ON THE INCIDENCE OF STRONG Mg II ABSORBERS ALONG GAMMA-RAY BURST SIGHT LINES

Gabriel E. Prochter,[1] Jason X. Prochaska,[1] Hsiao-Wen Chen,[2] Joshua S. Bloom,[3] Miroslava Dessauges-Zavadsky,[4] Ryan J. Foley,[3] Sebastian Lopez,[5] Max Pettini,[6] Andrea K. Dupree,[7] and P. Guhathakurta[1]

ABSTRACT

We report on a survey for strong (rest equivalent width $W_r \geq 1$ Å), intervening Mg II systems along the sight lines to long-duration gamma-ray bursts (GRBs). The GRB spectra that comprise the survey have a heterogeneous mix of resolution and wavelength coverage, but we implement a strict, uniform set of search criteria to derive a well-defined statistical sample. We identify 14 strong Mg II absorbers along 14 GRB sight lines (nearly every sight line exhibits at least one absorber) with spectra covering a total path length $\Delta z = 15.5$ at a mean redshift $\bar{z} = 1.1$. In contrast, the predicted incidence of such absorber systems along the same path length to quasar sight lines is only 3.8. The roughly 4 times higher incidence along GRB sight lines is inconsistent with a statistical fluctuation at greater than 99.9% c.l. Several effects could explain the result: (1) dust within the Mg II absorbers obscures faint quasars giving a lower observed incidence along quasar sight lines, (2) the gas is intrinsic to the GRB event, and (3) the GRBs are gravitationally lensed by these absorbers. We present strong arguments against the first two effects and also consider lensing to be an unlikely explanation. The results suggest that at least one of our fundamental assumptions underpinning extragalactic absorption line research is flawed.

Subject heading: gamma rays: bursts

1. INTRODUCTION

Shortly after the discovery of quasars (Schmidt 1963), researchers realized that one could study distant gas in the universe by analyzing absorption lines in the spectra of these distant objects (e.g., Bahcall & Salpeter 1965). Although debate persisted for many years as to whether the observed gas was intrinsic to the quasar or at cosmological distance, the latter view is now almost universally accepted, and current research focuses on studying the dark matter power spectrum (e.g., Croft et al. 2002), the interstellar medium of high-z galaxies (Wolfe et al. 2005), metal enrichment (Schaye et al. 2003; Simcoe et al. 2004), and reionization (White et al. 2003).

Upon establishing that long-duration ($t > 2$ s) gamma-ray bursts (GRBs) are extragalactic (Metzger et al. 1997) with redshifts exceeding all but the most distant quasars (Kawai et al. 2006), researchers realized that one could use the transient, bright afterglows to perform similar observations as those for quasars (e.g., Vreeswijk et al. 2003; Chen et al. 2005). Although the majority of analysis to date has focused on the gas associated with the GRB host galaxy (e.g., Mirabal et al. 2002; Savaglio et al. 2003), even the first GRB spectrum showed the presence of intervening gas at redshifts significantly lower than the highest redshift system (Metzger et al. 1997). The proposed applications include studying reionization at yet greater distance than QSOs and probing the Lyα forest on a well-behaved, power-law continuum (e.g., Lamb & Reichart 2000; Lazzati et al. 2001).

Here we report the results from a survey of strong Mg II absorption systems. These systems were among the first intervening absorption lines discovered in quasar spectra because (1) the large rest wavelengths of the doublet allows for its detection in optical spectra for redshifts as small as 0.15; and (2) the doublet has a large oscillator strength and is resolved with even low-resolution (FWHM ≈5 Å) spectroscopy. As such, the Mg II absorbers were one of the first classes of quasar absorption-line systems to be surveyed (Steidel & Sargent 1992). Follow-up observations have shown that these absorbers trace relatively bright galaxies (Lanzetta 1993; Ménard et al. 2005; Zibetti et al. 2005) and reside in dark matter halos with $M \approx 10^{12}\ M_\odot$ (Bouché et al. 2004; Prochter et al. 2006b).

