GRBs as Probes of the IGM

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Abstract Gamma-ray Bursts (GRBs) are the most powerful explosions known, capable of outshining the rest of gamma-ray sky during their short-lived prompt emission. Their cosmological nature makes them the best tool to explore the final stages in the lives of very massive stars up to the highest redshifts. Furthermore, studying the emission from their low-energy counterparts (optical and infrared) via rapid spectroscopy, we have been able to pin down the exact location of the most distant galaxies as well as placing stringent constraints on their host galaxies and intervening systems at low and high-redshift (e.g. metallicity and neutral hydrogen fraction). In fact, each GRB spectrum contains absorption features imprinted by metals in the host interstellar medium (ISM) as well as the intervening intergalactic medium (IGM) along the line of sight. In this chapter we summarize the progress made using a large dataset of GRB spectra in understanding the nature of both these absorbers and how GRBs can be used to study the early Universe, in particular to measure the neutral hydrogen fraction and the escape fraction of UV photons before and during the epoch of re-ionization.

Keywords Gamma-ray Bursts · Interstellar medium · Intergalactic medium · re-ionization · cosmology

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1 Introduction

Gamma-ray Bursts (GRB) have been observed from \( z = 0.03 \) (Pian et al. 2006) to \( z \sim 9 \) (Campana et al. 2015): from matter near to the host (local ISM, Zafar et al. 2010) to other galaxies (intergalactic medium and/or IGM) at lower redshift (and different impact parameters). The gas located in each of these components leaves an imprint clearly identified in GRB (and QSO) optical and NIR spectra by the presence of absorption lines.

Therefore, absorption spectroscopy allows us to disentangle all these absorption systems allowing us to discern not only their properties (e.g. metal content and gas kinematics of these galaxies), but also the overall characteristics of the cosmic IGM during and after the end of re-ionization in a very similar fashion to QSOs (see Fan et al. 2006, for a review).

In the following sections we summarize the advantage of using GRB afterglows for these studies with respect to QSOs, the current status of studying the chemical evolution of the Universe using GRB intervening systems, and the investigation of the cosmic IGM (e.g. neutral hydrogen fraction) based on recent GRB spectroscopic datasets. We will also emphasize some of the drawback of using GRBs, e.g., their transient nature and the low number of events in comparison with QSOs over most redshifts.

2 Intervening systems

Quasar lines of sight have been explored in depth in recent years thanks to the availability of large spectroscopic surveys, like the Sloan Digital Sky Surveys (York et al. 2000). Since they are bright background sources, they probe gas and matter located in foreground objects at different impact parameters. These intervening systems can be identified in the QSO spectra based on metal absorption features at redshifts lower than the QSO systemic redshift (usually determined by Ly\( \alpha \), C\( \text{iv} \), and Mg\( \text{ii} \) emission lines). However, the complexity of the intrinsic QSO continuum and the decreased numbers of bright QSOs at high-redshift makes the study of the intervening systems challenging. Nevertheless, thanks to several observing campaigns spanning the near-UV to the near-Infrared, a large sample of such objects has been collected: the identification of Ly\( \alpha \) lines at the intervening system redshifts has offered a unique opportunity to use them as tracers of the metal enrichment of the Universe from low-redshift \( \langle \text{Lehmer} \ et al. \ 2013, \ Muzahid \ et al. \ 2016, \ Cooper \ et al. \ 2015 \rangle \) to \( z \sim 5 \). Furthermore, Mg\( \text{ii} \) intervening absorbers have been identified in several QSO spectra: in the last decade the presence and metal content of such absorbers have been matter of debate, in particular regarding the role of such absorbers in fuelling star-formation and/or tracing cosmological galaxy build up.

Both types of absorbers, Ly\( \alpha \) and Mg\( \text{ii} \), have been also identified in GRB afterglow spectra, the former indicating the presence of large reservoir of neutral hydrogen in the GRB host galaxy, while the latter are often produced by foreground absorbers along the GRB line of sight. The synchrotron emission responsible for the simple power-law afterglow continuum makes the identification and measurement of absorption lines
easier than QSOs, but the rarity and rapidly fading nature of the emission means that much lower numbers of such systems have been identified. Nevertheless, GRBs have been spectroscopically identified up to $z = 8.2$, providing unprecedented tool to study the epoch of re-ionization. Thanks largely to the sample of GRBs discovered by the Swift satellite (Gehrels 2004), and the identification of their afterglows in many cases (from X-ray to optical and NIR), we have been able to investigate samples of these absorbers in considerable detail. In the following sub-sections we will briefly discuss these two types of absorbers, though we direct the reader to the Host galaxy chapter for a more complete view of the GRB hosts properties.

2.1 Lyman-α absorbers

Intervening systems for which a Lyman-α line is identified in absorption are subdivided based on the total hydrogen column density: if log $N_{\text{HI}} \geq 20.3$ cm$^{-2}$ they are called “Damped Lyman-α systems” (DLAs), while if log $N_{\text{HI}} < 20.3$ cm$^{-2}$, the systems are generically called sub-DLAs (see Wolfe et al. 2005 for a detailed review on such absorbers and further subdivisions). This cool gas usually surrounds galaxies and can be used to characterize the circumgalactic (CGM) medium (Stewart et al. 2011; Stinson et al. 2012; Rudie et al. 2012) testing theoretical predictions (e.g. Nagamine et al. 2004; Berry et al. 2014; Cen 2012; Razoumov et al. 2008; Fumagalli et al. 2011). Because of their connection with star-formation, DLAs represent important laboratories to chart the metal enrichment of the Universe, from the end of re-ionization to the peak of star-formation ($z \sim 2$) and at lower redshifts. Recently, Rafelski et al. (2014) have shown how metallicity decreases with redshift up to $z \sim 4.5$ in a large QSO-DLA sample. Furthermore, these authors suggest that at even higher redshifts there is a steepening in the decline of cosmic metallicity, probably due to an increase of the covering fraction of neutral gas as function of redshift. Lyman-α absorbers have also been identified in the GRB afterglow spectra and offer a unique possibility to obtain not only higher signal-to-noise ratio spectra (bright GRB afterglows observed early are usually brighter than QSOs at any redshift) but also to trace the stellar content of such DLAs (GRB-DLAs): in fact, GRB-DLAs are associated with the host galaxies enabling, once the afterglow fades away, detailed studies of DLAs itself.

