ECHELLE SPECTROSCOPY OF A GRB AFTERGLOW AT Z = 3.969: A NEW PROBE OF THE INTERSTELLAR AND INTERGALACTIC MEDIA IN THE YOUNG UNIVERSE

HSIAO-WEN CHEN1,5, JASON X. PROCHASKA2, JOSHUA S. BLOOM3, AND IAN B. THOMPSON4
Accepted for Publication in the Astrophysical Journal Letters

ABSTRACT

We present an echelle spectrum of the Swift GRB 050730, obtained four hours after the burst using the MIKE spectrograph on the Magellan Clay Telescope when the afterglow was at R = 17.7. The spectrum reveals a forest of absorption features superimposed on a simple power-law shaped continuum, best described as \( f_r(\lambda) \propto \lambda^{\alpha} \) with \( \alpha = 1.88 \pm 0.01 \) over \( \lambda = 7000 - 9000 \) Å. We identify the GRB host at \( z_{\text{GRB}} = 3.96855 \) based on the hydrogen Lyman absorption series, narrow absorption lines due to heavy ions such as O I, C II, Si II, S II, Ni II, Fe II, C IV, Si IV, and N V, and fine structure transitions such as O I*, O I**, Si II*, C II*, and Fe II*. Together these transitions allow us to study the the properties of the interstellar medium (ISM) in the GRB host. The principal results are as follows. (1) We estimate a neutral hydrogen column density of \( \log N(\text{H I}) = 22.15 \pm 0.05 \) in the host. (2) The associated metal lines exhibit multiple components over a velocity range of \( \sim 80 \) km s\(^{-1}\), with more than 90% of the neutral gas confined in 20 km s\(^{-1}\). (3) Comparisons between different ionic transitions show that the host has little/no dust depletion and has 1/100 solar metallicity. (4) The absorbing gas has much higher density than that of intervening damped Ly \( \alpha \) absorption (DLA) systems. In addition, we report the identification of an intervening DLA system at \( z_{\text{DLA}} = 3.56439 \) with \( \log N(\text{H I}) = 20.3 \pm 0.1 \) and < 5% solar metallicity, a Lyman limit system at \( z_{\text{LLS}} = 3.02209 \) with \( \log N(\text{H I}) = 19.9 \pm 0.1 \), a strong Mg II absorber at \( z_{\text{Mg II}} = 2.25313 \), and a pair of Mg II absorbers at \( z_{\text{Mg II}} = 1.7731 \), 57 km s\(^{-1}\) apart. We demonstrate that rapid echelle spectroscopy of GRB afterglows helps to reveal a wealth of information in the ISM and the intergalactic medium along the sightline which, when followed up with late-time, deep imaging, will allow us to uncover a sample of distant galaxies with known ISM properties to constrain galaxy formation models.

Subject headings: gamma rays: bursts—ISM: abundances—ISM: kinematics—intergalactic medium

1. INTRODUCTION

Various surveys designed to detect emission at optical, near-infrared, and sub-mm wavelengths have yielded large samples of galaxies at redshift \( z > 2 \) (e.g. Steidel et al. 1999; Blain et al. 2002), but whether these galaxies are representative of the galaxy population at high redshifts and how they are related to the local population is not clear. Damped Ly \( \alpha \) absorption (DLA) systems probe high-redshift gaseous clouds of neutral hydrogen column density \( N(\text{H I}) \) consistent with what is observed in the disks of nearby luminous galaxies (e.g. Wolfe et al. 2004). They are selected uniformly with \( N(\text{H I}) \geq 2 \times 10^{20} \) cm\(^{-2}\) and represent a unique sample of distant galaxies with known interstellar medium (ISM) properties from absorption-line studies (e.g. Pettini et al. 1999; Prochaska et al. 2003). Indentifying the stellar counterpart of the DLAs has, however, been challenging because of the glare of background quasars (Colbert & Malkan 2002; Le Brun et al. 1997; Rao et al. 2003; Chen & Lanzetta 2003).