In many of the GRB spectra acquired to date, the authors have reported the presence of a Mg II absorber with rest equivalent width $W_r > 1$ Å. Jakobsson et al. (2004) noted that the galaxies identified with these absorbers may consistently occur at small impact parameter ($\rho \approx 10$ kpc) from the GRB sight line. Over the past year, our collaboration (GRAASP)[8] has obtained moderate- to high-resolution observations of afterglows for GRB discovered by the *Swift* satellite (Gehrels et al. 2004). In this Letter, we perform a search for strong ($W_r > 1$ Å) Mg II absorbers along these GRB sight lines and those reported in the literature. We compare the results to our recent determination of the incidence of strong Mg II systems along the sight lines to quasars in the Sloan Digital Sky Survey (SDSS; Prochter et al. 2006a, 2006b).

2. THE STRONG Mg II STATISTICAL SAMPLE ALONG GRB SIGHT LINES

Owing to the transient nature of GRB afterglows, optical spectroscopy has been obtained at many observatories with a diverse set of instruments and instrumental configurations. This

[1] UCO/Lick Observatory; University of California at Santa Cruz, Santa Cruz, CA 95064; xavier@ucolick.org.

[2] Department of Astronomy, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637; hchen@oddjob.uchicago.edu.

[3] Department of Astronomy, 601 Campbell Hall, University of California, Berkeley, CA 94720-3411.

[4] Observatoire de Genève, 51 Ch. des Maillettes, 1290 Sauverny, Switzerland.

[5] Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile.

[6] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom.

[7] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.

[8] Gamma-Ray Burst Afterglows As Probes (GRAASP), http://www.graasp.org.

TABLE 1
SURVEY DATA FOR Mg II ABSORBERS ALONG GRB SIGHT LINES

GRB	z_{GRB}	z_{start}	z_{end}	z_{abs}	W_r (2796 Å)	Δv (km s^{-1})	Reference
000926	2.038	0.616	2.0	...	...	...	1
010222	1.477	0.430	1.452	0.927	1.00 ± 0.14	74000	2
	...	...	...	1.156	2.49 ± 0.08	41000	
011211	2.142	0.359	2.0	...	...	...	3
020405	0.695	0.359	0.678	0.472	1.1 ± 0.3	65000	4
020813	1.255	0.359	1.232	1.224	1.67 ± 0.02	4000	5
021004	2.328	0.359	2.0	1.380	1.81 ± 0.37	97000	6
	...	...	...	1.602	1.53 ± 0.37	72000	
030226	1.986	0.359	1.956	...	...	...	7
030323	3.372	0.824	1.646	...	...	...	8
050505	4.275	1.414	2.0	1.695	1.98	176000	9
050730	3.97	1.194	2.0	...	...	...	
050820	2.6147	0.359	1.850	0.692	2.877 ± 0.021	192000	
	...	...	...	1.430	1.222 ± 0.036	113000	
050908	3.35	0.814	2.0	1.548	1.336 ± 0.107	147000	
051111	1.55	0.488	1.524	1.190	1.599 ± 0.007	45000	
060418	1.49	0.359	1.465	0.603	1.251 ± 0.019	124000	
	...	...	...	0.656	1.036 ± 0.012	116000	
	...	...	...	1.107	1.876 ± 0.023	50000	

REFERENCES.—(1) Castro et al. 2003; (2) Mirabal et al. 2002; (3) Vreeswijk et al. 2006; (4) Masetti et al. 2003; (5) Barth et al. 2003; (6) Mirabal et al. 2003; (7) Klose et al. 2004; (8) Metzger et al. 1997; (9) Berger et al. 2005.

includes our own data set (Prochaska et al. 2006; J. X. Prochaska et al. 2006, in preparation), which comprises observations acquired at the Las Campanas, Keck, and Gemini and Observatories with the HIRES (Vogt et al. 1994), MIKE (Bernstein et al. 2003), and GMOS (Hook et al. 2004) spectrometers, respectively. Nevertheless, a 1 Å Mg II absorber is sufficiently easy to identify that one can establish a set of criteria that will yield a well-defined search path and statistical sample.

