Aust. J. Phys., 1990, **43**, 227–39

Metal Enrichment, Dust and Star Formation in High-redshift Galaxies*

Max Pettini[A] *and Richard W. Hunstead*[B]

[A] Anglo-Australian Observatory, P.O. Box 296,
Epping, N.S.W. 2121, Australia.
[B] School of Physics, University of Sydney,
Sydney, N.S.W. 2006, Australia.

Abstract

QSO absorption systems exhibiting a damped Lyα line are thought to arise in the high-redshift progenitors of present-day disk galaxies. In order to clarify the evolutionary status of these absorbers and interpret the clues they provide to the process of galaxy formation in general, we have begun a programme of spectroscopic observations targeted at measuring their element abundances, dust concentration and star-formation rates. Abundance studies in the local interstellar medium (ISM) have identified Zn as a highly convenient species for surveying the overall level of metallicity of the damped systems, while a qualitative indication of the dust content can be obtained by consideration of the Zn-to-Cr ratio since, unlike Zn, Cr is readily bound to interstellar grains. In some favourable cases, higher-resolution observations of selected lines can provide additional information on abundance ratios of individual elements. Lastly, searches for weak emission in the black core of the damped Lyα absorption line have so far provided the most stringent limits on the Lyα luminosity of these supposedly young galaxies, and in one case led to a positive detection. The results obtained so far suggest that the damped Lyα galaxies are indeed at an early phase of chemical evolution, with metal abundances 1 to 2 orders of magnitude below solar and with perhaps only 1/10 of the dust content of the local ISM. Lyα fluxes are well below the predictions of many theoretical models, and star-formation rates $< 10\ M_{\odot}\ \mathrm{yr}^{-1}$ seem to be typical. These properties are similar to those of present-day H II galaxies of which the Lyα systems may therefore be high-redshift examples.

1. Introduction

The absorption lines evident in the spectra of all high-redshift QSOs can be broadly divided into two categories: the Lyman α forest, generally thought to arise in a population of intergalactic, primordial hydrogen clouds, and the metal line systems presumably formed in intervening galaxies. A subset of this second class of absorbers which has received much attention in the last few years is generally referred to as the "damped Lyα systems". These are systems with a sufficiently high column density of neutral hydrogen, $N(\mathrm{H\ I}) \geq 2\times10^{20}\ \mathrm{cm}^{-2}$, for the corresponding Lyα line to show well-developed damping wings and be easily recognised by its strength even in low resolution spectra.

* Paper presented at the joint Australia–USSR workshop on the Early Universe and the Formation of Galaxies held at Mount Stromlo Observatory, 28–29 June 1989.

0004-9506/90/020227$03.00

Surveys of the damped Lyα systems, principally by Wolfe and collaborators (see Wolfe 1988 for a review), have revealed two important properties. First, although they are relatively rare, $dN_{damp}/dz \simeq 0.3$ at $< z_{abs} > \simeq 2.4$, the mean column density of the damped systems is so high, $<N(\text{H I})> = 1 \times 10^{21}$ cm^{-2}, that they probably account for more mass than any other class of QSO absorber. Expressed in terms of the closure density, $\Omega_{damp} \simeq 2 \times 10^{-3}$ h^{-1}, where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}, this is comparable with the mass residing in the luminous disks of present-day spiral galaxies. Second, their frequency of occurrence along a random sight-line is ~5 times higher than expected from the known cross sections in H I of nearby disk galaxies. Mainly on the basis of these considerations, Wolfe and collaborators proposed that in the damped Lyα systems we are seeing the *progenitors* of present-day disk galaxies, at a time when they were still undergoing gravitational collapse and most of their baryonic mass resided in the interstellar medium (ISM).

While this is now a widely accepted interpretation, it is important to remember that a damped Lyα line is not in itself indicative of the *morphology* of the galaxy producing the absorption and that many of the observational properties of the damped systems are also consistent with an origin in dwarf galaxies, for example (Tyson 1988).

In order to clarify the nature of the high-redshift galaxies producing the damped Lyα lines, and thereby throw light on the process of galaxy formation in general, we have begun a programme of observations aimed at determining three key properties of these systems: the chemical composition, dust content and star-formation rate. We briefly describe the observational techniques employed to these ends, before reviewing the initial results of our programme. More detailed discussions of these issues are given in two papers now in press with the *Astrophysical Journal* (Pettini *et al.* 1990; Hunstead *et al.* 1990).

(a) Element Abundances

A knowledge of how far metal enrichment through stellar nucleosynthesis has progressed in the damped Lyα galaxies would undoubtedly be a major clue to their evolutionary status. In principle, abundance measurements in H I regions of the ISM are straightforward, since one observes the resonance lines of the favoured ionisation stages of elements of interest, thereby avoiding to a large extent the need to model the ionisation and excitation state of the gas, as is the case in stellar abundance work. In practice, however, two difficulties often complicate the derivation of accurate abundances (Pettini 1985; Jenkins 1987). First, in the local ISM it is found that most elements are present in the gas phase with only a fraction of their solar abundance, the "missing" atoms and ions having condensed into interstellar grains; for many of the astrophysically important elements the degree of depletion can be both large and variable, depending on the previous history of the gas. Secondly, for $N(\text{H I}) = 2.0 \times 10^{20}$ cm^{-2}, the commonly observed absorption lines of the most abundant species are so strongly saturated that the values of column density deduced from the line equivalent widths—and therefore the corresponding element abundances—can easily be in error by ~2 orders of magnitude.