In 2015, Cucchiara et al. (2015) compiled the largest sample of spectroscopic afterglow data available and determined uniformly the metallicities of 54 GRB-DLAs from weak metal absorption lines (like S ii Si ii). They compared this sample with the QSO-DLA results from Rafelski et al. and, despite having a smaller sample, showed a higher metallicity around GRB-DLAs at $z = 3 - 5$, roughly 10% the solar value (a factor of two higher than the one measured for QSO-DLAs). These authors suggest that GRB-DLAs may be the best tracer of the interconnection between DLAs and metal build up, especially at high redshift since usually GRBs occur within their host, in close proximity to star-forming regions. The host galaxy metallicity determination obtained by absorption lines diagnostics is an important aspect of cold gas fuelling star-formation and the advent of NIR spectrographs will enable comparisons with emission line (integrated over the whole galaxy) diagnostics, a critical step forward on our understanding of star-formation in the local Universe and at the highest redshifts. Furthermore, understanding the nature of the galaxies hosting these absorbers will provide insights on galaxy formation and evolution. The data required to perform such analyses (e.g. ex-
tensive multiband observations) is demanding because of the faint nature of the sources and the need for space-based observatory time in many cases.

2.2 Mg II absorbers

One of the most studied and commonly identified feature is the Mg II doublet at $\lambda\lambda 2796, 2803\text{Å}$, thanks to its large rest wavelength (which makes it then detectable at $z = 0.5 - 2.2$), the relatively high abundance, and its oscillator strength.

The Mg II systems are usually classified in terms of the rest-frame equivalent width, $W_r$, of the bluer component as “weak” ($W_{2796} < 0.3 \text{ Å}$), “strong” ($W_{2796} > 0.3 \text{ Å}$) as in Steidel and Sargent (1992) and Churchill et al. (1999), and “very strong” ($W_{2796} > 1.0 \text{ Å}$, like in Rodríguez Hidalgo et al. 2012).

In the last few years several surveys have expanded our samples of Mg II intervening systems up to $z = 5.2$, thanks to near-IR spectroscopy (e.g. Steidel and Sargent 1992; Nestor et al. 2003; Prochter et al. 2006a; Quider et al. 2011; Simcoe et al. 2011; Zhu and Ménard 2013). These surveys indicate that the very strong Mg II absorbers present an increasing trend up to $z \sim 3$ before declining at higher redshift (see Figure 1, Prochter et al. 2006a; Matejek and Simcoe 2012). Intriguingly, this behavior closely tracks the cosmic star formation history (Prochter et al. 2006a; Zhu and Ménard 2013), suggesting that some systems may be causally connected to on-going star formation (Ménard et al. 2011; Matejek and Simcoe 2012).

For many years, strong Mg II absorbers have been associated with galaxies ($L \approx L^*$) at modest impact parameter and gas around them (Bergeron 1986; Lanzetta et al. 1987; Steidel 1993), either in the outer disks and/or the circumgalactic medium (CGM).

More recently, QSO lines of sight have been explored in order to probe the baryon content around low-$z$ galaxies (Kacprzak et al. 2012; Chen and Tinker 2008, and reference therein), as well as a diagnostic of the inner part of these galaxies’ interstellar medium (Bowen et al. 1995).

In a similar fashion, Gamma-ray Bursts (GRBs) provide both information on their hosts and on the intercepting matter along their lines of sight (Metzger et al. 1997). There are two main advantages of using these powerful sources: first, they can be observed up to very high redshifts (Kawai et al. 2006; Danvir et al. 2009; Salvaterra et al. 2009; Cucchiara et al. 2011), which allows one to explore a larger redshift path length, and second, their discovery is largely unbiased with respect to intrinsic properties of their hosts (extinction, luminosity or mass). In fact, the detection GRBs, at least in X-ray is independent (or substantially less affected) by the presence of dust extinction along the line of sight (in the host or in the IGM) (Zafar et al. 2010; Watson and Jakobsson 2012; Watson and Jakobsson 2013; Schady et al. 2010).

Unfortunately, the number of GRBs discovered and observed (thanks also to the Swift satellite, Gehrels et al. 2004, 2009) is several orders of magnitude less than the number of quasars that have been found in large surveys. Nevertheless, in 2006 a survey of Mg II absorbers was performed for an early sample of Swift bursts and a heterogeneous sample of pre-existing GRB spectra (Prochter et al. 2006a; P06 hereafter). These authors revealed an extremely puzzling result: the incidence of strong ($W_{2796} \geq 1\text{ Å}$) intervening Mg II absorbers was about 4 times higher along GRB sightlines than quasar sightlines. No such excess was found in other common class of absorbers, e.g. C IV features (Tejos et al. 2007; Sudilovsky et al. 2007), or for weak Mg II absorbers (Tejos et al. 2009).
Several explanations for this discrepancies were proposed by P06, including: 1) a possible intrinsic origin of these absorbers, which would imply an average escape velocity from the GRB hosts of $\sim 10 - 30\%$ the speed of light (Cucchiara et al. 2009; Bergeron et al. 2011); 2) a significant dust bias along QSO lines of sight (Ménard et al. 2008; Porciani et al. 2007; Budzynski and Hewett 2011; Sudilovsky et al. 2009); 3) a geometric effect difference due to the sizes of the emitting regions between GRBs and QSOs (Stocke and Rector 1997; Frank et al. 2007; Porciani et al. 2007; Lawther et al. 2012); 4) a gravitational lensing effect (Vergani et al. 2009a; Porciani and Madau 2001; Rapoport et al. 2011, 2013).

Most of these suggestions were later on discarded, but the puzzling result was only solved few years ago: the original P06 work, and even the studies that followed, relied on a small sample of GRB afterglow spectra. Even the largest analysis used only 26 lines of sight (finding 22 absorbers), for a total redshift path of $\Delta z = 31.55$ (Vergani et al. 2009b). Furthermore, no study had analyzed a completely independent set of GRB sightlines from the P06 analysis.

In 2013 Cucchiara et al. (2013) collected the largest compilation of GRB spectroscopic data, exploring a larger redshift path length ($\Delta z = 44.9$, Figure 2). No excess was identified in an independent sample and further tests, including Montecarlo simulation and bootstrapping analysis, suggested that the earlier work by P06 was biased by a statistical fluke: in particular, the presence of a small set of lines of sight with multiple absorbers appears to have driven the results (as suggested by Kann et al. 2010). The inclusion of the original P06 dataset does not provide any significant improvement (Figure 3).

3 Neutral hydrogen fraction

The reionization era describes the time when all the intergalactic hydrogen was first ionized by the photons produced by early galaxies and stars. Moreover, the same process heated the IGM gas precluding the formation of sub-haloes, which ultimately would form the smaller dwarf galaxies. Therefore, in order to properly describe the evolution of the universe until the present time, it is critical to be able to characterize this important period of its history, for example how long it lasted and how it proceeded (patchy or continuously).

The intergalactic medium (IGM) is known to have been almost completely ionized since a redshift of $z \sim 6$ (Becker et al. 2006; Fan et al. 2006; Becker et al. 2015), while observations of the electron scattering of the cosmic microwave background radiation suggest the universe transitioned from a cold neutral IGM to a hot ionized one at an average redshift of $z \sim 9$ (Planck Collaboration et al. 2015), but with the possibility that it was a significantly extended and environment dependent process (we will come back to this issue in Section 4).