The criteria imposed are (1) the data must be of sufficient quality to detect both members of the doublet at $>3\,\sigma$ significance, (2) the spectral resolution must resolve the doublet (we demand FWHM $<$ 500 km s^{-1}), and (3) the search is limited to outside the Lyα forest. To provide a uniform comparison with low-resolution surveys, we group all individual Mg II components within 500 km s^{-1} of one another into a single system and measure the total equivalent width of the Mg II 2796 Å transition. For each of our GRB spectra and those reported in the literature, we define a starting and ending redshift to search for Mg II absorbers, z_{start} and z_{end}. We define z_{start} as the *maximum* of $1215.67(1+z_{GRB})/2796$, 0.359 (to match z_{min} for our SDSS survey), and $\lambda^{SNR}_{min}/2796$, where λ^{SNR}_{min} is the lowest wavelength in the spectrum where $\sigma(W_r) < 0.3$ Å. Similarly, we define the ending redshift to be the *minimum* of 3000 km s^{-1} within z_{GRB}, $\lambda^{SNR}_{max}/2803$, and 2 (to match the highest redshift with good statistics in the SDSS). We have been conservative in defining these quantities and in several cases have obtained the original spectra to verify the published results. Table 1 presents the value for each of the GRB sight lines in this survey.

We have then searched these sight lines for strong Mg II absorbers and measured the rest equivalent width of the Mg II 2796 transition. Figure 1 presents a gallery of Mg II profiles from our GRAASP collaboration. Details on these observations will be provided in future papers (Prochaska et al. 2006; J. X. Prochaska et al. 2006, in preparation). For the literature search, we rely on the reported equivalent width measurements. In nearly every case, the identification of the Mg II doublet is confirmed by the presence of strong Fe II absorption at shorter wavelengths. Table 1 lists the statistical sample. It is astonishing that nearly every GRB sight line exhibits a strong Mg II absorber. Furthermore, we note that there are additional sight lines with insufficient spectral resolution and/or signal-to-noise ratio (S/N) to enter the statistical sample, yet they have very strong Mg II absorbers ($W_r > 2$ Å). Including these sight lines in the sample would only bolster the results discussed below.

3. RESULTS AND DISCUSSION

In the top panel of Figure 2, we present the redshift path density $g(z)$, which describes the number of GRB sight lines available for a Mg II search as a function of redshift. This is a very small sample by quasar absorption-line (QAL) standards. In the bottom panel of Figure 2, we show the cumulative number of Mg II absorbers detected along GRB sight lines (*solid line*) versus the number predicted by QSO statistics (*dashed line*). This curve was generated by convolving the $g(z)$ function for the GRB sight lines with the observed incidence of Mg II systems per unit redshift $\ell^{QSO}(z)$ from our survey of the SDSS (Prochter et al. 2006a). Our updated analysis of Data Release 4 (DR4) shows that the incidence of strong Mg II absorbers per unit redshift $\ell^{QSO}(z)$ is well fitted by the following polynomial $\ell^{QSO}(z) = -0.026 + 0.374z - 0.145z^2 + 0.026z^3$ (Prochter et al. 2006b). Note that these results are based on over 50,000 quasars and 7000 Mg II systems with $W_r \geq 1$ Å.

An inspection of the figure reveals that one observes a significantly higher incidence of strong Mg II absorbers toward the GRB sight lines than along the SDSS quasar sight lines. Assuming Poisson statistics, the observed incidence of 14 strong Mg II absorbers is inconsistent with the average value seen toward QSOs at >99.9% significance. We have also assessed the significance of the observation by drawing 10,000 sets of quasars from the SDSS DR4 chosen to have a similar $g(z)$ function as the GRB sight lines. The results of this analysis are presented in Figure 3. We find an average of 3.8 strong Mg II absorbers, that less than 0.1% of the trials have over 10 systems, and that none has 14 absorbers. Therefore, it seems very unlikely that the difference in incidence between the GRB and QSO sight lines is only a statistical fluctuation. We note that GRB 060418, with three strong absorption systems, is a rare object. Monte Carlo simulations reveal that only 2.6% of randomly chosen sets of 14 quasar lines of sight result in the