These difficulties can be largely circumvented by targeting the abundance measurements to the weak Zn II doublet at $\lambda\lambda$2025,2062, for the following reasons: (*i*) Zn is among the few elements which are *not* depleted onto interstellar grains and are present in the gas-phase in near-solar proportions. This result is empirically well-established after extensive interstellar abundance surveys with the *Copernicus* and *IUE* satellites (e.g. Van Steenberg and Shull 1988). (*ii*) The solar abundance of Zn is sufficiently low, $(\mathrm{Zn/H})_{\odot} = (3.8 \pm 0.7) \times 10^{-9}$ (Aller 1987), that the Zn II doublet lines are unlikely to be heavily saturated, even at the high hydrogen column densities of the damped Lyα systems. In any case, the doublet nature of the transition, with the λ2062 line being intrinsically half as strong as the λ2025 line ($f = 0.202$ and 0.412 respectively; Morton *et al.* 1988), can help considerably in assessing the degree of line saturation. The additional considerations that: (*iii*) the abundance of Zn tracks closely that of Fe over a wide range of metallicities (Wheeler *et al.* 1989); (*iv*) in interstellar H I regions Zn is predominantly singly ionised and (*v*) at the redshifts of most of the known damped Lyα systems, $z \simeq 2 - 3.5$, the Zn II lines are redshifted into a convenient region of the optical spectrum, all reinforce the conclusion that the search for Zn II absorption associated with the damped Lyα systems is one of the most promising avenues for measuring the degree of metal enrichment in these high-redshift galaxies.

(b) Dust Content

The detection of a dust signature in QSO spectra has eluded astronomers for over fifteen years (e.g. McKee and Petrosian 1974). The damped Lyα systems are excellent candidates for locating dust at high redshifts because of the high column densities of interstellar matter involved. In the nearby ISM reddening due to dust is proportional to the column density of neutral hydrogen (in both atomic and molecular forms), with an average ratio $N(\mathrm{H})/E(B-V) = 5.2 \times 10^{21}$ cm^{-2} mag^{-1} (Shull and Van Steenberg 1985), so that at the mean $< N(\mathrm{H\ I}) > = 1 \times 10^{21}$ cm^{-2} of the damped systems we would expect both a considerable steepening of the intrinsic QSO spectrum and a pronounced 2175 Å bump, if high-redshift dust has similar properties to those of Galactic dust (Massa and Savage 1989). The difficulty here is that we have only an approximate idea of the intrinsic spectral distribution of any *individual* QSO; the problem is therefore best approached in a statistical way, by testing for differences in the spectral slope of the continuum between two samples of QSOs, respectively with and without damped systems. Reasoning along these lines, Fall *et al.* (1989) concluded that damped Lyα galaxies have *on average* a gas-to-dust ratio one-tenth of the local value, and an extinction curve lacking the distinctive 2175 Å bump produced by Milky Way dust and, in this sense, more akin to the extinction curves of the Magellanic Clouds.

The approach we have adopted in attempting to measure the dust content of the damped Lyα systems is to search for weak absorption lines of Cr II at $\lambda\lambda$2055, 2061, 2065 which fortuitously occur close to the Zn II doublet discussed above. Unlike Zn, Cr is among the most severely depleted elements in the local ISM, with only ~1% of the solar abundance present in gaseous form (e.g. Jenkins 1989). Thus, while Zn II/H I is a direct measure of the degree of metal enrichment, Zn II/Cr II depends on the level of depletion of refractory elements and therefore provides an indication of the dust content. Although this is of necessity a qualitative estimate, as there is no simple way to relate the degree of depletion of Cr to an extinction parameter such as $E(B-V)$, it is at least an estimate appropriate to an individual damped system—rather than a whole sample—and can thus be related to other properties of the system under study.

(c) Star-formation Rates

If the damped Lyα galaxies are in early stages of evolution, they may be undergoing an initial burst of star formation, characterised by high luminosity in the UV continuum and particularly in Lyα emission. Consequently, considerable effort has been devoted recently to searching for Lyα emission from damped systems. Two complementary methods have been used in pursuit of this goal; both take advantage of the fact that the QSO light is completely extinguished in the core of the damped absorption line. One approach is to record the QSO field through narrow-band interference filters centred at the wavelength of the Lyα absorption and look for faint images close to the QSO sight-line; the other uses spatially resolved, intermediate dispersion spectroscopy to search for weak Lyα emission close to the absorption redshift. Of these two methods, the first has been pursued more extensively (Smith *et al.* 1989 and references therein), possibly because it is the more direct and offers, at least in principle, the means to determine the morphology of the absorbing galaxies. However, no detection has been reported to date from imaging surveys by several groups (see Hunstead *et al.* 1990 for a review), indicating that the damped Lyα systems are overall weak Lyα emitters, with luminosities $L(\mathrm{Ly}\alpha) \lesssim 10^{42} - 10^{43}$ erg s^{-1} ($H_0 = 50$ km s^{-1}, $q_0 = 0.5$). These imaging attempts have also shown that the technical difficulties in matching precisely the filter characteristics to the properties of individual damped Lyα lines are not trivial (Smith *et al.* 1988, 1989). On the other hand, the spectroscopic approach—which is the one we have adopted—while reaching to fainter flux limits, has so far given only incomplete information on the extent and morphology of these distant galaxies, as discussed below. A detailed comparison of the relative merits of different techniques which have been applied to the search for high redshift Lyα emission is given by Hunstead *et al.*

2. Results

(a) The Zn II and Cr II Survey

This survey is only just underway, but the initial results are very encouraging. The first observations were conducted with the Double Spectrograph on the 5 m Hale Telescope at Palomar Observatory, in collaboration with Alec Boksenberg, and were successful in detecting weak lines of Zn II and Cr II in the $z_{abs} = 2.3091$ system in the bright ($V = 16.57$) QSO PHL 957. The discovery spectrum (this was the first unequivocal detection of Zn II in a QSO absorption spectrum) is reproduced in Fig. 1; the high signal-to-noise ratio (S/N) achieved corresponds to a 3σ detection limit of only $W_0 = 20$ mÅ for the rest frame equivalent width of an unresolved absorption line.

