a low optical extinction (see also Hjorth et al. 2003a).

Ly\(\alpha \) in emission is detected for GRB 030323, and we inferred a star-formation rate of about \( 1 \, M_\odot \) yr\(^{-1}\), which is in good agreement with the \( SFR \) value that we obtained from the UV continuum emission of the host galaxy. Fynbo et al. (2003a) note that Ly\(\alpha \) is commonly observed in all GRB host galaxies at high redshift for which it could be detected. In contrast, only 25\% of the Lyman-break galaxies are Ly\(\alpha \) emitters with an equivalent width \( EW > 20 \) \text{Å} (Shapley et al. 2003). Fynbo et al. (2003a) suggest that this difference is due...
to GRB hosts having a low metallicity and a low dust content, consistent with our observations of GRB 030323 and with those of GRB 020124 (Hjorth et al. 2003a). We note that QSO-DLAs also have a low metallicity and a low dust content, but they rarely show Lyα in emission. However, since most galaxy counterparts of QSO-DLAs are very faint, Lyα in emission is not expected to be detected in most cases with the current detection limits (see Fynbo et al. 1999). The low-dust inference for GRB 020124 (Hjorth et al. 2003a) and GRB 030323 is different from the results of Savaglio et al. (2003), who find evidence for a high dust content in three GRB host galaxies.

From the fine-structure lines Si II* λ1530, 1533, we estimated the H I column density of the gas producing this absorption: \( n_{H_1} = 10^{2}-10^{4} \text{ cm}^{-2} \), under the assumption that these fine-structure levels are populated by collisions, and not through direct excitation by infra-red photons (which is not an important excitation mechanism in the case of Si II*), or fluorescence (see Silva & Vegas 2002). This volume density is higher than inferred for QSO-DLA environments (Silva & Vegas 2002), but typical of Galactic molecular clouds (e.g. Blitz & Williams 1999; Reichart & Price 2002). As these lines has never been clearly detected up to now in QSO-DLAs, the detection of these Si I* lines in the GRB 030323 spectrum suggests an origin in the vicinity of the GRB place of birth (e.g. the star-forming region in which it exploded). Combining the measured H I column density with the order of magnitude estimate of the H I volume density, we obtain a size (diameter) of \( \sim 5 \text{ pc} \) (taking \( n_{H_1} = 10^{3} \text{ cm}^{-3} \)) and a mass of \( \sim 2 \times 10^{3} M_\odot \) for the Si II* absorbing region.

With the volume density so high, one would expect hydrogen molecules to be present, which, surprisingly, we do not detect. We obtain a rather strong upper limit on the mean molecular fraction of the gas in the GRB environment and the host galaxy: \( f \equiv 2N(H_2)/(2N(H_2) + N(H_1)) \leq 10^{-6} \). This could be explained by the low metallicity of the gas (see Ledoux et al. 2003), but it may also be that the molecules in the GRB environment have been dissociated by the strong GRB UV/X-ray emission (e.g. Draine & Hao 2002). In the latter case, however, the UV/X-ray flash would also ionize the neutral gas in the GRB vicinity (see Draine & Hao 2002), which would make the high H I column density detection improbable. Therefore, a large fraction of the H I column density may not be located close to the GRB explosion site, but elsewhere in the host galaxy, while the high volume density Si I* region (and the expected molecular hydrogen), is located in the vicinity of the burst. In this case, the disks of GRB host galaxies need to be much denser than the Galactic disk, as 7 random sight lines through the disk toward the location of the Earth would not result in 5 H I column densities above \( 10^{21} \text{ cm}^{-2} \) (see Fig. 5 ofDickey & Lockman 1990), as is observed for GRB sightlines (see Fig. 4). Finally, the population of the Si I* levels may have been partly caused by fluorescence of photons from the GRB itself, in which case the volume density estimate above is a strict upper limit.

The H I column density that we inferred toward GRB 030323 is higher than that of any (QSO- or GRB-) DLA measured using Lyα in absorption. It is generally assumed that the apparent H I column density limit of N(H I) \( \sim 10^{22} \text{ atoms cm}^{-2} \) for QSO-DLAs is due to an observational bias against the detection of such high-column density systems, as these would obscure the background QSO if they contain some dust (e.g. Ostriker & Heisler 1984; Fall & Pei 1993). However, a radio-selected QSO survey for DLA systems by Ellison et al. (2001) did not uncover a previously unrecognized population of \( N(H_1) > 10^{21} \text{ cm}^{-2} \) DLA systems in front of faint QSOs. An alternative scenario was proposed by Schaye (2001): the lack of high H I column density systems could be due to the conversion of H I to H2 as the neutral gas density increases. This picture is consistent with observations of Galactic molecular clouds (e.g. Blitz & Williams 1999). In GRB 030323, however, we do not find any evidence for the presence of H2 in addition to H I to support this scenario. Future GRBs with possibly even larger H I column densities than that toward GRB 030323 could provide further constraints to the existence of a rapid conversion of H I to H2 at high H I column densities.

We compared the metallicities and H I column densities of the (still very small) sample of GRB-DLAs with QSO-DLAs, and we found both quantities to be higher in GRB-DLAs than in QSO-DLAs. This is not surprising, as GRBs are now known to probe massive-star forming regions (Stanek et al. 2003; Hjorth et al. 2003b) where the gas density and the metallicity are higher than along random QSO sight lines through foreground galaxies. A KS test applied to the column densities shows that the probability that the GRB- and QSO-DLA samples are drawn from the same parent distribution is very low (0.0006). On the other hand, two GRB afterglows have very low column densities. A large sample of high-resolution spectra of GRB afterglows could provide statistical information about the distribution of the gas in high-redshift star-forming regions, in addition to the evolution of the metallicity and dust and H2 contents of GRB host galaxies. Such a sample can be created in the years to come thanks to rapid and accurate GRB localizations from future satellite missions such as Swift\(^5\) and EXIST\(^6\).

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\(^5\) See http://swift.gsfc.nasa.gov/
\(^6\) See http://exist.gsfc.nasa.gov/
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