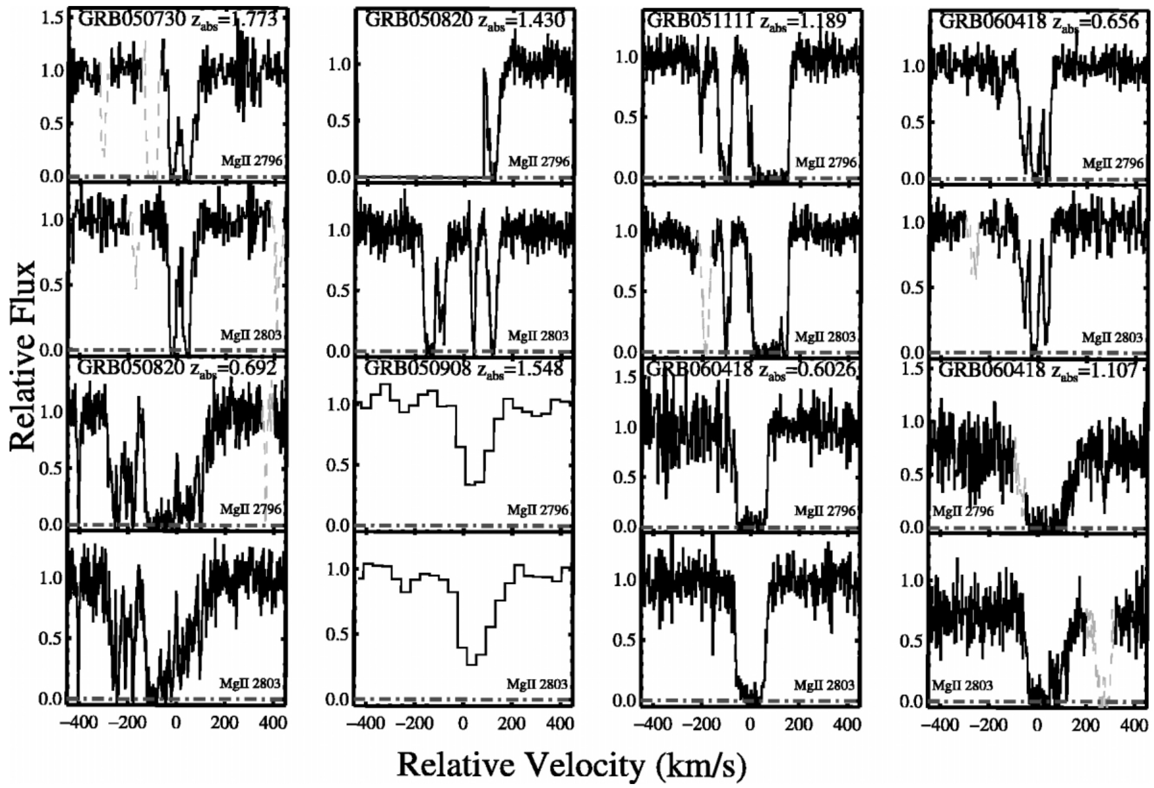

FIG. 1.—Velocity profiles of eight of the Mg II absorbers identified along the sight lines to GRBs by our GRAASP collaboration. See Prochaska et al. (2006; J. X. Prochaska et al. 2006, in preparation) for details of the observations. Dashed lines indicate features from coincident transitions. [*See the electronic edition of the Journal for a color version of this figure.*]

inclusion of such a system. We stress, however, that the results presented here are not dominated by this single sight line.