The weak Zn II and Cr II lines detected define the column densities of these ions with an error of $\sim \pm 10\%$; combining these values with the equally well determined $N(\mathrm{H\ I}) = (2.5 \pm 0.3) \times 10^{21}$ cm^{-2} from the profile of the damped

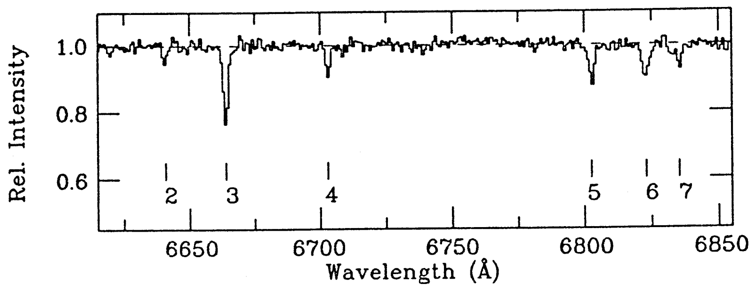

Fig. 1. Portion of the normalised Palomar spectrum of PHL 957, encompassing the Zn II and Cr II absorption lines in the $z_{abs} = 2.3091$ system. Line 4 is Zn II λ2025.5, while lines 5 and 7 are Cr II λ2055.6 and λ2065.5, respectively. Line 6 is a partially resolved blend of Cr II λ2061.5 and Zn II λ2062.0, while lines 2 and 3 are Fe II lines in a different absorption system, at $z_{abs} = 1.7975$. The resolution of these data is FWHM= 84 km s^{-1} and the S/N = 90.

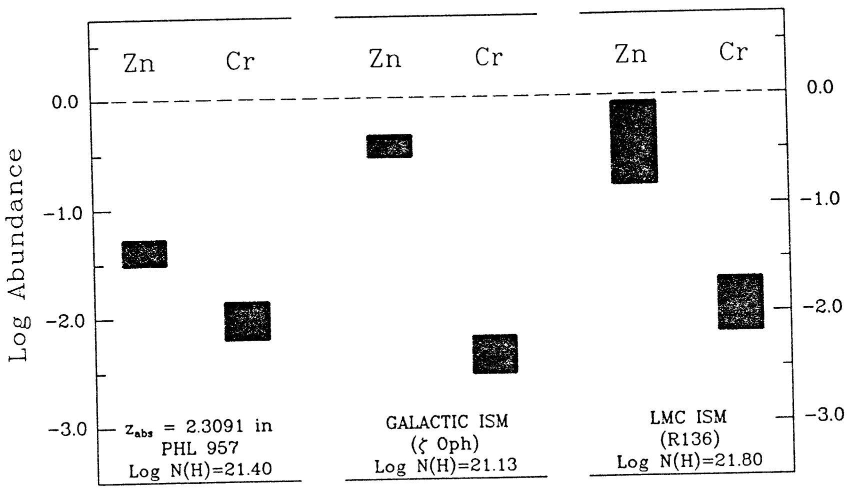

Fig. 2. The abundances of Zn and Cr in the $z_{abs} = 2.3091$ system in PHL 957 are compared with the values measured in diffuse interstellar clouds in the solar neighbourhood and in the Large Magellanic Cloud. The height of each box reflects the range of uncertainty in the measurements. The broken line at 0.0 corresponds to solar abundances.

Lyα line (see below) and with the upper limit for the column density of molecular hydrogen $N(H_2) \leq 5 \times 10^{15}$ cm^{-2} reported by Black *et al.* (1987), we deduce Zn and Cr abundances of 1.6 and 5.9 $\times 10^{-9}$ respectively. Comparison with the corresponding abundances in the Sun shows that Zn and Cr are underabundant by factors of ~24 and ~100 respectively. These results are illustrated in Fig. 2, where the abundances of the two elements in the high redshift galaxy presumed to give rise to the $z_{abs} = 2.3091$ system in PHL 957 are compared with representative values for interstellar clouds in the Milky Way and the Large Magellanic Cloud. Note that all three sight-lines sample similar column densities of gas.

Two conclusions can be readily drawn from inspection of Fig. 2. First, the galaxy at $z = 2.3091$ is genuinely metal-poor, with a Zn abundance ~24 times below solar and ~10 times lower than in the ISM of the Galaxy and the LMC. Second, the depletion of Cr is far less severe than in local interstellar gas, since Cr is overdeficient relative to Zn by only a factor of ~4, rather than by ~2 orders of magnitude, as is typically the case in local diffuse interstellar clouds. Presumably less Cr is hidden in solid form, consistent with the low average dust-to-gas ratio for the damped Lyα systems deduced by Fall *et al.* (1989). Both the low metal abundance and reduced dust content strongly suggest that this galaxy is at an early stage of chemical evolution and may have undergone perhaps only a few gas-star cycles.

