THE ASTROPHYSICAL JOURNAL, 348:48–56, 1990 January 1

METAL ENRICHMENT, DUST, AND STAR FORMATION IN GALAXIES AT HIGH REDSHIFTS. I. THE $z = 2.3091$ ABSORBER TOWARD PHL 957

MAX PETTINI[1]
Anglo-Australian Observatory
ALEC BOKSENBERG
Royal Greenwich Observatory
AND
RICHARD W. HUNSTEAD
School of Physics, University of Sydney
Received 1989 April 3; accepted 1989 July 1

ABSTRACT

We present the first results from a survey aimed at determining the degree of metal enrichment, the dust content, and the star formation rate of QSO absorption systems with damped Lyα lines. This class of absorbers is thought to arise in the high-redshift progenitors of present-day disk galaxies. We show how measurements of weak absorption lines of Zn II—detected here for the first time in a QSO spectrum—and of Cr II can provide accurate estimates of the metallicity and an indication of the dust-to-gas ratio, while an informative upper limit on the star formation rate can be obtained by searching for weak emission in the core of the damped Lyα line. The $z_{abs} = 2.3091$ system in PHL 957 has both a low metal abundance, 24 times below solar, and a low dust-to-gas ratio, approximately one order of magnitude lower than values typical of local interstellar clouds. These results suggest that the absorption system arises in a galaxy at an early stage of chemical evolution. The star formation rate is less than $\sim 30\ M_{\odot}\ \mathrm{yr}^{-1}$. These and other parameters are strikingly similar to those of nearby H II galaxies and, if found by future work to be typical of the damped Lyα sample in general, would suggest that disk galaxies at $z \simeq 2.5$ resembled closely the H II galaxies we see today. Alternatively, the damped Lyα lines may arise predominantly in dwarf galaxies whose properties have not changed significantly from $z \simeq 2.5$ to the present epoch. Further observations of damped Lyα systems should allow us to distinguish between these two possibilities and offer excellent opportunities for measuring the primordial abundance of deuterium.

Subject headings: galaxies: formation — galaxies: interstellar matter — nebulae: H II regions — quasars

I. INTRODUCTION: THE DAMPED Lyα SYSTEMS

It is generally recognized that the absorption spectra of QSOs are a powerful medium for tracing the evolution of matter over a significant fraction of the Hubble time. However, only in recent years have there been sufficient data to begin to realize the potential of this technique (see Steidel, Sargent, and Boksenberg 1988 for an example).

The class of absorbers known as the "damped Lyα" systems is characterized by neutral hydrogen column densities which are sufficiently high, $N(\mathrm{H\ I}) \geq 2 \times 10^{20}\ \mathrm{cm}^{-2}$, for the Lyα line to show conspicuous damping wings and, with a rest equivalent width $W_0 \geq 10$ Å, to be readily identified even in low-resolution spectra. A survey of such systems was first carried out by Wolfe and collaborators (Wolfe *et al.* 1986; Wolfe 1988). By analogy with the Galactic interstellar medium (ISM), where hydrogen column densities greater than $10^{20}\ \mathrm{cm}^{-2}$ are found predominantly along sight lines through the disk, Wolfe *et al.* (1986) identified the damped Lyα systems with disk galaxies at high redshifts. Their survey determined two important properties of the damped systems (Wolfe 1988). First, the mean density per unit redshift interval, $dN_{\mathrm{damp}}/dz = 0.29 \pm 0.08$ at an average redshift $\langle z_{abs} \rangle = 2.4$, is 5–6 times higher than that expected on the basis of the present-day cross sections of spiral galaxies for the same column density limit. This frequency of detection has subsequently been confirmed in an independent study by Sargent, Steidel, and Boksenberg (1989). Second, the average column density in the damped systems, $\langle N(\mathrm{H\ I}) \rangle = 1 \times 10^{21}\ \mathrm{cm}^{-2}$, and their incidence per unit redshift interval imply a density parameter $\Omega_{\mathrm{damp}} = 1.5\text{–}2.5 \times 10^{-3}\ h^{-1}$, depending on the value of q_0, directly comparable with $\Omega_{\mathrm{lum}} \approx 2 \times 10^{-3}\ h^{-1}$, the fraction of the critical density contributed by luminous matter in the disks of present-day galaxies (here $h = H_0/100\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$). On the basis of this evidence, Wolfe and collaborators proposed that in the damped Lyα systems we are seeing the progenitors of disk galaxies, at a time when they were still undergoing gravitational collapse and most of their baryonic content resided in the interstellar medium.