From the detection of the Gunn-Peterson trough (GP, Gunn and Peterson 1965) using high redshift quasars the optical depth of the universe to ionizing photons rapidly decreases from $z \sim 7$ to $z \sim 6$, suggesting that the IGM changed due to re-ionization. Counting the fraction of spectral pixels that are completely absorbed (McGreer et al. 2011) were able to place a conservative, almost model independent, lower bound on the filling factor of ionised regions. Specifically, first results showed that the neutral hydrogen fraction should be smaller than $f_{\text{HI}} < 0.2$ (1-\sigma confidence) in the $5 \leq z \leq 5.5$ redshift range. Later, McGreer et al. (2015), refined this result obtaining $f_{\text{HI}} < 0.11$ at...
z = 5.6, and \( f_{\text{HI}} \) < 0.09 at \( z = 5.9 \). Another technique, involves the size distribution of 'dark gaps' in the Ly\( \alpha \) forest (see for example Songaila and Cowie 2010, Gallerani et al. 2008, Mesinger 2010), which shows that reionization is indeed an inhomogeneous process, with \( f_{\text{HI}} \) < 0.1 at \( z \sim 5 \).

The large number of quasar spectra now available (largely thanks to SDSS, York et al. 2000), offers an opportunity to make such measurements, but unfortunately the signal to noise required to perform accurate measurements is only achieved in a small fraction of cases. Moreover, the GP trough gives only weak lower bounds on the neutral gas fraction and the quasar itself may have altered the ionization of the surrounding IGM (Barkana and Loeb 2004), making obtaining \( f_{\text{HI}} \) estimates even more complicated.

A new possibility to study the IGM and reionization comes by using high-redshift GRBs: the typical GRB afterglow intrinsic synchrotron emission can be fit by a power-law enabling better constraints on the red damping wing of Ly\( \alpha \) than is possible for quasars (Miralda-Escudé and Rees 1998, Lamb and Reichart 2000, Ciardi and Loeb 2000, McQuinn et al. 2008). Also GRBs are less biased than QSOs, tracing more typical IGM environments, their radiation has negligible affect on the IGM itself (shorter time-scale radiation than QSOs), and in the first couple of days after their discovery they are much brighter than the average QSO at \( z \gtrsim 6 \) (e.g. GRB 090423 at \( z = 8.2 \) was \( K = 20.6 \) at 4 days post-burst), with the potential for high-resolution, high signal-to-noise ratio spectroscopy.

For several years, only the spectrum of GRB 050904 (at \( z = 6.295 \) Totani et al. 2006) was able to provide constraints on the neutral hydrogen fraction (\( f_{\text{HI}} < 0.6 \)), based solely on analysis of the red-damping wing. Recently, a newly discovered GRB at \( z = 5.912 \), GRB 130606A, has provided a great dataset for a similar analysis (Chornock et al. 2013, Totani et al. 2014, Hartoog et al. 2015): the bright optical/NIR afterglow enabled not only a large follow-up effort, but absorption spectroscopy has shown a low HI column density in the host, implying a much better constraint on the actual \( f_{\text{HI}} \) of the IGM.

GRB 130606A was discovered by the Swift and KONUS-Wind (Golenetskii et al. 2013) and its redshift was identified based on HI and metal absorption features at the same redshift (\( z = 5.912 \)). The afterglow was observed spectroscopically with several instruments/telescopes: from the low-resolution FOCAS camera on Subaru telescope (resolving power of \( R \sim 900 \)) to the X-Shooter instrument on VLT (\( R \sim 10000 \)). Here we present the results from the former dataset and discuss some discrepancies with other groups’ conclusions (Chornock et al. 2013, Totani et al. 2014, Hartoog et al. 2015).

The FOCAS data were obtained during 9.3-16.5 hours after burst and clearly show the presence of a strong Ly\( \alpha \) line. Also, flux calibration was performed using the standard star Feige 34, obtained the same night.

The observed spectrum was fitted by a model which includes a simple power-law intrinsic continuum (\( F_\nu \propto \nu^\beta \)) and three components for the HI absorption feature: HI from the host galaxy (host DLA), a diffuse contribution from the IGM, and a possible intervening Damped Ly\( \alpha \) system at lower redshift (DLA). For the host component a simple Gaussian profile with radial dispersion \( \sigma_v \) and with a column density of \( N_{\text{HI}}^{\text{host}} \) was used.

For the diffuse IGM we used Lorentzian (or the Voigt profile when convolved with the Gaussian velocity distribution), and the two-level approximation formula by (Peebles 1993) and (Miralda-Escudé and Rees 1998), with neutral hydrogen fraction \( f_{\text{HI}} \) in a redshift range from \( z_{\text{IGM},1} = 5.67 \) and \( z_{\text{IGM},u} = [z_{\text{GRB}}, \text{free}] \). Also, the GP optical
depth is $\tau_{GP} = 3.97 \times 10^7 f_{\text{HI}}[(1+z)/7]^{3.2}$ calculated from the cosmological parameters of Komatsu et al. (2011) and the primordial helium abundances of Peimbert et al. (2007). These components can be seen in Figure 4. For this exercise we considered the reionization to be uniform (rather than, e.g., patchy).

Regions of the spectrum cleaned of absorption features like C II or NV, as well as strong skyline emission, were excluded by the fit and simple chi-squared minimization statistics were employed in order to find the best model. The best-fit model parameters are listed in Table 1 of Totani et al. (2014), and provide a neutral hydrogen fraction of $f_{\text{HI}} = 0.086^{+0.012}_{-0.011}$. Furthermore, we were able to exclude with high-confidence a model that contains only a host DLA, while one or two components (diffuse IGM only, or IGM+intervening DLA) are equally valuable good fits (Figure 5). The presence of a second Ly$\alpha$ feature at lower redshift ($z = 5.806$) is supported by several metal lines at such redshift, but further analysis of the possible presence (and strength) of the expected Ly$\beta$ line allows to exclude that this is another DLA along the line of sight.

We point out that the chances of finding an intervening DLA at lower $z$ is very low: from the $z \sim 5-6$ DLA numbers density the chance of random encountering such system is roughly $\sim 3\%$ (Songaila and Cowie 2010; Castro-Tirado et al. 2013). Finally, the GRB 130606A spectrum shows the power of using high-z GRBs to probe the diffuse IGM down to $f_{\text{HI}} = 0.1$ for gas close ($\leq 5$ Mpc in proper distance) to the host galaxy. This value is consistent with the limits obtained by QSO studies (e.g. Mortlock et al. 2011). Such analyses will be even more productive with the upcoming generation of 30m telescopes, which will be optimized for rapid follow-up of such transients as well as be equipped with powerful NIR spectrographs.

