CHEMICAL ABUNDANCES OVER COSMIC TIME

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Abstract

It has recently become possible to measure directly the abundances of several chemical elements in a variety of environments at redshifts up to $z \simeq 4$. In this review I summarise the latest observations of Lyman break galaxies, the Lyman alpha forest and damped Lyman alpha systems with a view to uncovering any clues which these data may offer to the first episodes of star formation. The picture which is emerging is one where the universe at $z = 3$ already included many of the constituents of today's galaxies—even at these early times we see evidence for Populations I and II stars, while the 'smoking gun' for Population III objects may be hidden in the chemical composition of the lowest density regions of the IGM, yet to be deciphered. The *FIRST* mission promises to extend such abundance studies to include components of the high redshift universe which are obscured by dust and are therefore probably missing from the current census of metals over the cosmic ages.

Key words: Cosmology: observations – Galaxies: abundances – Galaxies: ISM – Galaxies: evolution – Intergalactic medium – Quasars: absorption lines – Missions: FIRST

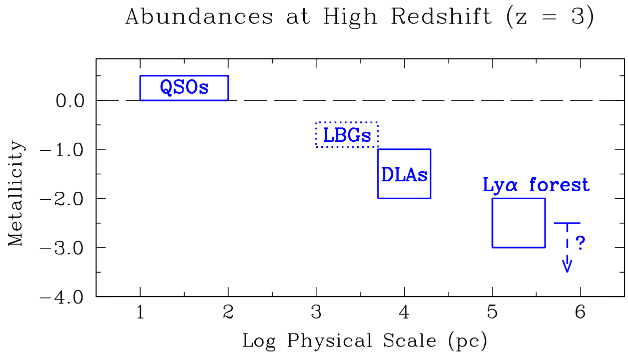

Figure 1. Summary of our current knowledge of abundances at high redshift. The 'metallicity' is plotted on the y-axis on a log scale relative to the solar reference; the latter is shown as the broken horizontal line at 0.0 and corresponds to approximately 2% of the baryons being incorporated in elements heavier than helium. The x-axis shows the typical linear dimensions of the strucures to which the abundance measurements refer, from the central regions of active galactic nuclei on scales of 10–100 pc to the intergalactic medium traced by the Lyα forest on Mpc scales. Generally speaking, these typical linear scales are inversely proportional to the overdensities of the structures considered relative to the background.

1. Introduction

One of the exciting developments in observational cosmology over the last few years has been the ability to extend studies of element abundances from the local universe to high redshifts. Thanks largely to the new opportunities offered by the VLT and Keck telescopes, we find ourselves in the exciting position of being able, for the first time, to detect and measure a wide range of chemical elements directly in stars, H II regions, cool interstellar gas and hot intergalactic medium, all observed when the universe was only $\sim 1/10$ of its present age. Our simple-minded hope is that, by moving back to a time when the universe was young, clues to the nature, location, and epoch of the first generations of stars may be easier to interpret than in the relics left today, some 11 Gyrs later. Furthermore, the metallicities of different structures in the universe and their evolution with redshift are key factors to be considered in our attempts to track the progress of galaxy formation through the cosmic ages. Figure 1 shows a snapshot of element abundances in different components of the universe at $z = 3$. Even from this simple sketch it seems clear that the degree of metal enrichment achieved at any particular cosmic epoch depends on the overdensity of the structures considered relative to the average density of the universe at that time. Thus, even at redshift $z = 3$,[1] the gas in the deepest potential wells where AGN are found had already undergone considerable processing and reached solar or super-solar abundances. At the other end of the scale, condensations in the Lyα forest which correspond to mild overdensities contained only traces of metals with metallicity $Z \simeq 1/100 - 1/1000\, Z_{\odot}$. The dependence of Z on the environment appears to be stronger than any age-metallicity relation—old does not necessarily mean metal-poor, not only for our own Galaxy but also on a global scale. This empirical picture can be understood in a general way within the framework of hi-

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[1] For $H_0 = 70\,\mathrm{km\ s^{-1}\ Mpc^{-1}}$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $z = 3$ corresponds to a look-back time of 11 Gyr. The age of the universe in this cosmology is ~ 13.5 Gyr

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erarchical structure formation in cold dark matter models (e.g. Cen & Ostriker 1999; Nagamine et al. 2001).

It can also be appreciated from Figure 1 that our knowledge of element abundances at early times is still very patchy. Given the limitations of space, my talk at this meeting focuses primarily on results obtained in the last year on three of the components of the high z universe indicated in the figure—Lyman break galaxies, the Lyα forest, and damped Lyα systems. An excellent review of abundance determinations in the emission line regions of AGN and associated absorbers has recently been published by Hamann & Ferland (1999).

