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Elemental Abundances in GRB Afterglows and High-Redshift DLAs

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Abstract. We present the results of a survey of GRB afterglows and DLA absorption line systems, in which we compare the abundances of elements from the absorbers with surveys of stars, and previous work. Our results detect high metallicity systems within GRB afterglow absorption, consistent with galactic disks having high rates of star formation and enrichment of heavy elements. We also detect some of the lowest metallicity systems yet found in DLA absorption lines, with many values of [X/H] < -2.8, including one system which has metallicity of [C/H] and [O/H} of approximately -3.5. The low metallicity DLA systems are useful for constraining nucleosynthesis from the first Pop III stars, and we compare our results with one nucleosynthesis model. Finally we describe some preliminary results from a survey of OVI absorbers within quasar Lyman alpha forest spectra, and the evidence within these spectra for low-metallicity IGM.

Keywords: Absorption Lines, Quasars, Gamma Ray Bursts
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INTRODUCTION

A key probe of nucleosynthesis in the early universe has been low metallicity stars and absorption line system. New samples of stars developed for this purpose have detected metallicity of Fe/H < -5.0 (Frebel et al, 2007; Cohen et al, 2007) and these stars have been classified as HMP, UMP and VMP, on the basis of values of [Fe/H] values of -5.0, -4.0 and -3.0, respectively. The abundance patterns of these metal poor stars have been compared with stellar nucleosynthesis models, and have provided useful constraints on the initial mass function and other properties of the Pop III stars (Matteucci, 2003; Meynet and Maeder, 2002, Woosley and Weaver (1995). Despite the success in finding many low metallicity stars, the abundances derived from stars have some uncertainty based on the unknown mixing and convection in the star, the possibility of separation of dust and gas in star formation, and enrichment of the stellar atmosphere from nearby companion stars.

Some work in recent years with Gamma Ray Bursts (GRB) and the optical afterglows (Penprase et al 2006; Berger, Penprase, et al 2005) have identified strong absorption systems similar to DLA systems within the GRB host galaxy. GRB afterglow spectra reveal gas that is indicative of active star formation, dust depletion, and the formation of a galactic disk. We review some aspects of the GRB spectra observed to date, and their relevance to Pop III stars.

Damped Lyman Alpha (DLA) systems have been a useful complementary probe of the early universe, and of metallicity in the intergalactic medium. Since early surveys of DLA systems (Sargent et al 1989; Bechtold et al 1994; Prochaska et al 2005), the number of DLA systems has continued to rise into the hundreds, allowing a statistically significant sample. Using the largest samples of DLA systems, it is also possible to determine the "floor" of metallicity within the DLAs. Previous works have reported the lowest metallicity of DLA systems with values of [X/H] = -2.7 or larger, with only a small fraction (10% or less) of DLA systems have [X/H] < -2.5.

In order to detect the lowest metallicity DLA systems, we began a survey to examine a very large sample of quasars with DLA systems of low metallicity using the Sloan Digitial Sky Survey (SDSS) fifth release (DR5), which contains over 77,000 newly detected quasars (Schneider, et al 2007). Our quasar sample was

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selected for strong, damped Lyman alpha absorption with log(N(HI)) > 20.0, and for weak absorption from the CII line at 1334 Å and the SiII line at 1260 Å, based on examination of the SDSS spectra. A Keck observing program with the ESI echellete spectrograph was then conducted to provide more accurate measurements of column densities of CII, OI, SiII and other species, to determine the actual metallicities of the DLA systems. By targeting the best candidates from such a large sample of quasars, it was hoped that we could find the lowest possible metallicity DLA systems, to enable comparison with nucleosynthetic models.

Our work also includes a survey of absorption within the Lyman alpha forest of a sample of 15 quasars observed with the Keck HIRES system. These spectra provide the highest quality data for the crucial blue region of the spectrum in which the lines of OVI and NV can be found, and build on the earlier works of Simcoe, Sargent and Rauch (2002, 2004).