As with any astronomical survey, there are a number of associated selection biases or possibly incorrect assumptions to the analysis. We identify three effects that could explain the results presented here: (1) dust in the Mg II absorbers has obscured faint quasars and led to a severe underestimate in $\ell^{\rm QSO}(z)$; (2) the majority of the strong Mg II absorbers along the GRB sight line are not cosmological but are intrinsic to the GRB event; (3) GRB with bright, optical afterglows have been gravitationally lensed by foreground galaxies hosting strong Mg II absorbers. The first effect, a selection bias, has been discussed extensively for QAL absorbers (Ostriker & Heisler 1984; Fall & Pei 1993). Recently, York et al. (2006) have shown that Mg II absorbers do impose a nonzero reddening on its quasar spectrum, but that the average reddening for $W_r < 2$ Å systems is $E(B-V) < 0.01$ mag. Therefore, we consider it very unlikely that obscuration bias is the dominant explanation.

Are the Mg II absorbers along GRB sight lines intrinsic to the GRB? Absorption systems intrinsic to the quasar environment have

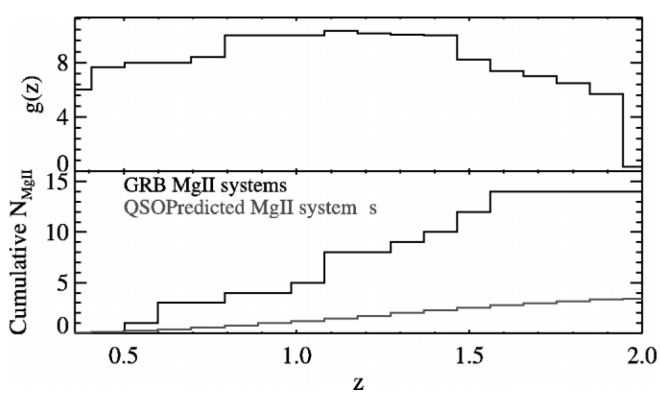

FIG. 2.—*Top*: Redshift path density $g(z)$ for the 14 sight lines that have sufficient S/N and spectral resolution to be included in the statistical sample. *Bottom*: Cumulative number of Mg II systems identified along the GRB sight lines (*black curve*). The red curve shows the predicted number of systems adopting the incidence of Mg II systems $\ell^{\rm QSO}(z)$ measured along QSO sight lines (Prochter et al. 2006b). The incidences observed for GRB and QSO sight lines are inconsistent at the greater than 99.9% level. [*See the electronic edition of the Journal for a color version of this figure.*]

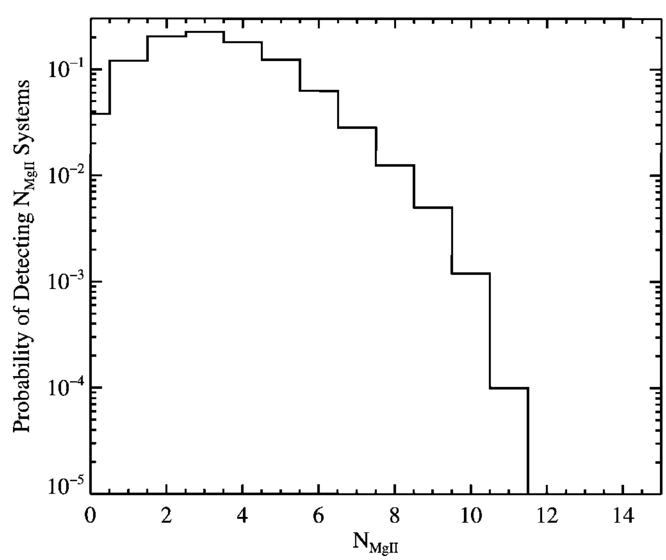

FIG. 3.—Probability of detecting $N_{\rm Mg\,II}$ strong Mg II systems calculated from a set of 10,000 trials where we randomly drew quasars from the SDSS data set constrained to have nearly the same $g(z)$ distribution as the GRB sight lines.