2. Lyman Break Galaxies

One of the turning points in extragalactic astronomy in the 1990s has been the realisation that high redshift galaxies can be found in large numbers using a highly efficient photometric selection technique based on the passage of the Lyman edge—at the rest wavelength of 912 Å—through the U-band. After many years of fruitless searches (targeted mainly to Lyα emission which turned out to be a less reliable marker than anticipated), we have witnessed a veritable explosion of data from the *Hubble Deep Fields* and ground-based surveys (see Figure 2). Galaxies with *measured* redshifts in excess of $z \simeq 2.5$ now number nearly one thousand; such large samples have made it possible to trace the star formation history of the universe over most of the Hubble time and to measure large-scale properties of the population, most notably their clustering and luminosity functions (Madau et al. 1996; Steidel et al. 1998, 1999 and references therein).

However, quantitative studies of the physical properties of individual Lyman break galaxies (LBGs) are still very few, as they require a considerable observational effort even with the largest telescopes at our disposal. In particular, element abundances are not easily determined in the rest-frame UV (which at $z = 3$ is redshifted into optical wavelengths); here the strongest—and therefore most easily recorded—interstellar absorption lines are usually saturated and tell us more about the kinematics of the gas than its chemical composition. In the nearby universe, element abundances in star forming regions have traditionally been measured from the ratios of optical emission lines from ionised gas; at $z = 3$ these features move to near-infrared wavelengths and have only become accessible in the last eighteen months with the commissioning of high resolution spectrographs on the VLT (ISAAC) and Keck telescopes (NIRSPEC).

Using these facilities, we have recently completed the first spectroscopic survey of Lyman break galaxies in the near-IR, bringing together data for 19 LBGs at $z \simeq 3$; the galaxies are drawn from the bright end of the luminosity function, from $\sim L^*$ to $\sim 4\,L^*$ (Pettini et al. 2001). Figure 3 shows an example of the quality of spectra which can be secured with a 2–3 hour integration. In five cases we at-

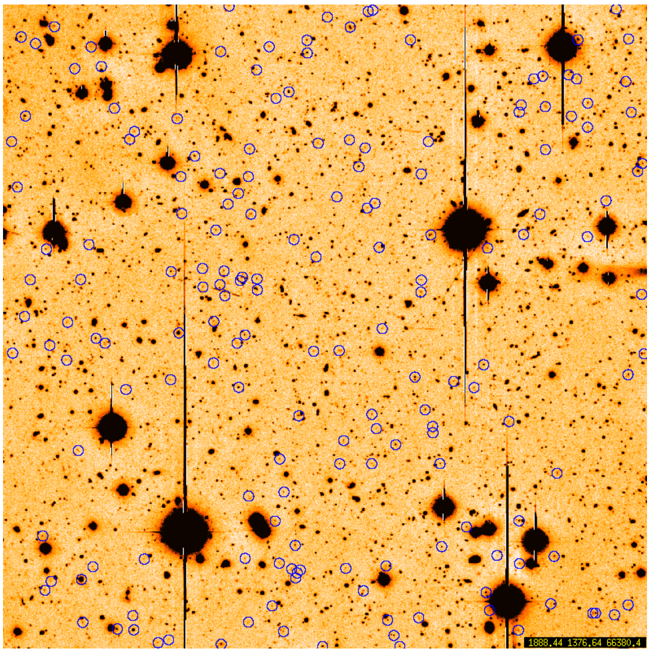

Figure 2. A typical deep image recorded at the prime focus of a 4m-class telescope. This particular image (of the field designated DSF2237a) was obtained with the COSMIC camera of the Palomar Hale telescope, by exposing for a total of two hours through our custom made $\mathcal{R}$ *filter. In the* 9×9 *arcmin field of view (corresponding to co-moving linear dimensions of* $11.6 \times 11.6\,h^{-1}$ *Mpc at* $z = 3$*) there are more than 4000 galaxies brighter than* $\mathcal{R} = 25.5$*; of these about 100–150 (circled) show Lyman breaks which place them at redshifts between* $z = 2.5$ *and 3.5.*

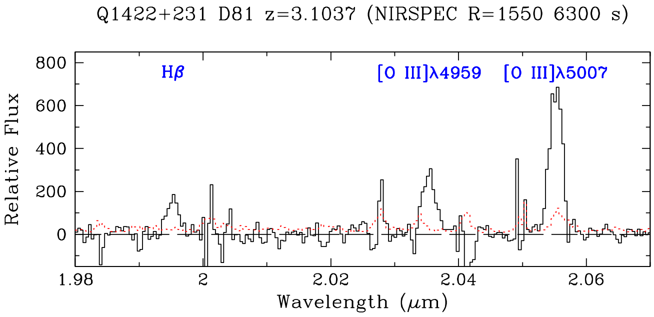

Figure 3. Example of a NIRSPEC K-band spectrum of a Lyman break galaxy. The objects targeted in our survey typically have $K = 21$ *(on the Vega scale) and remain undetected in the continuum. However, the nebular emission lines of* [O III] $\lambda\lambda 4859, 5007$, [O II] 3727 *(not shown), and* Hβ *usually show up clearly with exposures of 2–3 hours. The dotted line shows the* 1σ *error spectrum.*