Direct evidence that the damped Lyα systems arise in *extended disks* is, however, still tentative. On the one hand, at least one of the systems in the Wolfe *et al.* (1986) sample, at $z_{abs} = 2.04$ toward the radio-loud QSO PKS 0458−020, must extend more than 8 h^{-1} kpc across the line of sight to explain the similarity in the profiles of the 21 cm absorption line recorded toward different components of the extended radio structure (Briggs *et al.* 1989). Furthermore, examples of such extended protogalactic disks may exist even at the present epoch, as suggested by the serendipitous discovery of Malin 1, a low–surface brightness disk galaxy at $z = 0.083$, with an H I diameter in excess of 240 kpc, $\langle N(\mathrm{H\ I}) \rangle \simeq 2 \times 10^{20}\ \mathrm{cm}^{-2}$, and a total H I mass of $\sim 1 \times 10^{11}\ M_{\odot}$ (Impey and Bothun 1989). On the other hand, a damped Lyα line is not in itself indicative

[1] On leave of absence from Royal Greenwich Observatory.

of the *morphology* of the galaxy in which it is produced. Radio observations of gas-rich irregulars, for example, show that sight lines with $N(\text{H I}) = 10^{20}$–10^{22} cm^{-2} are common. As argued by Impey and Bothun (1989), the contribution of low-luminosity galaxies to the total absorption cross section presented by galaxies depends sensitively on the slope of the faint end of the galaxy luminosity function and on the slope of the luminosity-radius relation, two parameters which are poorly known. In particular, there are indications that the latter may be significantly flatter for low-luminosity galaxies than the commonly adopted Holmberg (1975) relation, $R_{26.5} \propto L^{0.4}$ (see Carignan and Freeman 1988 and Brinks and Klein 1989 for recent examples). Indeed, there have been suggestions that dwarf galaxies may dominate the damped Lyα sample (Tyson 1988).

In view of these uncertainties, we prefer to think of the damped Lyα systems as arising predominantly in the inner, mainly neutral, regions of high-redshift galaxies—of whatever morphology. In this respect, the damped systems form a population distinct from other samples of QSO absorbers, such as those selected by C IV, Mg II, or Lyman limit absorption, which are thought to have major contributions from gas in more extended, ionized, galactic halos. A further point to stress is that the damped Lyα lines give us an opportunity to study *unexceptional* galaxies at high redshifts, accessible to observation only because they lie fortuitously in the light path to a background QSO. Such objects are likely to be more representative examples of the process of galaxy evolution *in general* than the high-redshift galaxies detected by virtue of their association with highly luminous radio sources (e.g., Lilly 1988; Spinrad 1987).

II. ABUNDANCE DETERMINATIONS

A key property of the damped Lyα systems is their chemical composition: a measure of how far metal enrichment through stellar nucleosynthesis has progressed in these high-redshift galaxies would be a major clue to their evolutionary status. Measurements of the chemical composition of the interstellar medium are complicated by a number of difficulties which have been discussed in detail by Jenkins (1987). Although the damped nature of the Lyα line ensures that the column density of H I is well determined—Wolfe (1988) estimates to within ±50% for his sample—two problems are of particular relevance here (Pettini 1985). First, the gas phase abundances measured from atomic absorption lines are generally only a fraction of the true interstellar abundances, with the "missing" atoms being locked up in interstellar grains. For some refractory elements (e.g., Al, Ca, Ti, Cr, Ni) the degree of depletion is usually high (2–3 orders of magnitude) and shows a wide scatter, depending on the physical conditions and past history of the gas. Second, for $N(\text{H I}) > 10^{20}$ cm^{-2}, the commonly observed absorption lines of the most abundant astrophysical elements are so heavily saturated that their equivalent widths are not useful indicators of column densities. In general, this will lead to an underestimate of abundances because, if more than one component contributes to the absorption—as is almost invariably the case—narrow components can be effectively masked by broader ones, even if the former have many times the column density of the latter (e.g., Nachman and Hobbs 1973).

These difficulties can be largely circumvented by searching for the Zn II λλ2025, 2062 doublet associated with the damped Lyα lines. This species is a particularly good indicator of the metallicity of these systems for the following reasons:

1. Zn is thought to be produced primarily by nuclear statistical equilibrium, the same nucleosynthetic process responsible for the iron peak elements (Cameron 1982). Observationally, it is found that Zn tracks closely the abundance of Fe in metal-poor halo stars down to [Fe/H] = −2.5 (Luck and Bond 1985; Sneden and Crocker 1988), in Population I A and B stars (Sadakane, Jugaku, and Takada-Hidai 1988) and in LMC stars (Russell and Bessell 1989). Thus, it appears that [Zn/H] is as good a measure of metal enrichment as [Fe/H]. {Here we adopt the usual notation to indicate the abundance of element X relative to that measured in the Sun: $[\text{X/H}] \equiv \log(\text{X/H}) - \log(\text{X/H})_\odot$}.