RESULTS

For each of the three projects mentioned above, GRB afterglow spectroscopy, the DLA low metallicity survey, and the quasar Lyman Alpha forest OVI absorption line survey, we present a brief summary of our results in separate sections below. Separate papers on each of these projects are in preparation and should be published shortly.

GRB Afterglow Spectroscopy

GRB afterglow spectra have provided very interesting views of lower mass, star forming galaxies at redshifts ranging up to 6.295 (Kawai et al 2006). The host galaxies of GRBs appear to have morphologies which are typical of smaller galaxies in the process of forming galactic disks, and merging (Wainwright, Berger and Penprase, 2007). Studies of the absorption lines within the GRB afterglows can help constrain the densities, temperatures and metallicities of the galaxies, and help improve our understanding of galaxy evolution. In the section below we describe our results for two GRB afterglows, and compare their metallicities with other GRB afterglows, and DLA samples.

GRB 050505

One typical GRB afterglow system observed recently is the GRB 050505, which was observed with the Keck LRIS spectrograph (Berger, Penprase et al 2005). The GRB shows a strong and damped Lyman alpha profile, and many species are visible in absorption both at the host galaxy redshift of z=4.2748, and at two intervening redshifts of z=2.265 and z=1.694. Figure 1 shows the GRB 050505 spectrum, including the very strong DLA profile, which shows log(N(HI)) = 20.05 ± 0.10.

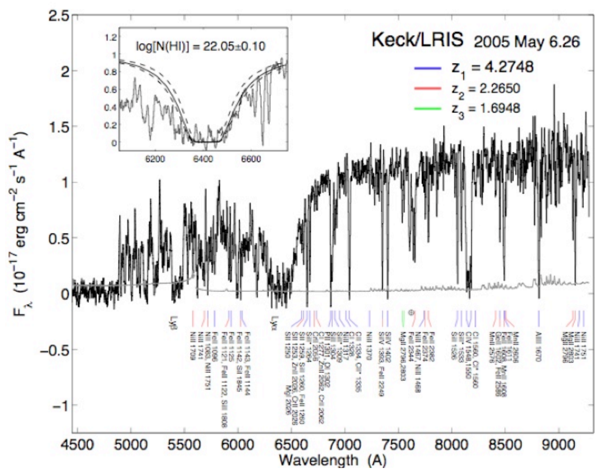

FIGURE 1. GRB 050505 spectrum (from Berger et al, 2005), showing both the damped Lyman alpha profile (inset) and the rich absorption from the host galaxy at three different redshifts, including the host galaxy redshift of z=4.2748.

After extracting column densities for this GRB spectrum, we compared the resulting columns with other GRB systems (Savaglio and Fall, 2003), as well as DLA systems as described by Wolfe, Gawiser and Prochaska (2005). Figure 2 shows the result of this comparision, and GRB 050505 appears as the cross, with higher metallicity than nearly all of the DLA systems at this redshift. The picture of GRB afterglow spectroscopy that is emerging is consistent with warm, dust-forming galactic disk materials, in which heavy element production is enhanced over the DLA sightlines. The absorption from GRB afterglows will probe the insides of galaxies in a way which is not possible from DLA systems, since the longer GRB emissions appear to arise from massive stars which would preferentially arise in the disks of galaxies.

GRB 051111

Figure 3 shows some of the elemental abundances detected within the GRB 051111 (Penprase et al 2006), in which the Keck HIRES spectrograph was able to extract a very high quality spectrum for this medium redshift GRB afterglow at z=1.5495. The

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GRB 051111 spectrum included detections of absorption lines of Zn, Cr, S, Fe, Si, Mg, and MgII, including multiple hyperfine excited states of FeII, to enable a detailed determination of the elemental abundances and excitation within the GRB 051111 host galaxy. The results are summarized in Figure 3, in which the abundance patterns are consistent with a "warm disk" depletion due to dust formation within the host galaxy.