It is interesting that other groups arrived at different results from that of Subaru presented above. Chornock et al. (2013) found no evidence for nonzero IGM HI, though their upper limit is not seriously in contradiction with the best-fit IGM HI of Totani et al. (2014). It should be noted that Chornock et al. (2013) used an intrinsic afterglow spectral index of $\beta = -1.99$, which is not supported by observed afterglow colors or the VLT spectrum that shows $\beta = -1.0$. However, Hartoog et al. (2015) found the best fit $f_{\text{HI}}$ to be zero, with a stringent $3\sigma$ upper limit of $f_{\text{HI}} \leq 0.05$, that is statistically inconsistent with the best-fit $f_{\text{HI}}$ of Totani et al. (2014). Totani et al. (2015) examined the origin of this discrepancy by analyzing the VLT data with the code adopted to the Subaru data. It is found that the same result as Totani et al. (2014) is obtained by adopting the same analysis method to the VLT spectrum, and hence the origin of the discrepancy is likely the difference of analysis methods, especially the wavelength ranges used. It is important to carefully optimize an analysis method to minimize systematic uncertainties, when very high precision spectra are obtained for high-z GRBs.

4 Escape fraction and re-ionization: first galaxies

We mentioned in the previous section that a transition from a cold neutral IGM to the hot ionized one must have occurred at some point in the Universe’s history. A key question is whether this phase change was predominantly driven by ionizing radiation from early generations of stars (UV emission from star forming galaxies), or whether other mechanisms (e.g. decaying particle ionizing background, contribution from accretion luminosity) must have had a significant effect. Considering the known star formation budget at $z \sim 6-9$, recent calculations confirm that it is plausible that massive stars provided sufficient ionizing photons, providing that a substantial fraction (typical anal-
yses suggest $f_{esc}$ of at least 10–20%) could escape the host galaxies in which the stars reside (e.g., Bouwens et al. 2015). Unfortunately it is highly challenging observationally to pin down the escape fraction even at lower redshifts, and most recent studies have concluded that it is likely to be rather low, e.g. a few percent or less at $z \sim 3$ (e.g., Grazian et al. 2015).

GRBs provide a novel route to addressing this question, since optical afterglow spectroscopy of $z > 2$ GRBs frequently provides a measurement of the neutral hydrogen column density along the line of sight through the host galaxy. Typically these columns are high, as measured in damped Lyman-$\alpha$ absorbers, and are a lower limit to the column that would have been in front of the GRB progenitor, in as much as hydrogen proximate to the burst may well be ionized by the burst itself. Thus most lines of sight are opaque to ionizing radiation, and in particular, very few GRB afterglows have ever been found with columns low enough to allow even a small fraction of ionizing radiation to escape and therefore to be measured directly (e.g. via far-UV photometry).

There are reasons to think that at higher redshifts, with more star formation occurring in smaller galaxies, the escape fraction may increase, although measurements of $N_{HI}$ from GRBs at $z > 4$ show at best a modest decline (Thöne et al. 2013; Chornock et al. 2014). Nevertheless, recently, thanks to the discovery of many $z > 2$ GRBs with spectroscopic redshift and $N_{HI}$ column measurements, $f_{esc}$ has been measured using an indirect technique, which involves only the determination of $N_{HI}$ distribution and it is not subject to systematics due background subtraction (Chen et al. 2007; Gnedin et al. 2008; Fynbo et al. 2009).

Following the work of Chen et al. (2007), the mean escape fraction of Lyman limit photons averaged over all directions (GRB sightlines) is evaluated according to

$$
\langle f_{esc} \rangle = \frac{1}{n} \sum_{i=1}^{n} \exp[-\sigma_{LL} N_i(H I)],
$$

where the sum extends over the total number of $n$ GRB sightlines in the sample and $\sigma_{LL} = 6.28 \times 10^{-18} \text{cm}^2$ is the photoionization cross section of hydrogen atoms. They find $\langle f_{esc} \rangle = 0.02 \pm 0.02$ (where error is estimated using the bootstrap re-sampling method). They also where able to determine a 95% c.l. upper limit of $\langle f_{esc} \rangle \leq 0.075$.

Fynbo et al. (2009), using a larger number of sight lines selected in a more unbiased way, found very similar results. These results are also consistent with measurements from Lyman Break Galaxies at $z \sim 3$, therefore suggesting that the $f_{esc}$ from QSOs and sub-$L^*$ galaxies, like the ones hosting GRBs, contribute for a comparable amount of ionizing radiation.

The large GRB sample detected by Swift, and accurate redshift measurement from ground based follow-up, have sparked deep observations of the highest redshift sample of GRB host galaxies, in particular near the time when re-ionization was complete. Numbers remain small at $z > 6$, so the constraints do not yet provide a critical problem for re-ionization, but samples with good spectroscopy will hopefully improve in the coming years.

**References**

R. Barkana, A. Loeb, Gamma-Ray Bursts versus Quasars: Ly$\alpha$ Signatures of Reionization versus Cosmological Infall. Astrophys. J. 601, 64–77 (2004). doi:10.1086/380435
**Fig. 1** Incident rate $dN/dz$ of very strong Mg II absorbers ($W_{2796} > 1.0$ Å). Blue points are from Zhu and Menard (2013) based on SDSS data at moderate redshifts, while the green points show near-infrared measurements from Matejek and Simcoe (2012). On the right axes we indicate the cosmic star formation rate density, $\dot{\rho}_* = dM_*/dt dA dX$, scaled by $dX/dz$, where $A$ is comoving area and $X$ is comoving distance.

**Fig. 2** Cumulative distribution of strong Mg II absorbers along GRB sight lines for an independent sample from Prochter et al. (2006b) (Sample I) and for the full sample (Sample F, black and blue solid curves, respectively). These are compared to the predicted incidence based on measurement along QSO lines of sight (dashed curves). The independent Sample I actually shows fewer absorbers than expected while a modest excess remains in Sample F. Neither result corresponds to a statistically significant difference from the QSO results.

G.D. Becker, W.L.W. Sargent, M. Rauch, R.A. Simcoe, Discovery of Excess O I Absorption toward the z=6.42 QSO SDSS J1148+5251. Astrophys. J. **640**, 69–80 (2006). doi:10.1086/500079

G.D. Becker, J.S. Bolton, P. Madau, M. Pettini, E.V. Ryan-Weber, B.P. Venemans, Evidence of patchy hydrogen reionization from an extreme Ly$\alpha$ trough below redshift six. MNRAS **447**, 3402–3419 (2015). doi:10.1093/mnras/stu2646

E. Behar, S. Dado, A. Dar, A. Laor, Can the Soft X-Ray Opacity Toward High-redshift...
Fig. 3 Incidence of very strong Mg $\text{ii}$ absorption intervening systems, $dN/dz$ or $\ell(z)$, evolution for the sample of GRB sight lines: triangles and square symbols refer to the Sample I and Sample F, respectively (see Cucchiara et al. 2013, for more details). The red curve shows the evolution of the Mg $\text{ii}$ incidence along quasar sight lines as recently computed by Zhu and Ménard (2013). We derive an average $\ell(z) = 0.20$ for Sample I, in agreement with the prediction, while $\ell(z) = 0.36$ for Sample F, indicating a slight overabundance of absorbers compared to the QSOs.