2. In interstellar H I regions, Zn in predominantly singly ionized, since the ionization potential of Zn^+, 17.96 eV, exceeds that of H I. Consequently, the gas phase abundance of Zn follows directly from the ratio $N(\text{Zn}^+)/N(\text{H})$, without the need to account for unobserved ion stages.

3. Zn has a near-solar abundance in interstellar gas with little, if any, depletion onto interstellar grains. This empirical result, indicated from early observations with the *Copernicus* satellite (Morton 1975, 1978), is now well established following the completion of several studies with the *IUE* satellite (*IUE* is particularly well suited for observations of the Zn II doublet, since the lines fall near the region of maximum sensitivity of the short-wavelength camera). In the most extensive of these studies, Van Steenberg and Shull (1988) recorded the Zn II doublet over 188 sight lines within 6 kpc of the Sun—with $N(\text{H I}) = 10^{20}$–10^{22} cm^{-2}, *directly comparable with those of the damped Lyα systems*—and found a mean depletion of only $[\text{Zn/H}]_{\text{ISM}} = -0.23$. Evidently, Zn either does not condense readily onto grains, or is easily returned to the gas phase in diffuse interstellar clouds.

4. The low solar abundance of Zn, $(\text{Zn/H})_\odot = 3.8 \pm 0.7 \times 10^{-8}$ (Aller 1987), and the *f*-values of the Zn II λλ2025, 2062 doublet, $f = 0.412$ and 0.202 respectively (Morton, York, and Jenkins 1988), generally result in only a small, easily measurable degree of saturation of the absorption lines. Specifically, the quantity $\log(\text{Zn/H})_\odot + \log(f\lambda)$ is −4.5 and −4.8 for the two lines respectively; the optical depths in the line centers are then less than 2 for (i) values of the velocity dispersion parameter $b \geq 3$ km s^{-1} (in the usual notation, $b = \sqrt{2}\ \sigma$, where σ is the one-dimensional velocity dispersion along the line of sight); (ii) $N(\text{H I}) \leq 1 \times 10^{21}$ cm^{-2}; (iii) $[\text{Zn/H}] \leq -1$ (Jenkins 1987). Thus, we would expect the equivalent widths of the Zn II lines to be close to the linear part of the curve of growth, where the corresponding column density of Zn^+ is relatively well determined.

5. At the redshifts of most damped Lyα systems in existing samples, $z_{\text{abs}} \simeq 2$–3, the Zn II lines are redshifted into an easily observable part of the optical spectrum, where the efficiency of CCD detectors is high and absorption by the Earth's atmosphere does not generally present serious problems. Furthermore, the difference in rest wavelength between the Zn II doublet and Lyα is sufficiently high to ensure that the Zn II lines associated with damped Lyα systems occur to the red of the QSO Lyα emission and are therefore free of contamination by Lyα forest lines.

As an added bonus, this spectral interval also includes the Cr II triplet λλ2055, 2061, 2065. All of the above considerations apply to this species as well, with the exception of point (3). In the local ISM, Cr is mostly locked up in interstellar grains,

TABLE 1

OBSERVATIONS OF THE $z_{abs} = 2.3091$ SYSTEM IN PHL 957

Date (1987)	Telescope	Detector	Wavelength Range (Å)	Resolution (Å)	Integration Time (s)	S/N	$W_0(3\ \sigma)$[a] (mÅ)
Oct 17 and 18 ...	Hale	TI CCD	6435–7075	1.9	12,000	90	20
Sep 21	AAT	IPCS	3725–4335	1.3	10,400	15	80

[a] 3 σ detection limit for the rest frame equivalent width of an unresolved absorption line in the $z_{abs} = 2.3091$ system.

being among the most heavily depleted elements in the gas phase with typically $[Cr/H]_{ISM} \simeq -2$ (e.g., Morton 1975, 1978). Thus, less than 200 Å of the red spectrum of QSOs with damped Lyα systems can provide two important parameters relevant to the evolutionary status of these high-redshift galaxies. While [Zn/H] is a direct measure of the degree of metal enrichment, [Zn/Cr] depends on the level of depletion of refractory elements and therefore provides an indication—albeit a qualitative one—of the dust content of these systems.