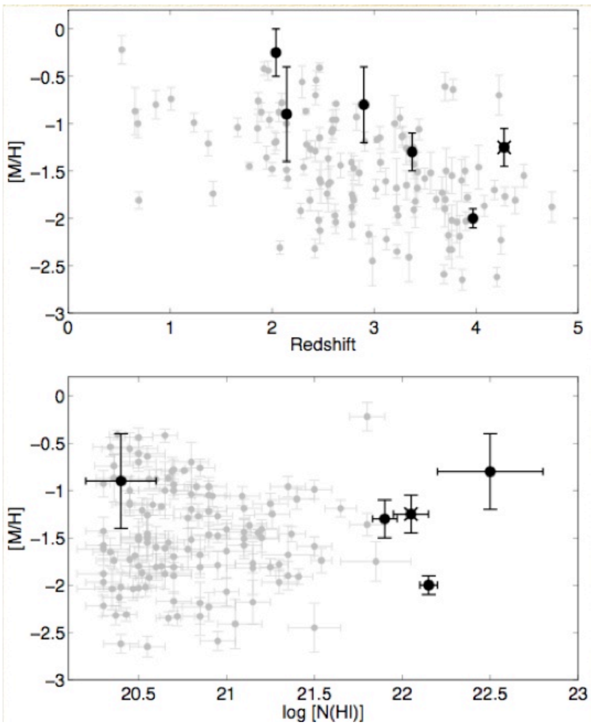

FIGURE 2. GRB abundances from GRB 050505 (dark cross) compared with a small sample of GRB afterglows from Savaglio and Fall (2003) (dark circles), and with a DLA sample (grey symbols). (From Berger et al 2005).

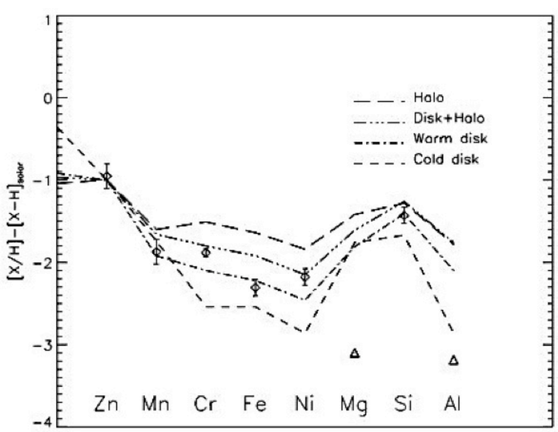

FIGURE 3. GRB 051111 was able to reveal a pattern of depletion within the GRB afterglow, from the detection of multiple species. The resulting pattern is closest to the Warm Disk depletion pattern, consistent with the picture of GRB absorption arising from afterglows within forming galactic disks. (From Penprase et al 2006).

Keck ESI Spectroscopy of Low Metallicity DLA Systems

We have observed 11 of the lowest metallicity SDSS quasars with the Keck ESI spectrograph, to acquire new spectra and elemental abundances of low metallicity DLA systems. The values of [M/H] from our sample reach as low as [M/H]=-3.5 for the elements C and O, enabling new tests of primordial nucleosynthesis. A comparison with a larger sample of DLA systems is provided in Figure 4 below.

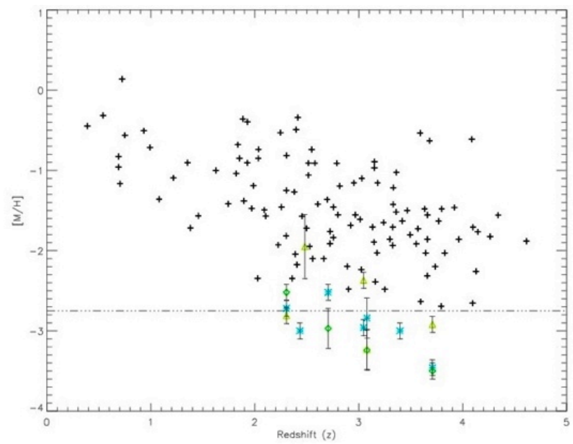

FIGURE 4. DLA elemental abundances as a function of redshift for a large sample described in Wolfe, Gawiser and Prochaska (2005), and the results from our new Keck/ESI survey (symbols with error bars). The results show the metallicities of [C/H], [O/H], and [Si/H] with triangles, asterisks and diamonds, respectively.