Long-duration gamma-ray bursts (GRBs) are believed to originate in the death of massive stars (e.g. Woosley 1993; Paczyński 1998; Bloom et al. 2002; Stanek et al. 2003). Some bursts are followed by optical afterglows (e.g. Akerlof et al. 1999) that can be used to acquire the absolute brightness of any known quasar by orders of magnitude and serve as bright background sources for probing intervening gas along the line of sight. Because of their transient nature, however, optical afterglows do not interfere with follow-up studies of absorbing galaxies close to the sightlines. Early-time, high-resolution spectroscopy of GRB afterglows together with deep, late-time imaging of galaxies along the sightlines suggests a novel means to uncover a sample of high-redshift galaxies based on their absorption properties. In the context of hierarchical structure formation, GRB progenitors can form before massive black holes, and therefore may be used to probe early universe, well into the age of reionization.

Prompt localization of GRB afterglows is critical in order to take advantage of their brief but extreme brightness for acquiring echelle spectroscopy. It has been difficult in the past to carry out rapid spectroscopy for the optical transient (OT) because of time-consuming processes to localize the bursts. Despite an extensive effort, only a small number of GRBs have been spectroscopically identified at \( z > 2 \) with low-to-moderate resolution spectra available and two with echelle data available (Fiore et al. 2005). Together these data show that all GRB host galaxies have abundant neutral gas, and some have the largest \( N(\text{H I}) \) among all DLA systems (Jensen et al. 2001; Møller et al. 2003).
The current generation gamma-ray satellite, Swift, is designed to provide nearly-instant localization of new GRBs. Over the past two years, our group has been pursuing well-localized GRB afterglows with moderate-to-high resolution spectroscopy (e.g. Prochaska et al. 2004; Bloom et al. 2005). The primary goal of our project is to collect a statistically significant sample of galaxies along the sightlines. While intervening DLA systems arise preferentially in the outskirts of distant galaxies (because of a gas cross-section selection effect), the GRB host sample offers a unique opportunity to study ISM physics more immediate to vigorous star-forming regions in high-redshift galaxies (that have relatively small cross-section).

Here we present the first echelle spectrum of a Swift GRB, obtained four hours after the burst. The spectrum, which spans a wavelength range from 3300 Å through 9400 Å, exhibits abundant absorption features superimposed on a simple power-law shaped continuum. We identify the GRB at $z_{\text{GRB}} = 3.969$ based on a strong damped absorption trough centered at 6040 Å and a suite of associated metal absorption features. In addition, we identify an intervening DLA system at $z_{\text{DLA}} = 3.564$ and a number of strong MgII absorbers along the sightline. We demonstrate that rapid echelle spectroscopy is plausible for well-localized afterglows and that the observations provide new insight into the nature of GRB host environments, as well as the physical properties of the intergalactic medium (IGM) along the sightlines.

2. OBSERVATIONS AND DATA REDUCTION

We observed the OT of GRB050730 that was first reported by Hollan et al. (2005) and later confirmed by Sota et al. (2005) at RA(J2000) = 14$^h$08$^m$17$^s$.14 and Dec(J2000) = $-03^\circ$46$'$17$''$.8, using the MIKE echelle spectrograph (Bernstein et al. 2003) on the 6.5 m Magellan Clay telescope at Las Campanas Observatory. The spectrograph contains a blue camera and a red camera, allowing a full wavelength coverage from near-ultraviolet 3300 Å through near-infrared 9400 Å. The observations were carried out in a sequence of three exposures of duration 1800 s each, starting at UT 00:00 on 2005 July 31 (four hours after the initial burst) when the OT had $R \approx 17.7$ (Holman et al. 2005). The mean seeing condition over the period of integration was 0.7$''$. We used a 0.7$''$ slit and 2 $\times$ 2 binning during readout, yielding a spectral resolution of FWHM $\approx 10$ km s$^{-1}$ at wavelength $\lambda = 4500$ Å and $\approx 12$ km s$^{-1}$ at $\lambda = 8000$ Å. The data were processed and reduced using the MIKE data reduction software developed by Burles, Prochaska, & Bernstein. Wavelengths were calibrated to a ThAr frame obtained immediately after each exposure and subsequently corrected to vacuum and heliocentric wavelengths. Flux calibration was performed using a sensitivity function derived from observations of the flux standard NGC7293.

The final stacked spectrum of the afterglow is presented in Figure 1. The signal-to-noise of the echelle data is

$$S/N = 12 \text{ at } 4800 \text{ Å and } S/N = 13 \text{ at } 8000 \text{ Å per resolution element.}$$

We have performed a $\chi^2$ fitting routine over the spectral region between 7000 Å and 9000 Å, corresponding to a wavelength range between 1400 Å and 1800 Å in the rest frame of the host) and obtained a best-fit power-law model $f_\nu(\lambda) \propto \lambda^\alpha$ with $\alpha = 1.88 \pm 0.01$, which is presented as the dotted curve in Figure 1. The best-fit power-law index is significantly steeper than what has been measured for the OT of GRB020813 ($\alpha = 1$) at rest-frame optical wavelengths (Barth et al. 2003).