III. OBSERVATIONS AND DATA REDUCTION

For the reasons outlined above, we have begun a survey of the Zn II and Cr II spectral region using the 5 m Hale telescope at Palomar Observatory and the 3.9 m telescope of the Anglo-Australian Observatory (AAT) at Siding Spring, Australia. Here we present the first results from this program, obtained from observations of the $z_{abs} = 2.3091$ system in the bright ($V = 16.57$) QSO PHL 957 at $z_{em} = 2.681$ (Hewitt and Burbidge 1987). Table 1 gives the journal of observations and relevant details of the spectra.

a) Palomar Observations

The portion of the red spectrum of PHL 957 covering the Zn II and Cr II lines at $z_{abs} = 2.3091$ was recorded at the Cassegrain focus of the 5 m telescope with a Texas Instruments CCD on the red camera of the double spectrograph on two successive nights in 1987 October. The CCD has 800 × 800 pixels, each 15 μm square, and a readout noise of 10 electrons rms. A 1200 grooves mm^{-1} grating used in first order gave a dispersion of 54.6 Å mm^{-1} and, with a 1″ wide slit, a resolution $\Delta\lambda = 1.9$ Å FWHM—corresponding to $\Delta v = 84$ km s^{-1}—sampled with 2.4 CCD pixels. Six 2000 s exposures were secured, each bracketed by spectra of Ne and Fe-Ar hollow-cathode comparison lamps providing a wavelength reference scale. Many exposures of the spectrum of a tungsten lamp were recorded at the end of each night and then combined to produce a high-accuracy map of the pixel-to-pixel variations in the photometric response of the detector at the wavelengths of interest.

Data reduction was carried out with the FIGARO software package. After removing cosmic-ray–induced events (typically ≤10 per frame, none of which fell close to the spectral features sought), subtracting the electronic bias and flat-fielding, one dimensional spectra of QSO + sky and of sky were extracted from each 2000 s CCD frame. Only rows where the object counts greatly exceeded the sky counts were included in the extraction (typically 3–4 rows). The sky spectrum was averaged from 9–12 spatial increments along the slit, in order to reduce the noise introduced by sky subtraction. After rebinning all spectra onto a common linear wavelength scale and subtracting the sky signal, the six object spectra were added together with weights proportional to the average signal-to-noise ratio (S/N) of each.

Finally, the QSO spectrum was normalized by division by a spline fit to portions judged to be free of absorption features. The measured rms deviation of the data points from the continuum fit showed that a S/N ≃ 90 was achieved in the spectral region of interest. At a resolution of 1.9 Å FWHM (measured from emission lines in the comparison lamp spectra, processed in the same way as the QSO spectra), the corresponding detection limit (3 σ) for the equivalent width of an unresolved absorption line is $W_\lambda = 65$ mÅ. Therefore, in the rest frame of the $z_{abs} = 2.3091$ system, our data are sensitive to features as weak as $W_0 = 20$ mÅ. Portions of the normalized spectrum of PHL 957 encompassing the Zn II and Cr II lines are reproduced in Figure 1.

b) AAT Observations

The blue spectrum of PHL 957 in the region of the damped Lyα line at $z_{abs} = 2.3091$ was recorded with the IPCS and the RGO spectrograph at the Cassegrain focus of the AAT in 1987 September as part of a program aimed at detecting Lyα *emission* associated with the damped systems (Hunstead, Pettini, and Fletcher 1990). The negligible dark count of the photon-counting detector (typically 2×10^{-5} counts s^{-1} $pixel^{-1}$ for 15 × 75 μm pixels), and the dark sky of Siding Spring Observatory ($B \simeq 22.7$ mag $arcsec^{-2}$) are particularly well suited to the search for weak emission features in the black core of the damped Lyα absorption line. The 82 cm camera of the RGO spectrograph and a 600 grooves mm^{-1} grating used in first order produced a dispersion of 20.3 Å mm^{-1}; with a 0″.7 wide spectrograph slit, the spectral resolution was $\Delta\lambda = 1.3$ Å FWHM ($\Delta v = 97$ km s^{-1}). Each spatial increment of the detector covered 1″.4 on the sky, adequately sampling the FWHM ≃ 2″–3″ of the seeing profile during the observations. The total integration time was 10,400 s, divided into 10 separate exposures: between each exposure, the object was stepped along the slit so as to average out the fixed-pattern noise of the detector by using different regions of the photocathode to record the spectrum. Wavelength calibration was by reference to the emission spectrum of a Fe-Ar hollow cathode lamp, observed every 2000 s. Throughout the observations, the spectrograph slit was maintained to within ±15° of the parallactic angle, corresponding to position angles on the sky of between 150° and 180°.