The absence of significant amounts of dust in high-redshift galaxies is of relevance to several problems, including the measurement of abundance ratios as a function of metallicity for a wide range of elements (as discussed in Section 1*a*), the quenching of Lyα emission in primeval galaxies (see Section 2*c*), and the visibility of QSOs at very high redshifts (Boissé and Bergeron 1988; Heisler and Ostriker 1988). Here we point out that lower concentrations of dust may also help to explain the finding that molecular hydrogen and neutral carbon are generally weak or absent in QSO absorption line systems, including the damped Lyα sample (e.g. Black *et al.* 1987; Foltz *et al.* 1988; Chaffee *et al.* 1988; Lanzetta *et al.* 1989). In diffuse interstellar clouds, dust is an essential catalyst for the production of H_2 and an important ingredient regulating the ionisation balance of C through shielding of far-UV photons.

(b) Results from Echelle Spectroscopy

While observations of the Zn II and Cr II lines allow us to survey the degree of chemical evolution of high-redshift galaxies on a reasonably large scale (some 30 damped Lyα systems at $z = 2-3.5$ are currently known to be accessible to this work), higher resolution observations of selected systems in the brightest QSOs in the sample can, in some circumstances, provide information on the relative abundances of a wider selection of elements. An example is provided by our recent work on the QSO 2206−199*N* using the new echelle spectrograph at the coudé focus of the Anglo-Australian Telescope (AAT). The data, which cover ~630 Å of the QSO spectrum between 3730 and 4360 Å with a resolving power $\lambda/\Delta\lambda = 45000$ (corresponding to 6.7 km s^{-1} FWHM), were obtained with the primary aim of resolving the intrinsic profiles of absorption lines in the Lyα forest, as discussed in an accompanying paper (Hunstead and Pettini 1990, present issue p. 211). However, the spectral region recorded also includes several metal lines in two damped systems, at $z_{abs} = 1.92050$ and 2.07623 respectively. Although these have been known for a number of years, the resolution of the echelle data, which is exceptionally high for QSO absorption line work, has produced exciting new results for both systems.

First of all, we note that while the two absorbers in 2206 − 199*N* have similar hydrogen column densities, N(H I) = (4.5 ± 0.8) and $(3.0 \pm 0.5) \times 10^{20}$ cm^{-2} respectively (measured by fitting the damping wings of the corresponding Lyα lines), they differ remarkably in the strengths of the metal lines, as demonstrated vividly by Fig. 3. The lines in the $z_{abs} = 2.07623$ system are so

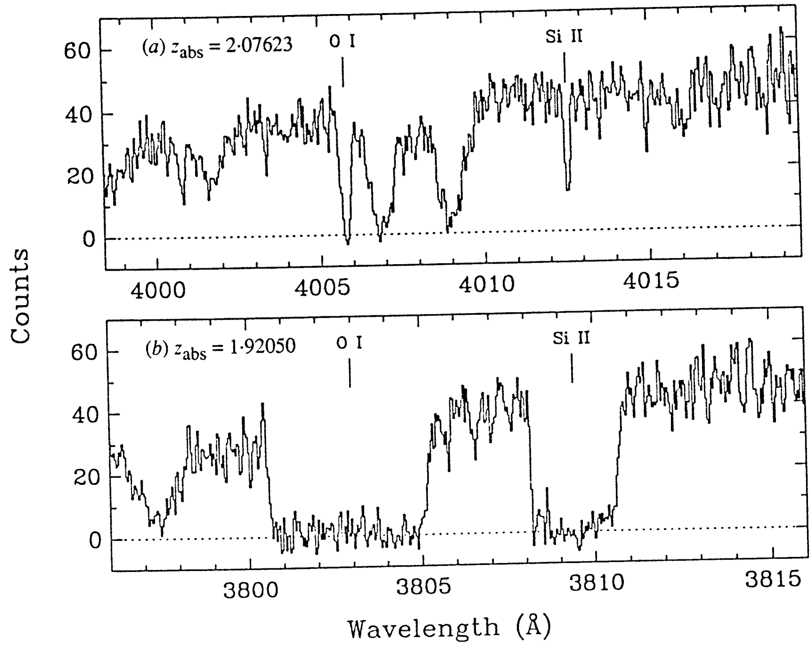

Fig. 3. Comparison of portions of the AAT echelle spectrum of 2206 – 199*N* encompassing the O I λ1302.2 and Si II λ1304.4 absorption lines in the two damped Lyα systems at (*a*) $z_{abs} = 2.07623$ and (*b*) 1.92050. Unlabelled absorption lines are members of the Lyα forest.

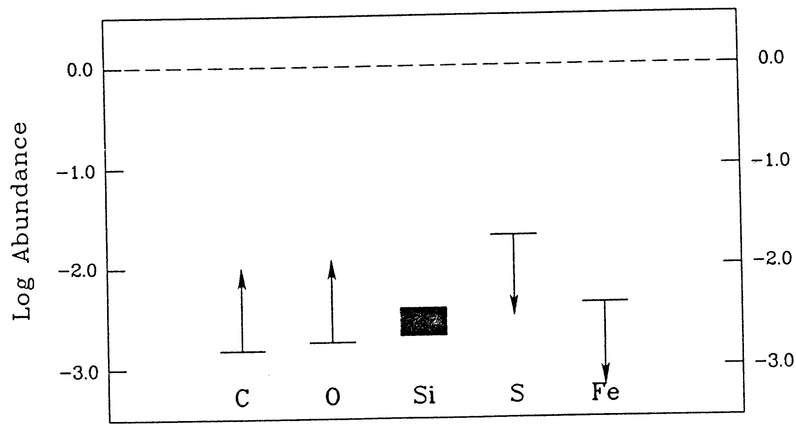

Fig. 4. Abundances relative to hydrogen of selected elements in the $z_{abs} = 2.07623$ system in 2206 – 199*N*. The symbols have the same meaning as in Fig. 2.