3. ANALYSIS

The echelle spectrum of the OT of GRB050730 exhibits a large number of absorption features due to the H I Ly$\alpha$ transition and various heavy ions in the ISM of the GRB host as well as in intervening gaseous clouds at $z < z_{\text{GRB}}$. Most notably is the strong damping trough centered at roughly 6040 Å, blueward of which we observe a forest of absorption features that are not present on the red side of the damped absorption profile. We identify the damped absorber as the DLA originating in the host galaxy of the GRB at $z_{\text{GRB}} = 3.969$ and the forest lines as the Ly$\alpha$ forest at $z < z_{\text{GRB}}$. In addition, we also identify an intervening DLA at $z_{\text{DLA}} = 3.564$ and a number of strong metal-line absorbers. Here we summarize the physical properties of these strong absorbers.

3.1. The GRB Host Environment at $z_{\text{GRB}} = 3.969$

The redshift measured for the GRB host using the DLA feature is confirmed by associated metal-line transitions. We measure a more precise redshift of the GRB at $z_{\text{GRB}} = 3.96855 \pm 0.00005$ using narrower metal absorption lines. At this redshift, we measure $N$(H I) of the GRB host by fitting Voigt profiles to the observed Ly$\alpha$ and Ly$\beta$ transitions simultaneously using the VPFIT software package. We obtain log $N$(H I) = 22.15 ± 0.05 for the host, with the error estimated from varying the continuum level of the absorption line profiles. This is the highest $N$(H I) observed in DLA systems, including those arising in GRB hosts (c.f. Vreeswijk et al. 2004).

In addition to absorption features due to neutral hydrogen, the spectrum also exhibits a suite of metal-absorption lines at the GRB host redshift (Figure 2), from neutral species such as O I, to low-ionization transitions such as C II, S II, C II, Si II, and Fe II, and to high-ionization transitions such as C IV, Si IV, and NV. We also identify strong fine structure lines such as O I $\ast$, O I $\ast\ast$, Si II*, O I $\ast\ast$, C II*, and Fe II*. With the exception of C II*, the absorption features are only observed locally in Eta Carinae (Gull et al. 2005). These saturated fine structure transitions indicate an extreme ISM environment with high gas density that is rarely observed in intervening DLA systems. In particular, Fe II absorption features are only observed locally in Eta Carinae (Gull et al. 2005). These saturated fine structure transitions indicate an extreme ISM environment with high gas density that is rarely observed in intervening DLA systems. Furthermore, the profiles of well resolved lines (e.g. C II 15250) show that >90% of the neutral gas is confined to a velocity width 20 km s$^{-1}$, which is considerably smaller than the median value of intervening DLA systems and implies a quiescent environment. But the profiles of saturated lines do exhibit absorption extending to $\approx 80$ km s$^{-1}$ (e.g. Si II 1526). Finally, the asymmetry of these line profiles

\[ \text{see http://web.mit.edu/~burles/www/MIKE/mike_cookbook.html.} \]

\[ \text{see http://www.ast.cam.ac.uk/~rfc/vpfit.html.} \]
Fig. 1.—Stacked echelle spectrum of the OT of GRB050730. The signal-to-noise of the echelle data is $S/N = 12$ at 4800 Å and $S/N = 13$ at 8000 Å per resolution element. Blueward of the Lyα absorption trough at 6040 Å from the GRB host environment is a forest of foreground Lyα absorbers, including a DLA system at 5550 Å ($z_{DLA} = 3.564$). The Lyβ absorption feature of the GRB host is apparent at 5090 Å. The absence of flux at wavelengths below 4530 Å indicates little/no high energy photons beyond the Lyman limit transition escape the host of the GRB. The continuum at $\lambda = 7000 - 9000$ Å is best-described by a power-law model $f(\lambda) \propto \lambda^{1.88}$ as shown in the solid red curve. Note that the power-law fit from 7000 Å to 9000 Å somewhat underpredicts the apparent continuum flux from 4600Å to 5000Å (dotted curve).

is suggestive of an organized velocity field, e.g. rotation or outflow.