Of particular interest in the low-metallicity elements are Carbon, Oxygen and Silicon, which are expected to be produced from Pop III stars, but at very different yields, depending on the particular parameters in the stellar model. Our sample provides valuable data on low-metallicity [C/H] and [O/H] ratios, which extend the previous data available in the literature both from stellar and earlier DLA samples (Akerman et al, 2002).

Figure 5 presents our new results compared with those of Akerman et al 2004, which includes some results from stellar observations (squares), new DLA systems (triangles). The new results are shown with error bars in Figure 5, and the error bars include our estimate of the combined uncertainty of the column densities of H, C and O within the quasar sample. The results from our new ESI survey extend the trend for

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enhanced values of [C/O] at low values of [O/H], a result consistent with the Pop III nucleosynthesis models of Cieffi and Limongi (2002).

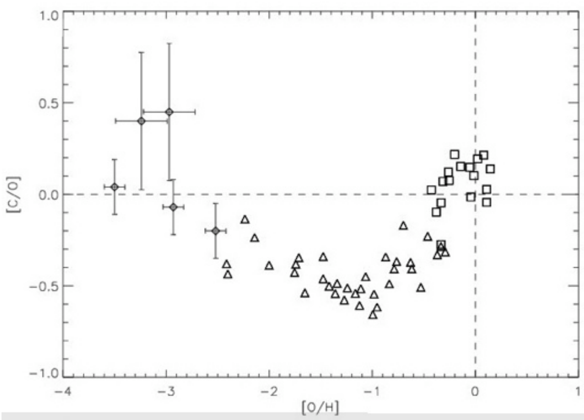

FIGURE 5. New results from our ESI data (diamonds) compared with the data within Akerman et al (2004). The new results extend the trend shown from other observations of low metallicity DLA systems (triangles), which have approach the values of [C/O] of disk stars (squares) for low metallicity.

A summary of our ESI results is shown below in Figure 6, which compares the results of our DLA systems with the nucleosynthesis pattern from Heger and Woosley (2002). For each element C, O, Al, Si, and Fe, we have computed the mean abundance relative to solar, and have normalized our abundance pattern to match the yield of Heger and Woosley for the element C. The results show a pattern in which on average the ratios of [C/O] , [C/Si] and [C/Fe] in our results are significantly enhanced over the Pop III model. Some hint of enhanced production of Al is also in evidence from our data. These results are very preliminary but show an interesting possibility of using DLA abundances to help constrain Pop III nucleosynthesis.

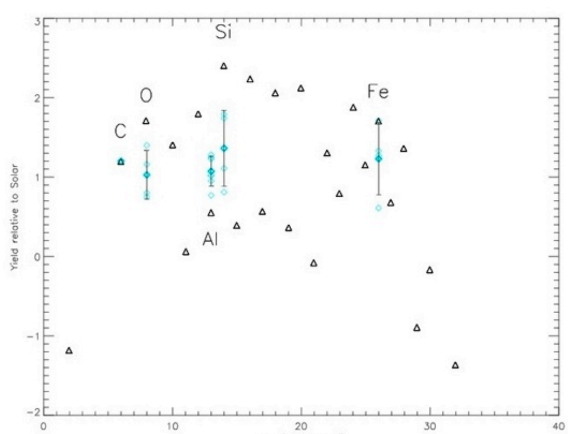

FIGURE 6. Comparison of our ESI abdunaces for the elements C,O, Al, Si, and Fe with the nucleosynthetic yield from Heger and Woosley (2002) of Population III stars with a range of masses from 140-260 Mo with a Salpeter-like IMF. Our results show enhanced ratios of [C/O], [C/Si], and [C/Fe] over this model.