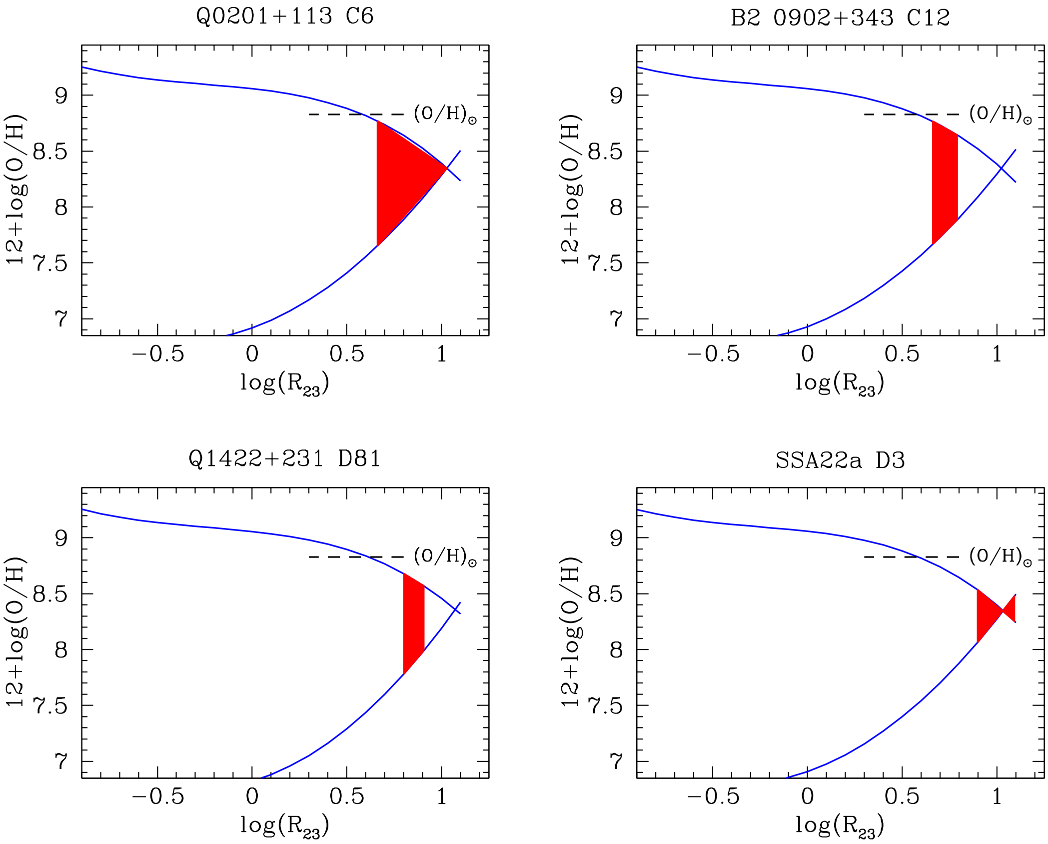

Figure 4. Oxygen abundance from the R_{23} = ([O II]+[O III])/Hβ ratio. In each panel the continuous lines are the calibration by McGaugh (1991) for the ionisation index O_{32} = [O III]/[O II] appropriate to that object. The shaded area shows the values allowed by the measured R_{23} and its statistical 1σ error. The broken horizontal line gives for reference the most recent estimate of the solar abundance 12 + log(O/H) = 8.83 (Grevesse & Sauval 1998).

tempted to deduce values of the abundance of oxygen by applying the familiar $R_{23} = ([\text{O II}] + [\text{O III}])/\text{H}\beta$ method first proposed by Pagel et al. (1979). We found that generally there remains a significant uncertainty, by up to 1 dex, in the value of (O/H) because of the double-valued nature of the R_{23} calibrator (see Figure 4). Thus, in the galaxies observed, oxygen could be as abundant as in the interstellar medium near the Sun, or as low as $\sim 1/10$ solar. While this degeneracy can in principle be resolved by measuring the [N II]/Hα ratio (and in the one case where this has proved possible—Teplitz et al. 2000—values of (O/H) near the upper end of the range are indicated), this option is not normally available for galaxies at $z \simeq 3$ because the relevant lines are redshifted beyond the K-band.