weak—as already noted by Robertson *et al.* (1983)—that for many transitions uncertainties due to line saturation are alleviated. Fig. 4 illustrates the pattern of element abundances deduced. The values for C and O are *lower* limits, since the two lines observed—C II λ1334 and O I λ1302—are saturated; the abundance of Si is tightly constrained by the well-resolved Si II λ1304 and

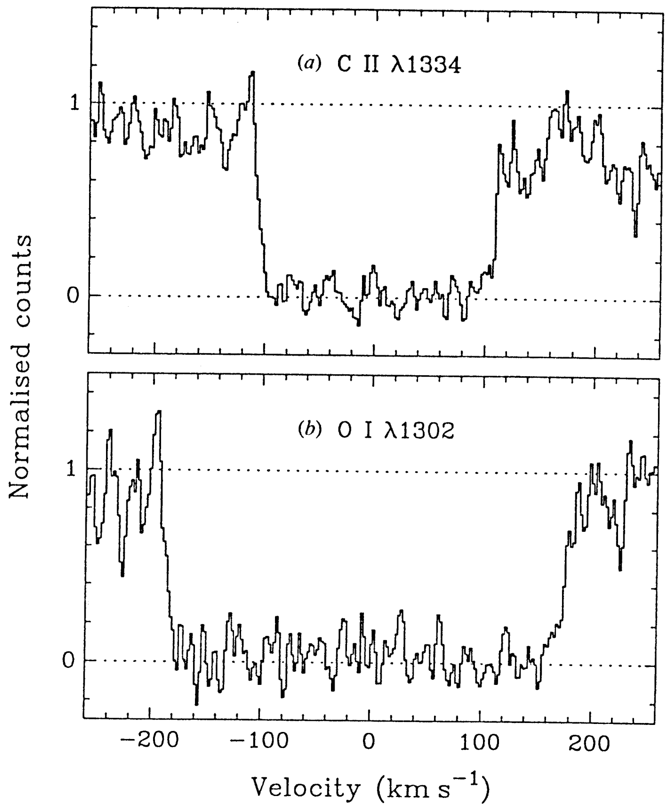

Fig. 5. Comparison of the high-resolution profiles of absorption lines of (*a*) C II and (*b*) O I in the $z_{abs} = 1.92050$ system in 2206−199*N*.

λ1260.4 lines; and the *upper* limits on S and Fe are derived from the fact that S II λ1259 and Fe II λ1260.5 are below our detection limit. The striking conclusion is that the gas at $z_{abs} = 2.07623$ is extremely metal poor, with element abundances at least two orders of magnitude below solar.

By contrast, most of the absorption lines in the $z_{abs} = 1.92050$ system have wide, saturated profiles, with black cores and steep sides (see Fig. 3). Such profiles most likely result from a *combination* of more complex velocity structure *and* higher abundances than the $z_{abs} = 2.07623$ system, and cannot be used to measure the metallicity of the gas. Nevertheless, detailed comparison of the profiles of C II λ1334 and O I λ1302—shown in Fig. 5—indicates that at least *some* of the gas associated with the $z_{abs} = 1.92050$ system appears to be at an early stage of chemical evolution. As can be seen from Fig. 5, the two lines are centred at the same redshift, but O I λ1302 extends ~80 km s^{-1} further to the blue and to the red than C II λ1334. This is most plausibly interpreted as an abundance effect since, for a given *N*(H I) and solar relative abundances, the product $Nf\lambda$ (where *N* is the ion column density, *f* the oscillator strength and λ the wavelength of the transition) is *greater* for C II λ1334 than for O I λ1302 by a factor of 1.4. Furthermore, differences in the relative ionisation fractions of C and O cannot explain the lack of C II absorption, since: (a) no C I absorption is present at the relevant velocities, and (b) any contribution from ionised gas would favour C II over O I. Thus, it is difficult to escape the conclusion that in the velocity ranges $v = -200$ to -120 and $+110$ to $+190$ km s^{-1}, relative to $z_{abs} = 1.92050$, O is overabundant with respect to C; conservatively we estimate [O/C] $\gtrsim +1$.

This abundance anomaly is particularly suggestive because it is in the same sense as expected for gas in the initial stages of chemical enrichment, dominated by the nucleosynthetic products of the most massive stars. A similar, but less pronounced, overabundance of O is seen in old Galactic stars, where [O/Fe] $\simeq 0.5$ for [Fe/H] $\lesssim -1$ (Wheeler *et al.* 1989). Some puzzling features remain, however. First, current models for the yields of massive stars (e.g. Arnett 1978) predict overabundances of O relative to C as high as one order of magnitude only from stars with $M > 100\ M_{\odot}$. These stars evolve on time-scales only a factor of ~2 shorter than those of stars with $M \simeq 25 M_{\odot}$ (Maeder and Meynet 1987) which in Arnett's model release C and O in essentially solar relative proportions. Thus, we need to invoke an initial mass function (IMF) much more heavily biased towards massive stars than that of gas of solar composition, unless by chance we are observing the gas during a very brief period early on in its chemical history. A metallicity-dependent IMF has been proposed by a number of workers (e.g. Melnick 1987), but it remains to be seen how extreme an effect is required to explain an overabundance of oxygen by a factor of 10. Second, we have no way of determining from the absorption line data the physical location of the high-velocity, oxygen-rich gas relative to the rest of the material producing the $z_{abs} = 1.92050$ system. It is interesting to speculate that we may be seeing a galaxy accreting outlying material which is undergoing an initial burst of star formation, dominated by very massive stars.