Sources Probe the Missing Baryons? Astrophys. J. 734, 26 (2011). doi:10.1088/0004-637X/734/1/26
J. Bergeron, The Mg II absorption system in the QSO PKS 2128-12 - A galaxy disc/halo with a radius of 65 KPC. Astron. Astrophys. 155, 8–11 (1986)
J. Bergeron, P. Boisse, B. Ménard, Incidence of Mg II absorbers towards blazars and the GRB/QSO puzzle. Astron. Astrophys. 525, 51 (2011). doi:10.1051/0004-6361/201015265
M. Berry, R.S. Somerville, M.R. Haas, E. Gawiser, A. Maller, G. Popping, S.C. Trager, Damped Lyα absorption systems in semi-analytic models with multiphase gas. MNRAS 441, 999–963 (2014). doi:10.1093/mnras/stu613
R.J. Bouwens, G.D. Illingworth, P.A. Oesch, J. Caruana, B. Holwerda, R. Smit, S. Wilkins, Reionization After Planck: The Derived Growth of the Cosmic Ionizing Emissivity Now Matches the Growth of the Galaxy UV Luminosity Density. Astrophys. J. 811, 140 (2015). doi:10.1088/0004-637X/811/2/140
D.V. Bowen, J.C. Blades, M. Pettini, Interstellar Mg II Absorption Lines from Low-Redshift Galaxies. Astrophys. J. 448, 634 (1995). doi:10.1086/175993
J.M. Budzynski, P.C. Hewett, Dusty Mg II absorbers: population statistics, extinction curves and gamma-ray burst sightlines. MNRAS 416, 1871–1889 (2011). doi:10.1111/j.1365-2966.2011.19158.x
S. Campana, R. Salvaterra, A. Ferrara, A. Pallottini, Missing cosmic metals revealed by X-ray absorption towards distant sources. Astron. Astrophys. 575, 43 (2015). doi:10.1051/0004-6361/201425083
A.J. Castro-Tirado, R. Sánchez-Ramírez, S.L. Ellison, M. Jelínek, A. Martín-Carrillo, V. Broum, J. Gorosabel, M. Bremer, J.M. Winters, L. Hanlon, S. Meegan, M. Topinka, S.B. Pandey, S. Guiti, S. Jeong, E. Soufas, A.S. Pozanenko, R. Cunniffe, R. Fernández-Muñoz, P. Ferrero, N. Gehrels, R. Hudec, P. Kubánek, O. Lara-Gil, V.F. Muñoz-Martínez, D. Pérez-Ramírez, J. Strobl, C. Alvarez-Iglesias, R. Inasaridze, V. Rumyantsev, A. Volnova, S. Hellmich, S. Mottola, J.M. Castro Cerón, J. Ceja, E. Göğüş, T. Güver, O. Oral Taş, I.H. Park, L. Sabau-Graziati, A. Tejero, GRB 130606A within a sub-DLA at redshift
Fig. 4 Flux attenuation factor of the Lyα damping wing by various HI components and extinction at the host. The red solid curve is the total attenuation by HI in IGM and the host galaxy. The IGM and host components of this model are also separately shown. The IGM absorption model and the DLA component of the intervening DLA model are also shown for comparison. The green curves are the effect of introducing extinction by dust in the host galaxy (normalized to unity at 8900 Å), using the MW or SMC extinction curves (Fitzpatrick 1999; Gordon et al. 2003).

5.9 R. Cen, The Nature of Damped Lyα Systems and Their Hosts in the Standard Cold Dark Matter Universe. Astrophys. J. 748, 121 (2012). doi:10.1088/0004-637X/748/2/121
H.-W. Chen, J.X. Tinker, The Baryon Content of Dark Matter Halos: Empirical Constraints from Mg II Absorbers. Astrophys. J. 687, 745–756 (2008). doi:10.1086/591927
H.-W. Chen, J.X. Prochaska, N.Y. Gnedin, A New Constraint on the Escape Fraction in Distant Galaxies Using γ-Ray Burst Afterglow Spectroscopy. Astrophys. J. Lett. 667, 125–128 (2007). doi:10.1086/522306
R. Chornock, E. Berger, D.B. Fox, R. Lunnan, M.R. Drout, W.-f. Fong, T. Laskar, K.C. Roth, GRB 130606A as a Probe of the Intergalactic Medium and the Interstellar Medium in a Star-forming Galaxy in the First Gyr after the Big Bang. Astrophys. J. 774, 26 (2013). doi:10.1088/0004-637X/774/1/26
R. Chornock, E. Berger, D.B. Fox, W. Fong, T. Laskar, K.C. Roth, GRB 140515A at z=6.33: Constraints on the End of Reionization From a Gamma-ray Burst in a Low Hydrogen Column Density Environment. ArXiv e-prints (2014)
C.W. Churchill, J.R. Rigby, J.C. Charlton, S.S. Vogt, The Population of Weak Mg II Absorbers. I. A Survey of 26 QSO HIRES/Keck Spectra. Astrophys. J. Supp. 120, 51–75 (1999). doi:10.1086/313168
B. Ciardi, A. Loeb, Expected Number and Flux Distribution of Gamma-Ray Burst Afterglows with High Redshifts. Astrophys. J. 540, 687–696 (2000). doi:10.1086/309384
T.J. Cooper, R.A. Simcoe, K.L. Cooksey, J.M. O’Meara, P. Torrey, The Incidence of Low-metallicity Lyman-limit Systems at z ~ 3.5: Implications for the Cold-flow Hypothesis of Baryonic Accretion. Astrophys. J. 812, 58 (2015). doi:10.1088/0004-637X/812/1/58
Fig. 5  Top: The optical spectrum of GRB 130606A afterglow taken by the SUBARU telescope, around the redshifted Ly$\alpha$ and its red damping wing region. The best-fit curves of the host HI only model and the host+IGM model are shown by thick dashed and solid curves, respectively. Bottom: The fit residuals ($f_{\text{obs}} - f_{\text{model}}$)/$\sigma_{\text{obs}}$ are shown for the two models. The gray shaded regions indicate the wavelength ranges removed from the fits because of apparent features of absorption lines or airglow.
E.L. Fitzpatrick, Correcting for the Effects of Interstellar Extinction. PASP 111, 63–75 (1999). doi:10.1086/316293

S. Frank, M.C. Bentz, K.Z. Stanek, S. Mathur, M. Dietrich, B.M. Peterson, D.W. Atek, Disparate Mg II absorption statistics towards quasars and gamma-ray bursts: a possible explanation. ApSS 325–330 (2007). doi:10.1007/s10509-007-9699-x

M. Fumagalli, J.X. Prochaska, D. Kasen, A. Dekel, D. Ceverino, J.R. Primack, Absorption-line systems in simulated galaxies fed by cold streams. MNRAS 418, 1796–1821 (2011). doi:10.1111/j.1365-2966.2011.19599.x