Even so, it is still possible to draw some interesting conclusions from these preliminary results. First, LBGs are definitely more metal-rich than the galaxies seen in absorption against background QSOs at the same redshifts and which are discussed in §4 below—hence their position in Figure 1. This is not surprising. LBGs are among the most active sites of star formation at $z = 3$, while galaxies selected by absorption cross-section presumably are drawn with near-equal probability from the whole of the galaxy luminosity function. Thus, the population of absorbers may well be dominated by the more numerous objects at the faint end of the distribution.

Second, LBGs do not conform to today's metallicity-luminosity relation and are overluminous for their oxygen abundance (see Figure 5). This is probably an indication that they have relatively low mass-to-light ratios, as also suggested by their kinematical masses ($\gtrsim 10^{10}\,M_\odot$); an additional possibility is that the whole (O/H) vs. M_B correlation shifts to lower metallicities at high z, when galaxies were younger.

Third, it is quite conceivable that a significant fraction of the metal-enriched gas in Lyman break galaxies is lost altogether in galaxy-wide outflows. Evidence of coherent large-scale motions is provided by the systematic velocity offsets which are seen in almost every case between interstellar absorption lines (formed in the approaching part of a swept-up shell of ambient gas and dust), nebular emission lines (presumably at the systemic redshift

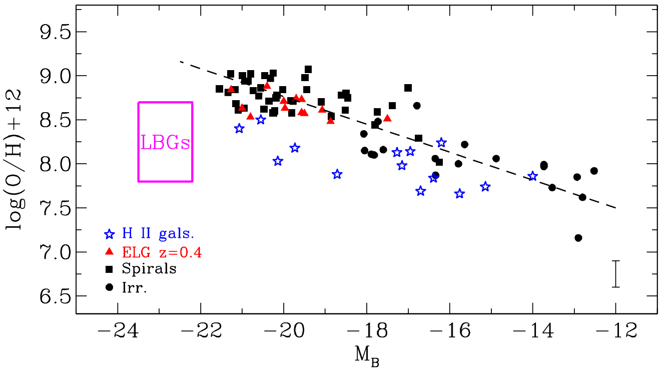

Figure 5. Metallicity-luminosity relation for local galaxies, from the compilation by Kobulnicky & Koo (2000) adjusted to the $H_0 = 70$ *km s*$^{-1}$ *Mpc*$^{-1}$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ *cosmology adopted in this work. The vertical bar in the bottom right-hand corner gives an indication of the typical error in log(O/H). In the Sun 12 + log(O/H) = 8.83. The box shows the approximate location of the Lyman break galaxies in our sample at a median* $z = 3.1$ *. Like many local H II galaxies, LBGs are overluminous for their metallicity. The height of the box results largely from the double-valued nature of the calibration of (O/H) in terms of the* R_{23} *index; the one case where the ambiguity can be resolved (MS 1512-cB58) lies in the upper half of the box.*

of the star-forming regions), and the Lyα emission line (back-scattered from the inner side of the receding portion of the shell). Such 'superwinds', which appear to be a common characteristic of galaxies with large rates of star formation per unit area at all redshifts (e.g. Heckman 2000), involve comparable amounts of matter as is being turned into stars (the mass outflow rate is of the same order as the star formation rate) and about 10% of the total kinetic energy delivered by the starburst (Pettini et al. 2000b). Furthermore, they have a number of important astrophysical consequences. They provide self-regulation to the star formation process (Efstathiou 2000); can distribute the products of stellar nucleosynthesis over large volumes (the outflow speeds often exceed the escape velocities of the galaxies—Ferrara, Pettini, & Shchekinov 2000); may account for some of the 'missing' metals at high redshift (Pettini 1999; Pagel 2000); and may also allow Lyman continuum photons to leak from the galaxies into the intergalactic medium, easing the problem of how the universe came to be reionised (Steidel, Pettini, & Adelberger 2001).

3. THE LYMAN ALPHA FOREST

The next component to be considered is the all-pervading intergalactic medium which manifests itself as fluctuating absorption bluewards of the Lyα emission line of every QSO. As can be appreciated from Figure 6, the effect is dramatic at high redshift. Observationally, the term Lyα forest is used to indicate the bulk of discrete Lyα absorption lines with column densities in the range $10^{16} \gtrsim N(\mathrm{HI}) \gtrsim 10^{12}$ cm^{-2}; since this gas is highly ionised, it may account for most of the baryons at high, as well as low, redshift (Rauch 1998; Penton, Shull, & Stocke 2000). Hydrodynamical simulations have shown that the Lyα forest is a natural consequence of structure formation in a universe dominated by cold dark matter and bathed in a diffuse ionising background (e.g. Weinberg, Katz, & Hernquist 1998). In this picture, which has become widely accepted although it is only now beginning to be tested observationally (Adelberger et al., in preparation), the physics of the absorbing gas is relatively simple and the run of optical depth $\tau(\mathrm{Ly}\alpha)$ with redshift can be thought of as a 'map' of the density structure of the IGM along a given line of sight. At low densities, where the temperature of the gas is determined by the balance between photoionisation heating and adiabatic cooling, $\tau(\mathrm{Ly}\alpha) \propto (1+\delta)^{1.5}$, where δ is the overdensity of baryons $\delta \equiv (\rho_b/\langle\rho_b\rangle - 1)$. At $z = 3$, $\tau(\mathrm{Ly}\alpha) = 1$ corresponds to a region of the IGM which is just above the average density of the universe at that time ($\delta \approx 0.6$).