(c) Lyα Emission

In Fig. 6 we have reproduced two examples of damped Lyα lines recorded with the RGO spectrograph at the Cassegrain focus of the AAT. The dark sky of Siding Spring observatory and the availability of the IPCS, a two-dimensional photon counting detector of zero read-out noise and negligible dark count, form a potent combination for searching for weak emission in the black core of the Lyα absorption line. Crucial to this is the ability to record the sky background at high signal-to-noise ratio and thereby minimise the noise in the sky-subtracted signal in the core of the line. Fig. 6*b* gives an indication of the typical accuracy that can be achieved at the AAT with careful observing and data reduction methods. In the case of PHL 957 we are able to place an upper limit of 4.5×10^{-17} erg s^{-1} cm^{-2} $arcsec^{-2}$ to the surface brightness in Lyα of the galaxy producing the $z_{abs} = 2.3091$ system, a factor of ~2 lower than previous limits. The corresponding Lyα luminosity is $L(\mathrm{Ly}\alpha) \leq 3.5 \times 10^{42}$ erg s^{-1} ($H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$).

In the QSO 0836+113, on the other hand, a clear, narrow emission line is detected centred on the damped Lyα absorption at $z_{abs} = 2.4652$. The feature is significant at the $4.0-4.5\ \sigma$ level, is not an artifact caused by detector defects or poor sky subtraction (the sky spectrum is relatively smooth in this region), and is unlikely to be a gap between two Lyα absorption components, since no

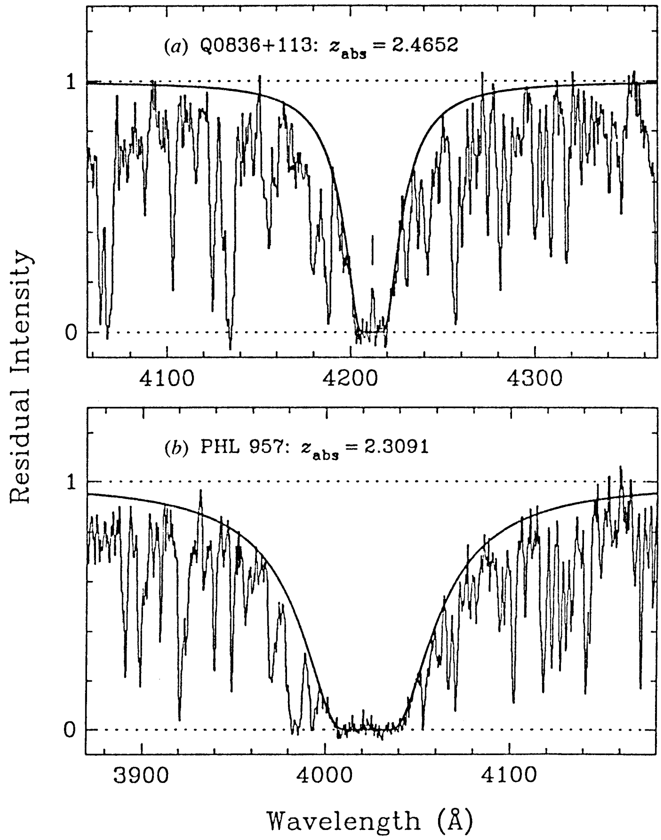

Fig. 6. Examples of the profiles of damped Lyα lines recorded at the AAT with a resolution of ~1.5 Å FWHM. Superposed on the data are the theoretical damping profiles for column densities (*a*) N(H I) = 4.2×10^{20} cm^{-2} and (*b*) 25×10^{20} cm^{-2}. The narrow emission in the base of the damped absorption line in Q0836+113 is marked.

corresponding gap is seen in Lyβ nor in any of the metal lines in this system. Our conclusion is that we have detected—for the first time—Lyα emission associated with a damped system. Of course, emission and absorption need not originate from the same region and, in fact, most likely refer to different sight-lines through the galaxy lying in front of 0836+113.

In Table 1 we have summarised the most important properties of the Lyα emission discovered. It is remarkable to find that the emission region is no larger than our spatial resolution on the sky (1.2×2.2 arcsec, corresponding to 9×17 kpc at $z = 2.465$) and is closely aligned, spatially with the background QSO and spectrally with the absorption system. Together with the narrow width of the line, these properties are highly suggestive of an origin in a dwarf galaxy, rather than the extended (~100 kpc) disks generally identified with the damped Lyα systems. While it could be argued that we are seeing a single, "naked" H II region which may be part of a much larger "disk"

Table 1. Properties of the $z_{abs} = 2 \cdot 465$ system

Parameter	Value
Absorption system:	
$\bar{z}_{abs}$ (metal lines)	$2 \cdot 4652 \pm 0 \cdot 0002$
$\bar{z}_{abs}$ (Lyα profile fit)	$2 \cdot 4651 \pm 0 \cdot 0003$
N(H I)	$(4 \cdot 2 \pm 0 \cdot 6) \times 10^{20}$ cm^{-2}
Lyα emission:	
z_{em}	$2 \cdot 4654 \pm 0 \cdot 0001$
Δv $(em - abs)$	25 ± 30 km s^{-1}
Line flux	$2 \cdot 9 \times 10^{-17}$ erg s^{-1} cm^{-2}
Line luminosity[A]	$1 \cdot 2 \times 10^{42}$ erg s^{-1}
Surface brightness	$1 \cdot 1 \times 10^{-17}$ erg s^{-1} cm^{-2} arcsec^{-2}
Linewidth	$\leq 60^{B}$ km s^{-1} FWHM
Emission region[A]	$<9 \times 17$ kpc