We measure the column density of each transition using both the apparent optical depth method (Savage & Sembach 1991) and the VPFIT software package. Comparing column density ratios between different transitions allow us to constrain the physical properties of the ISM in the GRB host. The principal results are as follows. (1) We measure [S/H] = $-2.0 \pm 0.1$. Because S is non-refractory, its gas-phase abundance gives a direct measurement of the gas metallicity. (2) We find [S/Fe] = +0.3, consistent with the gas phase [$\alpha$/Fe] measurements of low-metallicity DLA systems. Even if we adopt an intrinsic solar abundance pattern, the dust-to-gas ratio in the host ISM is very low (c.f. Savaglio et al. 2003). (3) We measure [N/S] = $-1.0 \pm 0.2$, again consistent with low-metallicity DLA systems (Prochaska et al. 2002). (4) We detect no molecular lines in the Lyα forest, suggesting a warm gas phase. (5) Based on the observed ratio of $N$(Fe II$^+$)/$N$(Fe II), we infer a number density $n_H > 10^7$ cm$^{-3}$ for a temperature $T < 30000$ K. This constrains the size of the host DLA cloud to be $l_{DLA} < 4.6$ pc.

In summary, aside from the large gas density $n_H$ inferred from saturated fine structure lines, the ISM of the GRB host has very similar characteristics to known DLA systems at $z \sim 4$.

3.2. Intervening Absorbers

We have identified a number of strong absorbers along the sightline toward GRB050730. We briefly summarize each system below:

DLA system at $z_{DLA} = 3.56439$: We identify Lyα and Lyβ transition for this absorber and measure $N$(H I) = 20.3 ± 0.1. In addition, we also find associated metal-line absorbers due to SiII, AlII, FeII, SiIV, and CIV. The weak line strengths of these metal absorption lines suggest a low metallicity in the neutral gas, [Si/H] < −1.3.

Lyman Limit system at $z_{LLS} = 3.02209$: We measure $N$(H I) using the Lyα feature and find $N$(H I) = 19.9 ± 0.1 for this Lyman limit system. In addition, we identify SiII, AlII and FeII, but we do not detect CIV absorption at the absorber redshift. Including no ionization correction, we find [Si/H] = −1.5 ± 0.2.

Mg II system at $z_{MgII} = 2.25313$: We identify saturated Mg II doublet at this redshift. In addition, we find strong
Mg I 2852 and Fe II absorption features for this absorber. **Double Mg II systems at** $z_{\text{Mg II}} = 1.7731$: We identify a pair of Mg II absorbers at $\Delta v = 57$ km s$^{-1}$ apart, for which we also find Mg I 2852 and the Fe II absorption series.

4. DISCUSSION AND CONCLUSIONS

GRB afterglows clearly provide a novel alternative to quasars for probing the ISM and IGM in the young universe. In the case of GRB050730, the afterglow reached an initial brightness of $R = 15.5$ (Klotz et al. 2005) and faded to $R = 17.5$ four hours later when the echelle spectroscopy was commenced. At $z = 3.969$, $R = 15.5$ corresponds to an absolute magnitude $M_{1450} = -29.3 + 5 \log h$ at rest-frame 1450 Å. This intrinsic luminosity, within a minute after the burst, is comparable to the most luminous quasar known (c.f. HS 1700+6416 at $z = 2.73$; Schneider et al. 2003). Even at $R = 17.5$, the corresponding intrinsic luminosity easily competes with the brightest quasars known at this redshift (see e.g. Fan et al. 2001). While absorption line systems uncovered toward the sightlines of optically selected quasars are likely to miss dusty absorbers, the extreme brightness of early GRB afterglows offers an unbiased view of the IGM at all epochs. In addition, the simple power-law shaped continuum of a GRB afterglow allows a more precise and accurate measurement of IGM opacity.

The sightline toward GRB050730 is particularly interesting with a strong DLA feature arising in the GRB host galaxy and an intervening DLA system at lower redshift. The GRB host DLA system ($z_{\text{DLA}} = z_{\text{GRB}}$), which are presumably selected by vigorous star formation and therefore probe deep into the center regions of distant galaxies, presents a nice contrast to the intervening DLA system ($z_{\text{DLA}} < z_{\text{GRB}}$), which arises preferentially at large galactocentric radii due to a larger cross-section of the outskirts than the inner regions. Our study shows that aside from having a much higher neutral gas density, the GRB host DLA has very similar characteristics to known $z \sim 4$ DLA systems, such as low dust content, low metallicity, and α-element enhanced chemical composition.