The data reduction proceeded along the same lines as for the Palomar data, apart from steps which are CCD-specific. The sky signal was extracted from spatial increments on either side of those containing the QSO spectrum, averaging over 6 times as many increments as for the QSO. After rebinning to a common linear wavelength scale, the sky-subtracted spectra were added together with weights proportional to the individual S/N and normalized to the underlying QSO continuum, which averaged ~240 counts per 0.6 Å wavelength bin on

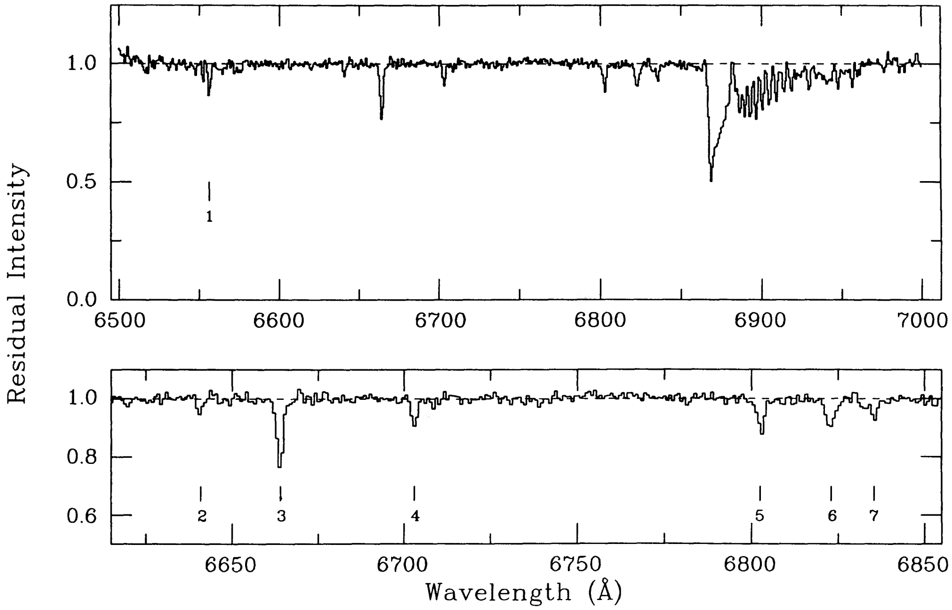

FIG. 1.—*Upper panel:* portion of the Hale telescope spectrum of PHL 957 between 6500 and 7000 Å, normalized to the underlying QSO continuum. The atmospheric B band can be seen clearly longward of 6867 Å. *Lower panel:* expanded portion of the upper panel spectrum, showing to best advantage the Zn II and Cr II absorption lines at $z_{abs} = 2.3091$ (lines 4, 5, 6, and 7; see Table 2). The S/N in the continuum is $\simeq 90$.

either side of the damped Lyα line. This portion of the final spectrum is reproduced in Figure 2.

IV. RESULTS

a) Metal Lines in the Red Spectrum of PHL 957

As can be seen from Figure 1, we detect seven narrow absorption lines in the spectrum of PHL 957 between 6500 and 7000 Å. Their observed wavelengths and equivalent widths, together with associated 1 σ errors, are listed in columns (2)–(5) of Table 2. Columns (6) and (7) give, respectively, the identifications of these lines and the *f*-values of the transitions (from the compilation by Morton, York, and Jenkins 1988); columns (8) and (9) list the corresponding absorption redshifts and associated errors. All measured wavelengths and redshifts are vacuum heliocentric.

Lines 1–3 are Fe II transitions from multiplets UV2 and UV3 in the rich absorption system at $z_{abs} = 1.7975$, already known from earlier observations of PHL 957 (Coleman *et al.* 1976; Gilbert *et al.* 1976). With a rest frame equivalent width $W_0 = 30 \pm 7$ mÅ, line 2 (λ2373.737) is most likely on the linear part of the curve of growth and implies $N(Fe^+) = (1.5 \pm 0.4) \times 10^{13}$ cm^{-2}. However, without a knowledge of the hydrogen column density in this system (which will require high-resolution data in the near–UV since, at 3400.8 Å, Lyα in this system is partially blended with Lyβ at $z_{abs} = 2.3091$), we cannot deduce an estimate of the Fe abundance. Accordingly, these lines will not be discussed further here.

Lines 4–7 are the Zn II and Cr II multiplets in the $z_{abs} = 2.3091$ system, to which the present investigation is directed. While there is one previous report of Cr II in a QSO absorption system, at $z_{abs} = 2.142$ in 0528−250 (Meyer and York 1987), to our knowledge this is the first time that Zn II has been detected with confidence (a possible detection in the $z_{abs} = 1.345$ system in the BL Lac object 0215+015 reported by Pettini 1985 remains to be confirmed with better data when the source brightens again to $V \leq 16$).