The lack of associated metal lines was originally one of the defining characteristics of the Lyα forest and was interpreted as evidence for a primordial origin of the clouds. As is often the case, subsequent improvements in the observations have shown this to be an oversimplification and in reality weak metal absorption lines, principally by C IV $\lambda\lambda1548, 1550$, are present at the redshift of most Lyα clouds down to the detection limit of the data (Songaila & Cowie 1996). The degree of metal enrichment implied is relatively high, ([C/H]$\simeq -2.5$ with a scatter of perhaps a factor of ~ 3—Davé et al. 1998), in the sense that stars with significantly lower metallicities are known to exist in the halo of our Galaxy.

It is not easy to understand how the low density IGM came to be polluted so uniformly by the products of stellar nucleosynthesis at such an early epoch. While, as explained above, we see directly the outflow of metal-enriched gas in 'superwinds' from Lyman break galaxies at the same redshift, most of this gas is not expected to travel far from the production sites, because it is either trapped by the gravitational potential of the galaxies, if they are sufficiently massive, or is confined by the pressure of the hot IGM (Ferrara et al. 2000). Whether an early episode of pre-galactic star formation is required depends on whether C IV lines continue to be seen in Lyα clouds of diminishing H I column density. Current limits are for $N(\mathrm{H\ I}) \gtrsim 3 \times 10^{14}$ cm^{-2} (some 75% of such Lyα clouds have associated C IV absorption—Songaila & Cowie 1996) corresponding to moderately overdense gas ($\delta \gtrsim 10$) which in the simulations is preferentially found in the vicinity of collapsing structures and may thus reflect local, rather than universal, metal pollution.

The detection of C IV lines in the $N(\mathrm{H\ I}) \lesssim 1 \times 10^{14}$ cm^{-2} regime is a challenging task, even with a 10-m telescope, because we are dealing with observed equivalent widths $W_\lambda(1550) \lesssim 2.5$ mÅ. A possible approach in these