Keck HIRES Spectroscopy of Lyman a Forest Clouds and OVI Metallicity

We also present results from a new survey of Lyman alpha forest clouds, which are derived from a sample of quasars with $2.0 < z < 2.6$, optimized to detect the absorption from the OVI lines at rest wavelengths of 1037.61 and 1031.92 Angstroms. Earlier work using the Keck HIRES spectrograph (Simcoe, Sargent and Rauch, 2004) has provided some good constraints on the low-metallicity IGM using the limited signal available within the very blue spectra of a small sample of quasars. Our new survey uses the new blue sensitive CCD of the Keck HIRES spectrograph to obtain higher SNR spectra of a larger sample of quasars, to give a larger number of clouds. With this new sample we have measured over 7000 Lyman alpha forest clouds with limits of OVI columns, with a lower limit of log(N(HI)) = 11.5, and have detected many new low-metallicity IGM systems.

Figure 7 presents the comparison between the older sample of Simcoe Sargent and Rauch (top) and our data (bottom). In the lower panel we present very preliminary results from the OVI survey which includes values of (N(HI)) and the resulting OVI upper limit. Since many of OVI lines from the crowded Lyman alpha forest are blended with additional Lyman alpha clouds, the plot shows a large number of blended components – indeed the majority of the values of measured OVI actually result from blended HI absorption. However in many cases we detect low-metallicity gas, which is visible as the symbols below the locus of points (visible as a parabola in the figure) for [O/H] = -2.5. We plan further study of this sample to remove the blended components, as well as to provide additional column densities of OVI, NV and CIV for the detected low-metallicity forest clouds.

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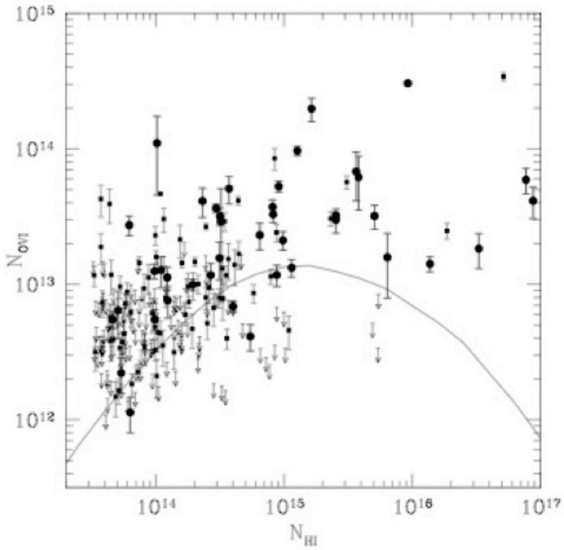

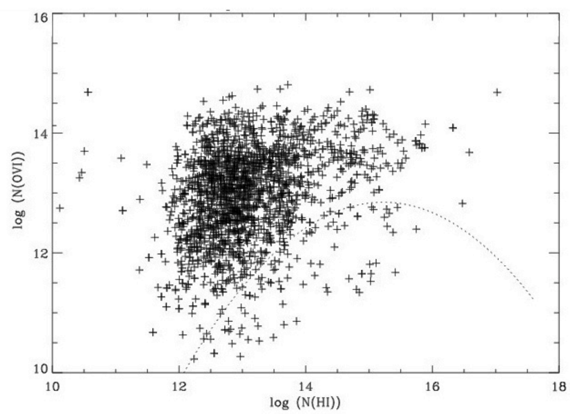

FIGURE 7. Comparison of older OVI results from Simcoe, Sargent and Rauch (2004) (top) with some preliminary new results (bottom). The very large number of points with high values of N(OVI) represent non-detections or blends with forest clouds. However, many new low-metallicity systems appear in our new data as points below the parabolic locus which represents [O/H] = -2.5. These points will be studied further to help constrain Pop III nucleosynthesis, and radiative processes and mixing in the IGM.

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