J.P.U. Fynbo, P. Jakobsson, J.X. Prochaska, D. Malesani, C. Ledoux, A. de Ugarte Postigo, M. Nardini, P.M. Vreeswijk, K. Wiersema, J. Hjorth, J. Sollerman, H. Chen, C.C. Thöne, G. Björnsson, J.S. Bloom, A.J. Castro-Tirado, L. Christensen, A. De Cia, A.S. Fruchter, J. Gorosabel, J.F. Graham, A.O. Jaunsen, B.L. Jensen, D.A. Kann, C. Kouveliotou, A.J. Levan, J. Maund, N. Masetti, B. Milvang-Jensen, E. Palazzi, D.A. Perley, E. Pian, E. Rol, P. Schady, R.L.C. Starling, N.R. Tanvir, D.J. Watson, D. Xu, T. Augusteijn, F. Grundahl, J. Teling, P. Quirion, Low-resolution Spectroscopy of Gamma-ray Burst Optical Afterglows: Biases in the Swift Sample and Characterization of the Absorbers. Astrophys. J. Supp. 185, 526–573 (2009). doi:10.1088/0067-0049/185/2/526

S. Gallerani, A. Ferrara, X. Fan, T.R. Choudhury, Glimpsing through the high-redshift neutral hydrogen fog. MNRAS 386, 359–369 (2008). doi:10.1111/j.1365-2966.2008.13029.x

N. Gehrels, The swift gamma-ray burst mission. ApJ 611 (2004)

N. Gehrels, E. Ramirez-Ruiz, D.B. Fox, Gamma-Ray Bursts in the Swift Era. ARA&A 47, 567–617 (2009). doi:10.1146/annurev.astro.46.060407.145147

N. Gehrels, G. Chincarini, P. Giommi, K.O. Mason, J.A. Nousek, A.A. Wells, N.E. White, S.D. Barthelmy, D.N. Burrows, L.R. Cominsky, K.C. Hurley, F.E. Marshall, P. Meszaros, P.W.A. Roming, L. Angelini, L.M. Barbari, T. Belloni, S. Campana, P.A. Caraveo, M.M. Chester, O. Citterio, T.L. Cline, M.S. Cropper, J.R. Cummings, A.J. Dean, E.D. Feigelson, E.E. Fenimore, D.A. Frail, A.S. Fruchter, G.P. Garmire, K. Gendreau, G. Ghisellini, J. Greiner, J.E. Hill, S.D. Hunsberger, H.A. Krimm, S.R. Kulkarni, P. Kumar, F. Lebrun, N.M. Lloyd-Ronning, C.B. Markwardt, B.J. Mattson, R.F. Mushotzky, J.P. Norris, J. Osborne, B. Paczynski, D.M. Palmer, H. Park, A.M. Parsons, J. Paul, M.J. Rees, C.S. Reynolds, J.E. Rhoads, T.P. Sasseen, B.E. Schaefer, A.T. Short, A.P. Smale, I.A. Smith, L. Stella, G. Tagliaferri, T. Takahashi, M. Tashiro, L.K. Townsley, J. Tueller, M.J.L. Turner, M. Vietri, W. Voges, M.J. Ward, R. Willingale, F.M. Zerbì, W.W. Zhang, The Swift Gamma-Ray Burst Mission. Astrophys. J. 611, 1005–1020 (2004). doi:10.1086/422091

N.Y. Gnedin, A.V. Kravtsov, H.-W. Chen, Escape of Ionizing Radiation from High-Redshift Galaxies. Astrophys. J. 672, 765–775 (2008). doi:10.1086/524007

S. Golenetskii, R. Aptekar, D. Frederiks, V. Pal’Shin, P. Oleynik, M. Ulanov, D. Svinkin, T. Cline, Konus-wind observation of GRB 130606B. GRB Coordinates Network 14803, 1 (2013)

K.D. Gordon, G.C. Clayton, K.A. Misselt, A.U. Landolt, M.J. Wolff, A Quantitative Comparison of the Small Magellanic Cloud, Large Magellanic Cloud, and Milky Way Ultraviolet to Near-Infrared Extinction Curves. Astrophys. J. 594, 279–293 (2003). doi:10.1086/376774

A. Grazian, E. Giallongo, R. Gerbasi, F. Fiore, A. Fontana, O. Le Fevre, L. Pentericci, E. Vanzella, G. Zamorani, P. Cassata, B. Garilli, V. Le Brun, D. Maccagni, L.A.M. Tasca, R. Thomas, E. Zucca, R. Amorin, S. Bardelli, L.F. Cassara’, M. Castellano, A. Cimatti, O. Cucciati, A. Dunkele, M. Giavalisco, N.P. Hathi, O. Ilbert, B.C. Lemaux, S. Paltani, B. Ribeiro, D. Schaerer, M. Scodellaro, V. Sommariva, M. Talia, L. Tresse, D. Vergani, A. Bonchi, K. Boutsia, P. Capak, S. Charlot, T. Contini, S. de la Torre, J. Dunlop, S. Fotopoulou, L. Guaita, A. Koekemoer, C. Lopez-Sanjuan, Y. Mellow, E. Merlin, D. Paris, J. Pforr, S. Pilo, P. Santini, N. Scoville, Y. Taniguchi, P.W. Wang, The Lyman Continuum escape fraction of galaxies at z ~ 3 in the VUDS-LBC/COSMOS field. ArXiv e-prints (2015)

J.E. Gunn, B.A. Peterson ApJ 142, 1633 (1965)

O.E. Hartoog, D. Malesani, J.P.U. Fynbo, T. Goto, T. Krühler, P.M. Vreeswijk, A. De Cia, D. Xu, P. Møller, S. Covino, V. D’Elia, H. Flores, P. Goldoni, J. Hjorth, J. Jakobsson, J.-K. Kroghager, L. Kaper, C. Ledoux, A.J. Levan, B. Milvang-Jensen, J. Sollerman, M. Sparre, G. Tagliaferri, N.R. Tanvir, A. de Ugarte Postigo, S.D. Vergani, K. Wiersema, J. Dutson, R. Salinas, K. Mikkelsen, N. Aghanim, VLT/X-Shooter spectroscopy of the afterglow of the Swift GRB 130606A. Chemical abundances and resonance at z ~ 6. Astron. Astrophys. 580, 139 (2015). doi:10.1051/0004-6361/201425001
B. Ménard, D. Nestor, D. Turnshek, A. Quider, G. Richards, D. Chelouche, B. Rao, Lensing, reddening and extinction effects of MgII absorbers from z = 0.4 to 2. MNRAS 385, 1053–1066 (2008). doi:10.1111/j.1365-2966.2008.12909.x

B. Ménard, V. Wild, D. Nestor, A. Quider, S. Zibetti, B. Rao, D. Turnshek, Probing star formation across cosmic time with absorption-line systems. MNRAS 417, 801–811 (2011). doi:10.1111/j.1365-2966.2011.18227.x