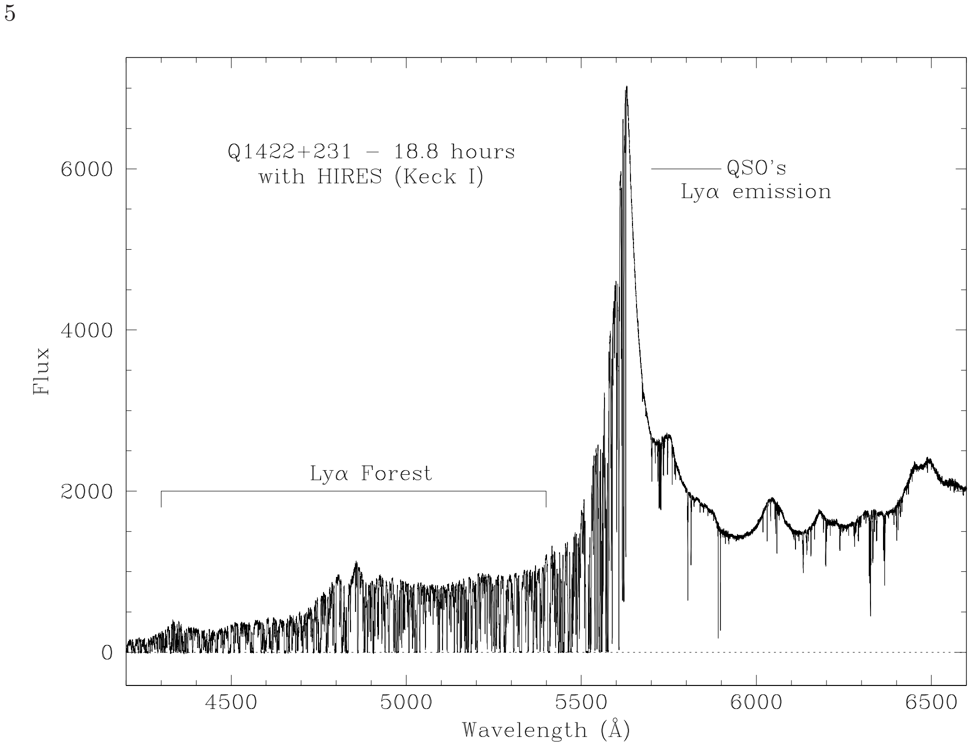

Figure 6. (Reproduced from Ellison 2000). This is one of the best QSO spectra ever obtained thanks to the combination of the bright magnitude of the gravitationally lensed QSO ($V = 16.5$), long exposure time (amounting to several nights of observation), and high spectral resolution offered by the Keck echelle spectrograph (FWHM$\simeq$ 8 km s^{-1}). The signal-to-noise ratio in the continuum longwards of the Lyα emission line is between 200 and 300. At these high redshifts ($z_{\rm em} = 3.625$) the Lyα forest eats very significantly into the QSO spectrum below the Lyα emission line and, with the present resolution, breaks into hundreds of absorption components.

circumstances is to try and recover such a weak signal from a statistical treatment of many lines which individually are below the detection limit. Unfortunately, different analyses have reached conflicting conclusions (Lu et al. 1998; Cowie & Songaila 1998). Furthermore, a recent reappraisal of the techniques with the help of extensive simulations of the spectra has indicated that many subtle effects, such as small random differences between the redshifts of Lyα and C IV absorption, make the interpretation of the results far from straightforward (Ellison et al. 1999).

A more direct way to tackle the problem is to push the detection limit further by securing spectra of exceptionally high signal-to-noise ratio; this is most effectively achieved with the aid of gravitational lensing. In this way Ellison et al. (2000) were able to reach S/N$\simeq 200 - 300$ in the C IV region between $z = 2.91$ and 3.54 of the gravitationally lensed QSO Q1422+231 after adding together data recorded over several nights with HIRES on Keck I (see Figure 6).

As can be seen from Figure 7, the number of weak C IV lines continues to rise as the signal-to-noise ratio of the spectra increases and any levelling off in the column density distribution presumably occurs at N(C IV)$<$ 5×10^{11} cm^{-2}. This limit is one order of magnitude more sensitive than those reached previously. In other words, we have yet to find any evidence in the Lyα forest for regions of the IGM which are truly of primordial composition or have abundances as low as those of the most metal-poor stars in the Milky Way halo. Pushing the sensitivity of this search even further is certainly one of the goals for the future.

4. Damped Lyman Alpha Systems

Finally we come to the damped Lyman alpha systems (DLAs) which, among the components in Figure 1 are the ones which I believe to be most accessible to *FIRST*. With neutral hydrogen column densities N(H I)$\geq 2 \times 10^{20}$ cm^{-2}, DLAs are the 'heavy weights' among QSO absorption systems, at the top of the N(H I) distribution which spans 10 orders of magnitude. DLAs provide us with the best opportunity to measure accurately the abundances of a wide range of elements at high redshift. The reason is simple: QSOs can be several hundred times brighter than Lyman break galaxies at the same redshift. Surveys with HIRES on Keck I have produced data of exquisite quality—a 10% accuracy in the determination of interstellar gas-phase abundances is achievable with only modest efforts (Lu et al. 1996; Prochaska & Wolfe 1999;

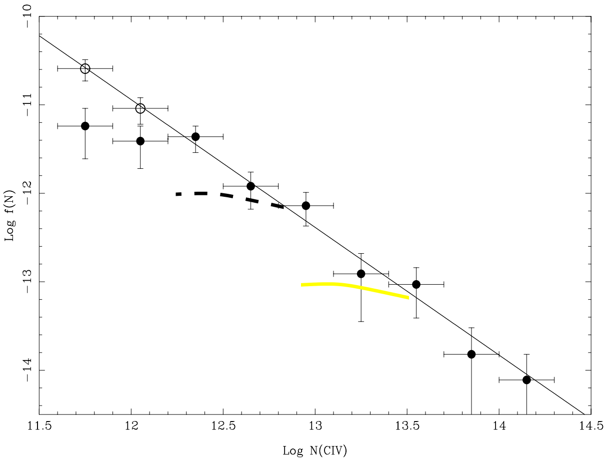

Figure 7. C IV column density distribution in Q1422+231 at $\langle z \rangle \simeq 3.15$*;* $f(N)$ *is the number of C IV systems per column density interval and per unit redshift path. The filled circles are the data; the straight line shows the best fitting power-law slope* $\alpha = 1.44$*, assuming the distribution to be of the form* $f(N)dN = BN^{-\alpha}dN$*. The open circles show the values corrected for incompleteness at the low column density end; with these correction factors there is no indication of a turnover in the column density distribution down to the lowest values of* N*(C IV) reached up to now. Earlier indications of a turnover shown by the grey (Petitjean & Bergeron 1994) and dashed (Songaila 1997) curves are now seen to be due to the less sensitive detection limits of those studies, rather than to a real paucity of weak Ly*α *lines.*

Pettini et al. 2000a). At redshifts $z \simeq 2-3$ the metallicity distribution of known DLAs is intermediate between those of stars in the halo and thick disk of the Milky Way; at this epoch most of the galaxies giving rise to damped systems were clearly less evolved chemically than the stellar population forming the thin disk of our Galaxy (see Figure 8).