The Zn II and Cr II lines are weak, with rest frame equivalent widths $W_0 = 51$ and 80 mÅ for the strongest members of the doublet and triplet, respectively, and the ratios of equivalent widths within each multiplet indicate that the lines fall on the linear part of the curve of growth. The corresponding column densities N are listed in column (2) of Table 3. Even though λ2062.003, the weaker member of the Zn II doublet, is partially blended with Cr II λ2061.575, the composite profile retains sufficient information to confirm that the lines are optically thin (see Fig. 3). Specifically, only for values of the velocity dispersion parameter $b < 4$ km s^{-1} would Zn II λ2025.484 have an optical depth greater than 2 in the line center and imply column densities more than a factor of 2 greater than $N(Zn^+) = 4 \times 10^{12}$ cm^{-2}, the value listed in Table 3. Under these circumstances, however, W_0 (λ2062.003) would be greater

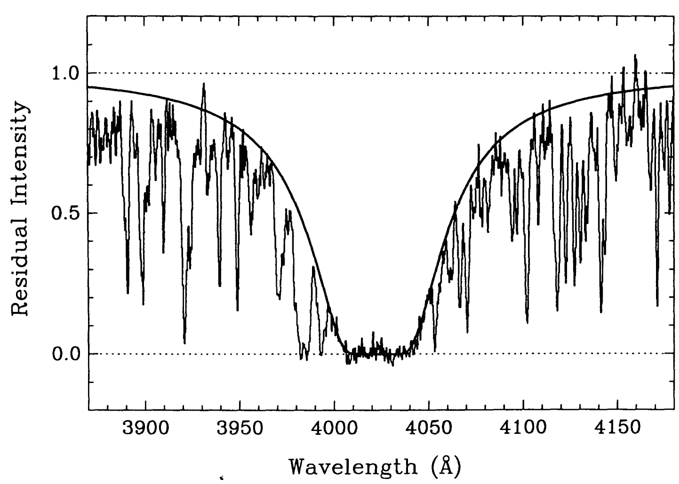

FIG. 2.—Portion of the normalized AAT spectrum of PHL 957, centered on the damped Lyα line at $z_{abs} = 2.3091$. Superposed on the data is the theoretical damping profile for a column density $N(H\ I) = 2.5 \times 10^{21}$ cm^{-2}.

TABLE 2

DETECTED ABSORPTION LINES

Line Number (1)	λ_{obs}[a] (Å) (2)	$\sigma(\lambda)$ (Å) (3)	W_{obs} (mÅ) (4)	$\sigma(W)$ (mÅ) (5)	Identification[b] (6)	f (7)	z_{abs}[a] (8)	$\sigma(z_{abs})$ (9)
1.........	6558.03	0.10	270	20	Fe II λ2343.496	0.108	1.79754	0.00004
2.........	6642.68	0.30	85	20	Fe II λ2373.737	0.0395	1.7976	0.0001
3.........	6665.81	0.11	570	25	Fe II λ2382.039	0.328	1.79751	0.00004
4.........	6704.77	0.25	170	20	Zn II λ2025.484	0.412	2.3091	0.0001
5.........	6804.33	0.14	265	20	Cr II λ2055.596	0.167	2.30910	0.00007
6.........	6824.76	0.21	320	25	{ Cr II λ2061.575+	0.121	2.3091[c]	...
					{ Zn II λ2062.003	0.202	...	...
7.........	6837.27:[d]	0.20	140	20	Cr II λ2065.501	0.0798	2.3092:[d]	...

[a] Wavelengths and corresponding absorption redshifts are vacuum heliocentric.

[b] Following the normal convention, the laboratory wavelengths of these lines are given in air.

[c] Determined by profile fitting; see text.

[d] The wavelength, and hence the redshift, of this line is somewhat uncertain due to its proximity to a sky emission line.

than 36 mÅ, which is excluded by the observed profile of line 6 (see Fig. 3).

In practice, more than one absorbing cloud may contribute to the lines. It is well known that if there are large differences in the values of b between different clouds, the absorption produced by a cloud with low b (b_1) may be effectively masked by that due to a second cloud with $b_2 \gg b_1$, even if $N_2 < N_1$; under these circumstances, the total column density $N_1 + N_2$ would generally be underestimated (e.g., Nachman and Hobbs 1973; Gómez-Gonzàlez and Lequeux 1975; see also Fig. 3.1 of Pettini 1978). We have explored this possibility for the Zn II lines in question by computing the composite absorption profile produced by two clouds with several combinations of widely differing b values, using a profile fitting technique