A. Mesinger, Was reionization complete by z ~ 5-6? MNRAS 407, 1328–1337 (2010). doi:10.1111/j.1365-2966.2010.16995.x

M.R. Metzger, S.G. Djorgovski, S.R. Kulkarni, C.C. Steidel, K.L. Adelberger, D.A. Frail, E. Costa, F. Frontera, Spectral constraints on the redshift of the optical counterpart to the γ-ray burst of 8 May 1997. Nature 387, 878–880 (1997). doi:10.1038/43132

J. Miralda-Escudé, M.J. Rees, Searching for the earliest galaxies using the gunn-peterson trough and the Hα emission line. ApJ 497, 21–27 (1998)

D.J. Mortlock, S.J. Warren, B.P. Venemans, M. Patel, P.C. Hewett, R.G. McMahon, C. Simpson, T. Theuns, E.A. González-Solares, A. Adamson, S. Dys, N.C. Hambly, P. Hirst, M.J. Irwin, E. Kuiper, A. Lawrence, H.J.A. Röttgering, A luminous quasar at a redshift of z = 7.085. Nature 474, 616–619 (2011). doi:10.1038/nature10159

S. Muzahid, G.G. Kacprzak, J.C. Charlton, C.W. Churchill, Molecular Hydrogen Absorption from the Halo of a z ≈ 0.4 Galaxy. ArXiv e-prints (2016)

K. Nagamine, V. Springel, L. Hernquist, Star formation rate and metallicity of damped Lyman α absorbers in cosmological smoothed particle hydrodynamics simulations. MNRAS 348, 435–450 (2004). doi:10.1111/j.1365-2966.2004.07180.x

D.B. Nestor, D.A. Turnshek, S.M. Rao, Mg II Absorption Systems in Sloan Digital Sky Survey QSO Spectra. Astrophys. J. 628, 637–654 (2005). doi:10.1086/427547

P.J.E. Peebles, *Principles of Physical Cosmology* 1993

M. Peimbert, V. Luridiana, A. Peimbert, Revised Primordial Helium Abundance Based on New Atomic Data. Astrophys. J. 666, 636–646 (2007). doi:10.1086/520571

E. Pian, P.A. Mazzali, N. Masetti, P. Ferrero, S. Klose, E. Palazzi, E. Ramirez-Ruiz, S.E. Woosley, C. Kouveliotou, J. Deng, A.V. Filippenko, R.J. Foley, J.F.U. Fynbo, D.A. Kann, W. Li, J. Hjorth, K. Nomoto, F. Patat, D.N. Sauer, J. Sollerman, P.M. Vreeswijk, E.W. Gueniter, A. Levan, P. O’Brien, N.R. Tanvir, R.A.M.J. Wijers, C. Dunns, O. Hainaut, D.S. Wang, D. Baade, L. Wang, L. Amati, E. Cappellaro, A.J. Castro-Tirado, S. Ellison, F. Frontera, A.S. Fruchter, J. Greiner, K. Kawabata, C. Ledoux, K. Maeda, P. Møller, L. Nicastro, E. Rol, R. Starling, An optical supernova associated with the X-ray flash XRF 060218. Nature 442, 1011–1013 (2006). doi:10.1038/nature05082

Planck Collaboration, P.A.R. Ade, N. Aghanim, M. Arnaud, M. Ashdown, J. Aumont, C. Baccigalupi, A.J. Banday, R.B. Barreiro, J.G. Bartlett, et al., Planck 2015 results. XIII. Cosmological parameters. ArXiv e-prints (2015)

C. Porciani, P. Madau, On the Association of Gamma-Ray Bursts with Massive Stars: Implications for Number Counts and Lensing Statistics. Astrophys. J. 548, 522–531 (2000). doi:10.1086/319027

C. Porciani, M. Viel, S.J. Lilly, Strong Mg II Systems in Quasar and Gamma-Ray Burst Spectra. Astrophys. J. 659, 218–224 (2007). doi:10.1086/512358

G.E. Prochter, J.X. Prochaska, S.M. Burles, On the Incidence and Kinematics of Strong Mg II Absorbers. Astrophys. J. 639, 766–780 (2006a). doi:10.1086/499341

G.E. Prochter, J.X. Prochaska, H. Chen, J.S. Bloom, M. Desai, Divya-Varadi, R.J. Foley, S. Lopez, M. Pettini, A.K. Dupree, P. Gulkhatkur, On the Incidence of Strong Mg II Absorbers along Gamma-Ray Burst Sight Lines. Astrophys. J. Lett. 646, 93–96 (2006b). doi:10.1086/508061

A.M. Quider, D.B. Nestor, D.A. Turnshek, S.M. Rao, E.M. Monier, A.N. Weyant, J.R. Busche, The Pittsburgh Sloan Digital Sky Survey MgII Quasar Absorption-line Survey Catalog. Astroph. J. 144, 137 (2011). doi:10.1088/0004-6256/144/4/137

M. Rafelski, M. Neeleman, M. Fumagalli, A.M. Wolfe, J.X. Prochaska, The Rapid Decline in Metallicity of Damped Lyα Systems at z ~ 5. Astrophys. J. 782, 29 (2014). doi:10.1088/2041-8205/782/2/L29

S. Rapoport, C.A. Onken, B.P. Schmidt, J.S.B. Wyithe, B.E. Tucker, A.J. Levan, Testing the gravitational lensing explanation for the MgII problem in GRBs. ArXiv e-prints (2011)

S. Rapoport, C.A. Onken, J.S.B. Wyithe, B.P. Schmidt, A.O. Thyesen, On the Significance of the Excess Number of Strong Mg II Absorbers Observed toward Gamma-Ray Bursts. Astrophys. J. 766, 23 (2013). doi:10.1088/0004-637X/766/1/23
Perri, P. Podsiadlowski, K. Roth, R.E. Rutledge, T. Sakamoto, P. Schady, B.P. Schmidt, A.M. Soderber, J. Sollerman, A.W. Stephens, G. Stratta, T.N. Ukwatta, D. Watson, E. Westra, T. Wold, C. Wolf, A \( \gamma \)-ray burst at a redshift of \( z \approx 8.2 \). Nature 461, 1254–1257 (2009). doi:10.1038/nature08459

N. Tejos, S. Lopez, J.X. Prochaska, H.-W. Chen, M. Dessauges-Zavadsky, On the Incidence of C IV Absorbers Along the Sight Lines to Gamma-Ray Bursts. Astrophys. J. 671, 622–627 (2007). doi:10.1086/525088

N. Tejos, S. Lopez, J.X. Prochaska, J.S. Bloom, H.-W. Chen, M. Dessauges-Zavadsky, M.J. Maureira, Casting Light on the "Anomalous" Statistics of Mg II Absorbers Toward Gamma-ray Burst Afterglows: The Incidence of Weak Systems. Astrophys. J. 700, 1309–1315 (2009). doi:10.1088/0004-637X/706/2/1309