We have also shown that this sightline runs through a number of strong intervening absorbers, including a Lyman limit system and two strong Mg II absorbers. Detailed analyses of various ionic transitions associated with these absorbers allows us to study physical properties of ISM and IGM over a wide redshift range from $z = 1.7$ through $z = 3.9$. Follow-up deep imaging and low-resolution spectroscopy of faint galaxies along the line of sight will allow a direct comparison between the physical properties of the cold ISM (such as metallicity, kinematics, and dust content as derived from absorption line studies) and stellar properties (such as luminosity, morphology, and star formation rate as extracted from absorbing-galaxy analyses). A large sample of GRB host DLA systems offers a unique opportunity to dissect the ISM properties that are directly connected to GRBs, while a statistical sample of intervening DLA systems identified toward GRB sightlines will provide important insights toward understanding the nature of high-redshift DLA systems and offer a sim-
We appreciate the expert assistance from the staff of the Las Campanas Observatory. It is a pleasure to thank John O'Meara and Scott Burles for assistance with the data reduction, and Chris Howk and Art Wolfe for helpful discussions. H.-W.C., JXP, and JSB acknowledge support from NASA grant NNG05GF55G.

REFERENCES

Akerlof, C. et al. 1999, Nature, 398, 400
Barth, A. J. et al. 2003, ApJ, 584, L47
Bernstein, R. et al. 2003, Proc. SPIE, 4841, 1694
Blain, A. W. et al. 2002, Phys. Rev., 369, 111
Bloom, J. S. et al. 2002, ApJ, 572, L45
Bloom, J. S. et al. 2005, ApJ in press (astro-ph/0505480)
Castro, S. et al. 2003, ApJ, 586, 128
Chen, H.-W. & Lanzetta, K. M. 2003, ApJ, 597, 706
Colbert, J. W. & Malkan, M. A. 2002, ApJ, 566, 51
Fan, X. et al. 2001, AJ, 121, 54
Fiore, F. et al. 2005, ApJ, 624, 853
Gull, T. R. 2005, ApJ, 620, 442
Haehnelt, M. G., Steinmetz, M., & Rauch, M. 2000, ApJ, 534, 594
Holland, S. T. et al. 2005, GCN Circ. 3704 (http://gcn.gsfc.nasa.gov/gcn3/3704.gcn3)
Holman, M., Garnavich, P., & Stanek, K. Z. 2005, GCN Circ. 3727
(http://gcn.gsfc.nasa.gov/gcn3/3727.gcn3)
Jakobsson, P. 2004, A&A, 427, 785
Jensen, B. L. 2001, A&A, 370, 909
Klotz A., Boer M., & Atteia J. L. 2005, GCN Circ. 3720 (http://gcn.gsfc.nasa.gov/gcn3/3720.gcn3)
Le Brun, F. et al. 1997, A&A, 321, 733
Möller, P. et al. 2002, A&A, 396, L21
Paczyński, B. 1998, ApJ, 494, 45
Pettini, M. et al. 1999, ApJ, 510, 576
Prochaska, J. X. et al. 2002, PASP, 114, 933
Prochaska, J. X. et al. 2003, ApJS, 147, 227
Prochaska, J. X. et al. 2004, ApJ, 611, 200
Rao, S. M. et al. 2003, ApJ, 595, 94
Savage, B. D. & Sembach, K. R. 1991, 379, 245
Savaglio, S., Fall, M. S., & Fiore, F. 2003, ApJ, 585, 638
Schneider, D. P. 2003, AJ, 126, 2579
Sota, A. et al. 2005, GCN Circ. 3705 (http://gcn.gsfc.nasa.gov/gcn3/3705.gcn3)
Stanek, K. Z. et al. 2003, ApJ, 591, L17
Steidel, C. C. et al. 1999, ApJ, 519, 1
Vreeswijk, P. et al. 2004, A&A, 419, 927
Wolfe, A. M., Prochaska, J. X., & Gawiser, E., 2003, ApJ, 593, 215
Wolfe, A. M. et al. 2005, ARA&A, 43, 200
Woosley, S. E. 1993, ApJ, 405, 273