The connection between DLAs and present day galaxies is still somewhat controversial, however. The working assumption adopted by many that DLAs are the progenitors of today's spirals, observed at a time when most of their mass was in the interstellar medium, has generally not been verified by deep imaging searches. These have shown that the absorbing galaxies are drawn from a wider variety of morphological types, with a preponderance of low luminosity and/or low surface brightness galaxies; an example is reproduced in Figure 9. Furthermore, the validity of DLAs as unbiased tracers of global quantities, such as the metallicity and gaseous content of the universe (a picture developed most extensively by Mike Fall and collaborators, e.g. Pei, Fall, & Hauser 1999; Fall 2001) is now being called into question by the apparent lack of evolution of these quantities over a redshift interval ($z \simeq 0.5-4$) during which most of today's stars were formed (see Figure 10). Possibly, existing samples of damped Lyα systems are subject to subtle selection effects of their own and may preferentially trace a particular stage in the evolution of

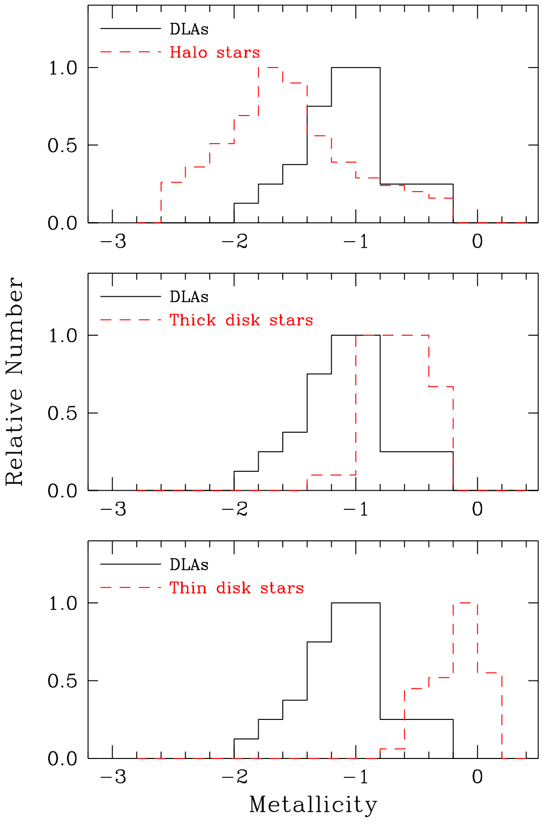

Figure 8. Metallicity distributions, normalised to unity, of DLAs at $z \simeq 2-3$ *and of stars belonging to the disk and halo populations in the Milky Way. See Pettini et al. (1997) for references to the sources of data and further details.*

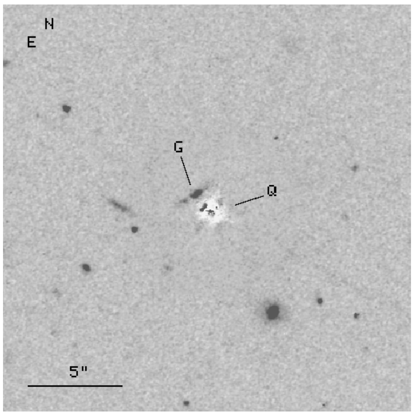

Figure 9. (Reproduced from Pettini et al. 2000a). WFPC2 F702W exposure of the field of Q0058+019 (PHL 938). A model point spread function has been subtracted from the QSO image, revealing the presence of a galaxy approximately 1.2 arcseconds to the NE of the QSO position. Given its proximity, this is likely to be the damped Lyα *absorber at* $z = 0.61251$*. Residual excess absorption of a diffraction spike cuts across the galaxy image. When this processing artifact is taken into account, the candidate absorber appears to be a low luminosity* ($L \simeq 1/6\,L^*$) *late-type galaxy seen at high inclination,* $i \approx 65°$*, at a projected separation of* $8\ h_{70}^{-1}$ *kpc from the QSO sight-line.*