been identified at velocities Δv in excess of 50,000 km s^{-1} (Jannuzi et al. 1996). These absorbers are identified because of very wide profiles, equivalent width variability, and/or evidence for partial covering in the doublet line ratios (e.g., Barlow et al. 1997). Although the strong Mg II absorbers show relatively wide absorption profiles (by default) for QAL systems, the velocity widths are less than several hundred km s^{-1}, i.e., much less than the implied relativistic speeds (Table 1). The gas is generally highly ionized, although there are also examples of low-ionization states. An excellent way to test for the cosmological nature of the Mg II absorbers along GRB sight lines is to search for the host galaxies. Indeed, several authors have reported the identification of the host galaxies for strong, intervening Mg II systems along GRB sight lines (Masetti et al. 2003; Vreeswijk et al. 2003; Jakobsson et al. 2004). Only a small fraction of the strong Mg II systems listed in Table 1 have been identified, however, and an intrinsic origin for individual members of the sample is not entirely ruled out. Nevertheless, we consider it an improbable explanation at the current time.

Are the galaxies hosting the strong Mg II absorbers lensing the background GRB events? There are several lines of evidence in support of this conclusion. First, the strong Mg II absorbers reside in relatively massive dark matter halos $M \approx 10^{12}\ M_\odot$ (Bouché et al. 2004; Prochter et al. 2006b). Second, the survey is biased to GRBs with bright optical afterglows; i.e., we are selecting a subset of the GRB population. Third, nearly every GRB sight line shows a $W_r > 0.5$ Å Mg II system. Fourth, the impact parameter for several of the foreground galaxies is small (Jakobsson et al. 2004). Fifth, the luminosities of low-redshift ($z < 0.5$) GRBs appear to be significantly lower than those of the high-z events (Kann et al. 2006). None of these arguments, however, is particularly strong.

Furthermore, there are a number of arguments against strong lensing. First, estimates for the lensing rate based on the photon number fluxes predict a small lensing rate (Porciani & Madau 2001). Second, one does not always identify a bright foreground galaxy at small impact parameter (<1″) from the GRB sight line. We note that lensing would deflect the sight line, perhaps by more than 10 kpc, but that for the redshifts of interest here this translates to ∼1.″3. Third, it is unlikely that galaxy or cluster lensing would provide sufficiently large magnification to explain the very bright afterglows. Finally, there have been no reports of multiple images in late-time optical follow-up observations (e.g., see Nemiroff et al. 2001). For these reasons, we consider strong lensing to be an unlikely explanation.

Frank et al. (2006) have considered an alternative explanation for the observed effect, namely that the difference in sizes between GRBs and QSOs leads to lower equivalent widths in QSO sight lines. We believe, however, that this model is ruled out because one does not observe unsaturated Mg II lines (at high resolution) where the doublet is not in a 2 : 1 ratio (Churchill 1997).

In summary, we have reported on a statistically significant difference in the incidence of strong Mg II absorbers between GRB and QSO sight lines. Although it is partly an a posteriori result, the result has the predictive test that a larger sample of GRB sight lines will continue to show an excess of systems in comparison with quasar sight lines. At present, we have not identified a satisfactory single explanation for this phenomenon. Our results suggest that at least one of our fundamental assumptions underpinning extragalactic absorption line research is flawed. Before concluding, we wish to note that Stocke & Rector (1997) reported a similar enhancement in the incidence of Mg II systems along the sight lines to BL Lac objects, quasar-like phenomenon with spectra similar to GRBs that are also believed to be relativistically beamed jets. It may be worth considering their result in greater detail.

This Letter includes data obtained at W. M. Keck Observatory, which is a joint facility of the University of California, CIT, and NASA; the Gemini Observatory, which is operated by AURA, Inc.; and with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile. We thank P. Madau for helpful conversations and S. Vogt, G. Marcy, J. Wright, and K. Hurley in obtaining the observations of GRB 050820. G. E. P. and J. X. P. are supported by NSF grant AST 03-07408. J. X. P., H.-W. C., and J. S. B. are partially supported by NASA/*Swift* grant NNG05GF55G.