C.C. Thöne, J.P.U. Fynbo, P. Goldoni, A.P. de Ugarte, S. Campana, S.D. Vergani, S. Covino, T. Krühler, L. Kaper, N. Tanvir, T. Zafar, V. D’Elia, J. Gorosabel, J. Greiner, P. Groot, F. Hammer, P. Jakobsson, T. Klose, A.J. Levan, B. Milvang-Jensen, A.G. Nicuesa, E. Palazzi, S. Piranomonte, G. Tagliaferri, D. Watson, K. Wiersema, R.A.M.J. Wijers, GRB 100219A with X-shooter - abundances in a galaxy at \( z = 4.7 \). MNRAS 428, 3590–3606 (2013). doi:10.1093/mnras/sts303

T. Totani, N. Kawai, G. Kosugi, K. Aoki, T. Yamada, M. Iye, K. Ohta, T. Hattori, Implications for Cosmic Reionization from the Optical Afterglow Spectrum of the Gamma-Ray Burst 050904 at \( z = 6.3 \). PASJ 58, 485–498 (2006). doi:10.1093/pasj/58.3.485

T. Totani, K. Aoki, T. Hattori, G. Kosugi, Y. Niino, T. Hashimoto, N. Kawai, K. Ohta, T. Sakamoto, T. Yamada, Probing intergalactic neutral hydrogen by the Lyman alpha red damping wing of gamma-ray burst 130606A afterglow spectrum at \( z = 5.913 \). PASJ 66, 63 (2014). doi:10.1093/pasj/psu032

T. Totani, K. Aoki, T. Hattori, N. Kawai, High Precision Analyses of Lyman alpha Damping Wing of Gamma-Ray Bursts in the Reionization Era: On the Controversial Results from GRB 130606A at \( z = 5.91 \). ArXiv e-prints (2015)

S.D. Vergani, P. Petitjean, C. Ledoux, P. Vreeswijk, A. Smette, E.J.A. Meurs, Statistics and characteristics of MgII absorbers along GRB lines of sight observed with VLT-UVES. Astron. Astrophys. 503, 771–781 (2009a). doi:10.1051/0004-6361/200911747

S.D. Vergani, P. Petitjean, C. Ledoux, P. Vreeswijk, A. Smette, E.J.A. Meurs, Statistics and characteristics of MgII absorbers along GRB lines of sight observed with VLT-UVES. Astron. Astrophys. 503, 771–781 (2009b). doi:10.1051/0004-6361/200911747

D. Watson, P. Jakobsson, Dust Extinction Bias in the Column Density Distribution of Gamma-Ray Bursts: High Column Density, Low-redshift GRBs are More Heavily Obscured. Astrophys. J. 754, 89 (2012). doi:10.1088/0004-637X/754/2/89

D. Watson, T. Zafar, A.C. Andersen, J.P.U. Fynbo, J. Gorosabel, J. Hjorth, P. Jakobsson, T. Krühler, P. Laursen, G. Leloudas, D. Malesani, Helium in Natal H II Regions: The Origin of the X-Ray Absorption in Gamma-Ray Burst Afterglows. Astrophys. J. 768, 23 (2013). doi:10.1088/0004-637X/768/1/23

A.M. Wolfe, E. Gawiser, J.X. Prochaska, Damped Ly α Systems. ARA&A 43, 861–918 (2005). doi:10.1146/annurev.astro.42.053102.133950

D.G. York, J. Adelman, J.E. Anderson Jr., S.F. Anderson, J. Annis, N.A. Bahcall, J.A. Balck, R. Barkhouse, S. Bastian, E. Berman, W.N. Boroski, S. Bracker, C. Briegel, J.W. Briggs, J. Brinkmann, R. Brunner, S. Burles, L. Carey, M.A. Carr, F.J. Castander, B. Chen, P.L. Colestock, A.J. Connolly, J.H. Crocker, I. Csabai, P.C. Carapata, J.E. Davis, M. Doi, T. Dombeck, D. Eisenstein, N. Ellman, B.R. Elms, M.L. Evans, X. Fan, G.R. Fedewitz, L. Fiscelli, S. Friedman, J.A. Frieman, M. Fukugita, B. Gillespie, J.E. Gunn, V.K. Gurbani, E. de Haas, M. Haldeman, P.H. Harris, J. Hayes, T.M. Heckman, G.S. Hennessey, R.B. Hindley, S. Holm, D.J. Holmgren, C.-h. Huang, C. Hull, D. Husby, S.-I. Ichikawa, T. Ichikawa, Z. Ivezic, S. Kent, R.S.J. Kim, E. Kinney, M. Klaene, A.N. Kleinman, S. Kleinman, G.R. Knapp, J. Korienek, R.G. Kron, P.Z. Kunst, D.Q. Lamb, B. Lee, B.F. Leger, S. Limmongkol, C. Lindenmeyer, D.C. Long, C. Loomis, J. Loveday, R. Lucinio, R.H. Lupton, B. MacKinnon, E.J. Mannery, P.M. Mantsch, B. Margon, P. McGee, T.A. McKay, A. Meiksin, A. Merelli, D.G. Monet, J.A. Munn, V.K. Narayanan, T. Nash, E. Neilsen, R. Neswold, H.J. Newberg, R.C. Nichol, T. Nicinski, M. Nonino, N. Okada, S. Okamura, J.P. Ostriker, R. Owen, A.G. Pauls, J. Peoples, R.L. Peterson, D. Petravick, J.R. Pier, A. Pope, R. Pordes, A. Prosapio, R. Rechenmacher, T.R. Quinn, G.T. Richards, M.W. Richmond, C.H. Rivetta, C.M. Rockosi, K. Ruthmansdorfer, D. Sandford, D.J. Schlegel, D.P. Schneider, M. Sekiguchi, G. Sergey, K. Shimazu, W.A. Siegmund, S. Smeel, J.A. Smith,
S. Snedden, R. Stone, C. Stoughton, M.A. Strauss, C. Stubbs, M. SubbaRao, A.S. Szalay, I. Szapudi, G.P. Szokoly, A.R. Thakar, C. Tremonti, D.L. Tucker, A. Uomoto, D. Vanden Berk, M.S. Vogesley, P. Waddell, S.-i. Wang, M. Watanabe, D.H. Weinberg, B. Yanny, N. Yasuda, SDSS Collaboration, The Sloan Digital Sky Survey: Technical Summary. Astrop. J. 120, 1579–1587 (2000). doi:10.1086/301513

T. Zafar, D.J. Watson, D. Malesani, P.M. Vreeswijk, J.P.U. Fynbo, J. Hjorth, A.J. Levan, M.J. Michalowski, No evidence for dust extinction in GRB 050904 at z ~ 6.3. Astron. Astrophys. 515, 94 (2010). doi:10.1051/0004-6361/200913795

G. Zhu, B. Ménard, The JHU-SDSS Metal Absorption Line Catalog: Redshift Evolution and Properties of Mg II Absorbers. Astrophys. J. 770, 130 (2013). doi:10.1088/0004-637X/770/2/130