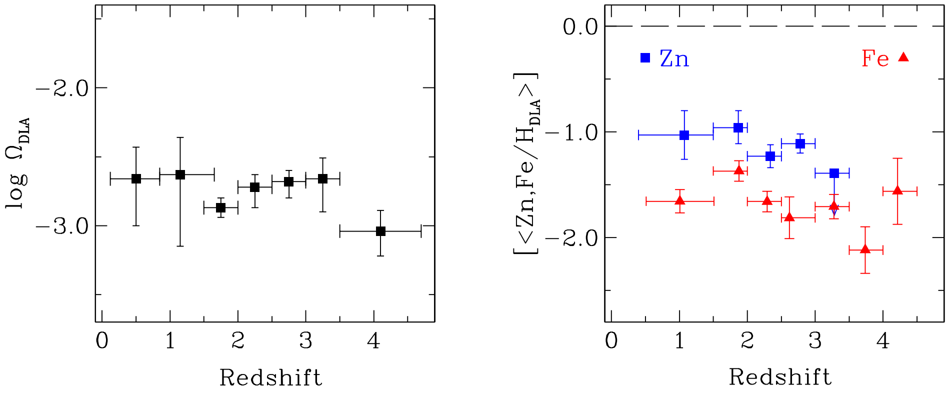

Figure 10. (Lack of) redshift evolution in the comoving mass density (left) and metallicity (right) of damped Ly α systems. The data points in the left-hand plot are from Rao & Turnshek (2000) for $H_0 = 65$ km s^{-1} Mpc^{-1}, $\Omega = 1$; those in the right-hand plot are from Pettini et al. (1999) for Zn, and from Prochaska, Gawiser, & Wolfe (2001) for Fe.

galaxies, when the gas has an extended distribution and only moderate surface density, and the metal—and therefore dust—content is low.

The extent to which dust biases our view of the distant universe has for a long time been a concern of UV-optical astronomers and the hobby-horse of the IR community who makes up most of the audience today! One thing is clear: galaxies with sufficiently high column densities of gas and dust to render any QSO behind them unaccessible to optical spectroscopy undoubtedly exist—quite a few are known for example from their CO emission (e.g. Wiklind & Combes 1999). What is not known is the impact which such objects would have on the overall census of baryons and metals shown in Figure 10, if they could somehow be included in the surveys in an unbiased fashion.

The key to answering this question may well be provided by the *FIRST* mission which, for the first time, will provide the means to probe DLA galaxies free from the selection effects inherent in all optical-UV surveys. As an example, I consider here the possibility of detecting [C II] 158 μm emission associated with damped absorbers.

This transition is familiar to many of the participants of this meeting as it has been studied extensively in the local universe with a variety of astronomical facilities, including *KAO* and *ISO* (e.g. Madden et al. 1997; Malhotra et al. 1999). What may not be so widely appreciated is that *absorption* from the energy level from which this line originates—the $^2P_{1/2}$ fine structure level of the ground state of singly ionised carbon—has already been detected in many DLAs in the 1335.7 Å UV line (e.g. Lu, Sargent, & Barlow 1999; Prochaska & Wolfe 1999). Thus, we have a reasonably good idea of the relative population of this level which in turn can be used to deduce cooling and (by inference) heating and star-formation rates in the host galaxies of DLAs. Wolfe (2001) has recently shown that at $z \gtrsim 2$ the 158 μm luminosity per H atom is some 30 times lower than in the H I disk of the Milky Way. This is probably a direct consequence of the lower abundance of C and other heavy elements at these redshifts (Figure 8), rather than a manifestation of the well-documented decline of the 158 μm luminosity with increasing dust temperature and star-formation rate in local galaxies (Malhotra et al. 1999). Thus, if there is a population of normal—but chemically evolved—DLA hosting galaxies which have been missed by optical-UV surveys, they should be accessible to the HIFI instrument on *FIRST* via the 158 μm emission line.

Specifically, the current estimate of a 5σ detection limit of 5×10^{-19} W m^{-2} at 650 GHz in one hour (de Graauw, these proceedings) implies that it should be possible to detect the integrated [C II] emission from a whole galaxy like NGC 891 ($\simeq 1.3 \times 10^8 L_\odot$ in the 158 μm line; Madden et al. 1997) out to $z \simeq 0.5$. More luminous local examples, such as NGC 6946 ($\simeq 6.3 \times 10^8 L_\odot$) could perhaps be detected at redshifts as high as $z \simeq 1$. If these expectations are met once *FIRST* flies, two types of observation immediately suggest themselves. First, it will be interesting to measure the luminosity in the 158 μm line from known, optically selected, DLAs to ascertain how typical of the whole galaxy the region (perhaps in the outer disk?) probed by the QSO sight-line is. Second, and most important, [C II] emission may be the only means at our disposal to probe physical conditions within DLAs which do *not* lie in front of background QSOs, but are discovered in blind H I 21 cm searches now being planned (e.g. Briggs 2000). In any case, it is clear that *FIRST*, by providing a 'clean' window on the interstellar media of galaxies at high redshifts, will play a crucial role in our long-term goal to piece together the chemical evolution of the universe over the Hubble time.

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