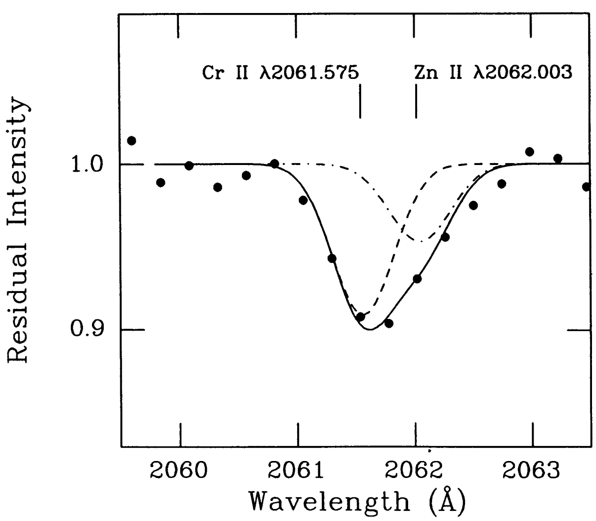

FIG. 3.—The observed profile of line 6 (*dots*), which is a blend of Cr II λ2061.575 and Zn II λ2062.003 at $z_{abs} = 2.3091$, is well reproduced by the theoretical profiles of these lines, assumed to be optically thin. *Broken line:* profile of Cr II λ2061.575 computed with $N(Cr^+) = 15 \times 10^{12}$ cm^{-2}, as deduced from the unblended Cr II λ2055.596; the corresponding equivalent width is $W_0 = 62$ mÅ. *Dot-dash line:* profile of Zn II λ2062.003 computed with $N(Zn^+) = 4 \times 10^{12}$ cm^{-2}, as deduced from the unblended Zn II λ2025.484; the corresponding equivalent width is $W_0 = 27$ mÅ. *Continuous line:* computed profile of Cr II + Zn II blend. All theoretical profiles have been convolved with the instrumental broadening function of FWHM = 1.9 Å.

described elsewhere (Pettini *et al.* 1983). After convolution with the instrumental broadening function, the computed profiles were compared with the observed Zn II absorption lines. These trials showed that in order to "hide" values of N as high as 4×10^{12} cm^{-2} in narrow, saturated components (and thereby underestimate the column density of Zn^+ by a factor of 2), it is necessary to invoke clouds with exceedingly low velocity dispersions, $b \lesssim 0.5$ km s^{-1}. More reaslistic parameters for the velocity structure of the gas, such as those deduced from the H I 21 cm absorption profile of the damped $z_{abs} = 2.0395$ system in PKS 0458−020, for example (Wolfe *et al.* 1985), would—if applicable here—lead to unsaturated Zn II lines. Similar considerations apply to the Cr II lines. We conclude that it is unlikely that the column densities of Zn^+ and Cr^+ in the $z_{abs} = 2.3091$ system have been underestimated by more than a factor of 2.

b) Hydrogen Column Density and Metal Abundances in the z_{abs} = 2.3091 System

As can be seen from Figure 2, the wings of the Lyα line are well reproduced by a damping profile with $N(\text{H I}) = 2.5 \times 10^{21}$ cm^{-2}; trial fits with different values of N(H I) suggest an uncertainty of ±10%. The hydrogen column density we derive is in excellent agreement with the value deduced by Black, Chaffee, and Foltz (1987) from MMT data of comparable resolution and S/N to those presented here. The redshift of the Zn II and Cr II lines, $z_{abs} = 2.3091$, differs by 23 km s^{-1} from $\overline{z_{abs}} = 2.30935$, the mean redshift of *all* the absorption lines identified in this system by Black, Chaffee, and

TABLE 3

Zn AND Cr ABUNDANCES IN THE z_{abs} = 2.3091 SYSTEM

Element (1)	$N(X^+)$ (10^{12} cm^{-2}) (2)	$N(X^+)/N(H)$[a] (10^{-9}) (3)	$[N(X)/N(H)]_\odot$[b] (10^{-9}) (4)	Depletion Factor (5)
Zn........	4 ± 0.5	1.6 ± 0.3	38 ± 7	24^{+8}_{-5}
Cr........	15 ± 1	5.9 ± 0.9	580 ± 200	100^{+55}_{-25}

[a] $N(H) = 2.5 \pm 0.3 \times 10^{21}$ cm^{-2} (Black, Chaffee, and Foltz 1987; this work).

[b] Aller 1987.

Foltz. As the lines cover a range of ionization stages, however, the velocity difference between different lines is probably an indication that they consist of multiple components which are blended at ~1 Å resolution. A shift of 23 km s^{-1} corresponds to only ~1 wavelength bin in Figure 2; consequently, the profile of the damped Lyα line is consistent with both z_{abs} = 2.3091 and 2.30935.