[A] Calculated for $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0 \cdot 5$.
[B] Instrumental resolution was 98 km s^{-1} FWHM.

system, it would be highly fortuitous, under these circumstances, to find such close coincidence between the absorption sight-line and the only H II region detected—at least along the direction sampled by the spectrograph slit.

There are in fact several similarities between the emission properties of the putative galaxy at $z = 2.465$ and the nearby dwarf irregular galaxies which are currently in an active phase of star formation (the H II galaxies described, for example, by Terlevich 1987). First, the total Lyα luminosity, L(Lyα) = 1.2×10^{42} erg s^{-1}, is within the range of values ($1.4 \times 10^{41} - 1.8 \times 10^{42}$ erg s^{-1}) measured for H II galaxies with *IUE* (Hartmann *et al.* 1988 and references therein), as is the lower limit $W_0 \geq 10$ Å for the equivalent width of the emission line, deduced from the lack of a measurable continuum underlying the feature. Second, the value of Hβ luminosity, derived assuming no dust and case B recombination, and the upper limit on the width of the line, which is unresolved in our data, fall close to the well-defined $L : \sigma$ trend for giant H II regions and H II galaxies (Terlevich 1987).

Lyα emission is usually weak in H II galaxies, well below the level expected from the Balmer lines and simple recombination theory. A possible explanation is quenching of Lyα by dust, enhanced by the multiple scattering a Lyα photon undergoes before escaping the H II region. This interpretation is supported by a trend for the Lyα-to-Hβ ratio to increase with *decreasing* metallicity, but the issue is far from settled (Hartmann *et al.* 1988). In the case of the emission at $z = 2.4654$, the small line width implies a very low column density of neutral hydrogen in front of the H II region, N(H I) $\leq 2 \times 10^{17}$ cm^{-2} (Neufeld and McKee 1988), and consequently negligible amounts of dust. Thus, we may be seeing the full, unobscured, Lyα luminosity of this high-redshift H II region. The corresponding Hα luminosity—$L(H\alpha) = 1.2 \times 10^{41}$ erg s^{-1}—and star-formation rate—SFR $\simeq 1 M_{\odot}$ yr^{-1} based on a Miller-Scalo initial mass function—are comparable with the values typical of present-day spirals and near the upper limits found for single, giant H II regions (Kennicutt and Kent 1983; Kennicutt *et al.* 1989).

Finally, we stress that the level at which we have detected Lyα emission at $z = 2.4654$ is entirely consistent with the null results obtained in previous searches, both with spectroscopy and direct imaging, in damped Lyα systems and in blank fields (Hunstead *et al.* 1990). The positive detection in 0836+113 stems in large part from the fact that the basic sampling volume of the observations, that is seeing disk×resolution, was (serendipitously) well-matched to the extent and velocity dispersion of the emitting region. Thus, all the data obtained so far, including detection and upper limits, support the view that the damped Lyα galaxies are *not* strong Lyα emitters. While attenuation by a mixture of dust and neutral hydrogen remains a possibility, the likely deficiency of dust in these high-redshift galaxies raises the same doubts on the validity of this interpretation as already voiced for nearby H II galaxies (e.g. Terlevich 1987). Possibly star formation in young disk galaxies is an episodic event with a low duty cycle, or the initial star-burst phase predicted by several models of galaxy formation is very short-lived.

3. Conclusions and Future Prospects

Our survey of the damped Lyα systems is still in its initial stages and it is premature to make general conclusions on their properties and evolutionary status. However, the results obtained so far—which are broadly in agreement with those of similar investigations by other workers (Meyer *et al.* 1989; Rauch *et al.* 1990)—are beginning to build a picture of a population of galaxies in an early phase of chemical evolution with metallicities mostly between 1 and 2 orders of magnitude below solar. In one case we find evidence of a large excess of oxygen relative to carbon, as may be produced by an initial burst of star formation, dominated by very massive stars. Dust is also less abundant in these high-redshift galaxies than in the disks of nearby spirals and typical star-formation rates seem to be below 10 $M_\odot$ yr^{-1}. Taken together, these properties are strikingly similar to those of present-day H II galaxies. From this we may conclude that disk galaxies were forming shortly before $z \simeq 2-3$ and that in the damped Lyα systems we see them early on in their star-formation history, when they resembled in several ways the lower-mass H II galaxies which are actively forming stars now. Alternatively, the whole damped Lyα sample may be dominated by dwarf galaxies, which according to some authors may be far more numerous than generally realised (see for example the discussion of this point by Impey and Bothun 1989). In this case, the properties of this population of galaxies need not have changed much over the last ~10 Gyr.