REFERENCES

Bahcall, J. N., & Salpeter, E. E. 1965, ApJ, 142, 1677
Barlow, T. A., Hamann, F., & Sargent, W. L. W. 1997, in ASP Conf. Ser. 128, Mass Ejection from Active Galactic Nuclei, ed. N. Arav, I. Shlosman, & R. J. Weymann (San Francisco: ASP), 13
Barth, A. J., et al. 2003, ApJ, 584, L47
Berger, E., Penprase, B. E., Cenko, S. B., Kulkarni, S. R., Fox, D. B., Steidel, C. C., & Reddy, N. A. 2006, ApJ, 642, 979
Bernstein, R., et al. 2003, Proc. SPIE, 4841, 1694
Bouché, N., Murphy, M. T., & Péroux, C. 2004, MNRAS, 354, L25
Castro, S., et al. 2003, ApJ, 586, 128
Chen, H.-W., et al. 2005, ApJ, 634, L25
Churchill, C. W. 1997, Ph.D. thesis, Univ. California, Santa Cruz
Croft, R. A. C., et al. 2002, ApJ, 581, 20
Fall, S. M., & Pei, Y. C. 1993, ApJ, 402, 479
Frank, S., et al. 2006, preprint (astro-ph/0605676)
Gehrels, N., et al. 2004, ApJ, 611, 1005
Hook, I. M., et al. 2004, PASP, 116, 425
Jakobsson, P., et al. 2004, A&A, 427, 785
Jannuzi, B. T., et al. 1996, ApJ, 470, L11
Kann, D. A., Klose, S., & Zeh, A. 2006, ApJ, 641, 993
Kawai, N., et al. 2006, Nature, 440, 184
Klose, S., et al. 2004, AJ, 128, 1942
Lamb, D. Q., & Reichart, D. E. 2000, ApJ, 536, 1
Lanzetta, K. M. 1993, in The Environment and Evolution of Galaxies, ed. J. M. Shull & H. A. Thronson (Dordrecht: Kluwer), 237
Lazzati, D., et al. 2001, in Gamma-Ray Bursts in the Afterglow Era, ed. E. Costa, F. Frontera, & J. Hjorth (Berlin: Springer), 191
Masetti, N., et al. 2003, A&A, 404, 465
Ménard, B., et al. 2005, in IAU Colloq. 199, Probing Galaxies through Quasar Absorption Lines, ed. P. Williams, C.-G. Shu, & B. Menard (Cambridge: Cambridge Univ. Press), 86
Metzger, M. R., et al. 1997, Nature, 387, 879
Mirabal, N., et al. 2002, ApJ, 578, 818
———. 2003, ApJ, 595, 935
Nemiroff, R. J., et al. 2001, in ASP Conf. Ser. 237, Gravitational Lensing: Recent Progress and Future Goals, ed. T. G. Brainerd & C. S. Kochanek (San Francisco: ASP), 129
Ostriker, J. P., & Heisler, J. 1984, ApJ, 278, 1
Porciani, C., & Madau, P. 2001, ApJ, 548, 522
Prochaska, J. X., et al. 2006, ApJS, submitted
Prochter, G. E., Prochaska, J. X., & Burles, S. M. 2006a, ApJ, 639, 766
Prochter, G., et al. 2006b, ApJ, submitted
Savaglio, S., Fall, S. M., & Fiore, F. 2003, ApJ, 585, 638
Schaye, J., et al. 2003, ApJ, 596, 768
Schmidt, M. 1963, Nature, 197, 1040
Simcoe, R. A., Sargent, W. L. W., & Rauch, M. 2004, ApJ, 606, 92
Steidel, C. C., & Sargent, W. L. W. 1992, ApJS, 80, 1
Stocke, J. T., & Rector, T. A. 1997, ApJ, 489, L17
Vogt, S. S., et al. 1994, Proc. SPIE, 2198, 362
Vreeswijk, P. M., Møller, P., & Fynbo, J. P. U. 2003, A&A, 409, L5
Vreeswijk, P. M., et al. 2006, A&A, 447, 145
White, R. L., et al. 2003, AJ, 126, 1
Wolfe, A. M., Gawiser, E., & Prochaska, J. X. 2005, ARA&A, 43, 861
York, D. G., et al. 2006, MNRAS, 367, 945
Zibetti, S., et al. 2005, ApJ, 631, L105