The prospects for making significant progress on these issues are very promising, now that we have learnt which observations are most effective. In the next few years it will be possible to get a broad picture of the *spread* of chemical abundances at $z = 2-3$, and perhaps gain an indication of its rate of change with redshift, particularly as more QSOs are discovered at $z > 4$ and as damped Lyα systems at low redshifts ($z < 1.5$) are identified with the Hubble Space Telescope. While at present the chronology of galactic chemical evolution is based primarily on the record provided by different stellar populations in our Galaxy—and the interpretation of this record is far from straightforward (Wheeler *et al.* 1989)—spectroscopy of the damped Lyα systems offers the exciting possibility of observing *directly* the process of metal enrichment in action over time-scales comparable with those of the oldest stars.

References

Aller, L.H. (1987). *In* 'Spectroscopy of Astrophysical Plasmas' (Eds A. Dalgarno and D. Layzer), p. 89 (Cambridge Univ. Press).

Arnett, W.D. (1978). *Astrophys. J.* **219**, 1008.

Black, J.H., Chaffee, F.H., and Foltz, C.B. (1987). *Astrophys. J.* **317**, 442.

Boissé, P., and Bergeron, J. (1988). *Astron. Astrophys.* **192**, 1.

Chaffee, F.H., Black, J.H., and Foltz, C.B. (1988). *Astrophys. J.* **335**, 584.

Fall, S.M., Pei, Y.C., and McMahon, R. (1989). *Astrophys. J. Lett.* **341**, L5.

Foltz, C.B., Chaffee, F.H., and Black, J.H. (1988). *Astrophys. J.* **324**, 267.

Hartmann, L.W., Huchra, J.P., Geller, M.J., O'Brien, P., and Wilson, R. (1988). *Astrophys. J.* **326**, 101.

Heisler, J., and Ostriker, J.P. (1988). *Astrophys. J.* **332**, 543.

Hunstead, R.W., and Pettini, M. (1990). *Aust. J. Phys.* **43**, 211.

Hunstead, R.W., Pettini, M., and Fletcher, A. (1990). *Astrophys. J.* (in press).

Impey, C., and Bothun, G. (1989). *Astrophys. J.* **341**, 89.

Jenkins, E.B. (1987). *In* 'Interstellar Processes' (Eds D.J. Hollenbach and H.A. Thronson), p. 533 (Reidel: Dordrecht).

Jenkins, E.B. (1989). IAU Symp. No. 135: *Interstellar Dust*, p. 23 (Kluwer: Dordrecht).

Kennicutt, R.C., Edgar, B.K., and Hodge, P.W. (1989). *Astrophys. J.* **337**, 761.

Kennicutt, R.C., and Kent, S.M. (1983). *Astron. J.* **88**, 1094.

Lanzetta, K.H., Wolfe, A.M., and Turnshek, D.A. (1989). *Astrophys. J.* **344**, 277.

McKee, C.F., and Petrosian, V. (1974). *Astrophys. J.* **189**, 17.

Maeder, A., and Meynet, G. (1987). *Astron. Astrophys.* **182**, 243.

Massa, D., and Savage, B.D. (1989). IAU Symp. No. 135: *Interstellar Dust*, p. 3 (Kluwer: Dordrecht).

Melnick, J. (1987). *In* 'Starbursts and Galaxy Evolution' (Eds T.X. Thuan, T. Montmerle and J. Tran Thanh Van), p. 215 (Ed. Frontières: Paris).

Meyer, D.M., Welty, D.E., and York, D.G. (1989). *Astrophys. J. Lett.* **343**, L37.

Morton, D.C., York, D.G., and Jenkins, E.B. (1988). *Astrophys. J. Suppl. Ser.* **68**, 449.

Neufeld, D.A., and McKee, C.F. (1988). *Astrophys. J. Lett.* **331**, L87.

Pettini, M. (1985). *In* 'Production and Distribution of C, N, O Elements' (Eds I.J. Danziger, F. Matteucci and K. Kjär), p. 355 (ESO Conference and Workshop Proceedings No. 21).

Pettini, M., Boksenberg, A., and Hunstead, R.W. (1990). *Astrophys. J.* **348**, 48.

Rauch, M., Carswell, R.F., Robertson, J.G., Shaver, P.A., and Webb, J.K. (1990). *Mon. Not. R. Astron. Soc.* **242**, 698.

Robertson, J.G., Shaver, P.A., and Carswell, R.F. (1983). *In* 'Quasars and Gravitational Lenses' (Proc. 24th Liège Astrophys. Colloq.), p. 602 (Université de Liège).

Shull, M.J., and Van Steenberg, M.E. (1985). *Astrophys. J.* **294**, 599.

Smith, H.E., Cohen, R.D., Burns, J.E., Moore, D.J., and Uchida, B.A. (1989). *Astrophys. J.* **347**, 87.

Smith, H.E., Cohen, R.D., Moore, D.J., and Uchida, B.A. (1988). *Bull. Amer. Astron. Soc.* **19**, 1106.

Terlevich, R. (1987). *In* 'High Redshift and Primeval Galaxies' (Eds J. Bergeron, D. Kunth, B. Rocca-Volmerange and J. Tran Thanh Van), p. 281 (Ed. Frontières: Paris).

Tyson, N.D. (1988). *Astrophys. J. Lett.* **329**, L57.

Van Steenberg, M.E., and Shull, J.M. (1988). *Astrophys. J.* **330**, 942.

Wheeler, J.C., Sneden, C., and Truran, J.W. (1989). *Ann. Rev. Astron. Astrophys.* **27**, 279.

Wolfe, A.M. (1988). *In* 'QSO Absorption Lines: Probing the Universe' (Eds J.C. Blades, D.A. Turnshek and C.A. Norman), p. 297 (Cambridge Univ. Press).

Manuscript received 11 December 1989, accepted 13 February 1990