The value of N(H I) derived from Lyα constitutes the total column density of neutral hydrogen at $z_{abs} = 2.3091$ in both atomic and molecular forms since, as reported by Black, Chaffee, and Foltz, molecular hydrogen is conspicuously absent in this system, with $2N(H_2)/N(H) \leq 4 \times 10^{-6}$. Thus, adopting $N(H) = (2.5 \pm 0.3) \times 10^{21}$ cm^{-2}, we deduce abundances of Zn and Cr relative to H of $(1.6 \pm 0.3) \times 10^{-9}$ and $(5.9 \pm 0.9) \times 10^{-9}$ respectively, as listed in column (3) of Table 3. Comparison with the corresponding abundances in the Sun (col. [4]) shows that in the $z_{abs} = 2.3091$ system Zn and Cr are underabundant by factors of ~24 and ~100, respectively (col. [5]).

c) Lyα *Emission*

From Figure 2 it can be seen that the black core of the Lyα lines does not show clear evidence of emission such as that seen in Q0836+113 (Hunstead, Pettini, and Fletcher 1990), although there may be a hint of excess flux near the line center. In order to place an upper limit on any Lyα emission, we divided the core of the line into seven spectral bins, each ~5 Å wide, with the central bin centered at the wavelength of Lyα at $z_{abs} = 2.3091$. As the QSO spectrum was recorded over two spatial increments along the slit, each 1".4 long, we also divided into seven spectral bins the sky-subtracted signal in the two pairs of spatial increments adjacent to the QSO, thus obtaining a total of 21 bins over which to assess the statistical significance of any excess flux. Of these, the bin with the greatest excursion from zero is the central bin in the core of the damped Lyα line, with a residual photon count of 42. This is to be compared with rms disperions $\sigma = 16$ counts expected on the basis of the sky signal, and $\sigma = 14$ counts measured from the dispersion of counts in the other 20 bins. Thus, the positive flux in the line core has a 2.7–3.0 σ significance and, accordingly, we adopt its value as an upper limit to Lyα emission associated with the $z_{abs} = 2.3091$ system, at least over the area sampled by the spectrograph slit (5 × 22 kpc—for $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$—at position angle 150°–180°).

The integrated flux corresponding to 42 counts in the central bin is 8.5×10^{-17} ergs cm^{-2} s^{-1}. (Flux calibration was referred to two flux standards from the compilation by Oke 1974; the resultant continuum magnitude agrees to ±0.2 mag with $B = 17.0$ given by Hewitt and Burbidge 1987 for PHL 957). Since this flux was recorded over an area of sky of dimensions 0".67 × 2".8, the corresponding surface brightness is 4.5×10^{-17} ergs s^{-1} cm^{-2} $arcsec^{-2}$ (≃24 mag $arcsec^{-2}$), a factor of ~2 lower than the previous upper limit set by Foltz, Chaffee, and Weymann (1986). With the above values of H_0 and q_0, the implied Lyα luminosity is $L(Ly\alpha) \leq 3.5 \times 10^{42}$ ergs s^{-1}. For comparison, the Lyα luminosity deduced from the detection of Lyα emission in the $z_{abs} = 2.465$ system in Q0836+113 is $L(Ly\alpha) = 1.2 \times 10^{42}$ ergs s^{-1} (Hunstead, Pettini, and Fletcher 1990).

V. DISCUSSION

The data of relevance to this discussion are collected in Table 4, where the relative abundances of Zn and Cr in the $z_{abs} = 2.3091$ system in PHL 957 are compared with values measured in (i) the Sun, (ii) the interstellar medium of our Galaxy, as probed by the sight line to ζ Oph, and (iii) the interstellar medium of the Large Magellanic Cloud in front of R136. The comparison is illustrated in Figure 4. As can be seen from column (2) of Table 4, the column density of hydrogen is similar in all three interstellar sight lines sampled. The values of Zn and Cr abundance toward ζ Oph and R136 reported in the original references, listed in column (6) of Table 4, have been scaled as appropriate to the *f*-values and solar abundances adopted in the present work. It is also worth noting, in passing, that the abundance of Zn in the LMC, as measured by the interstellar observations of de Boer, Fitzpatrick, and Savage (1985), is consistent with recent conclusions—based primarily on stellar abundance studies (e.g., Russell and Bessell 1989; Feast 1989)—that in the LMC iron-peak elements are deficient only by a factor of ~2 relative to the Sun (see col. [3] of Table 4).

a) *Metal Enrichment*

The first conclusion to be drawn from our results is that the interstellar medium sampled by the $z_{abs} = 2.3091$ system is genuinely metal-poor, since the abundance of Zn we measure is ~24 times lower than in the Sun and ~10 times lower than in interstellar gas in the Galaxy and the LMC. This strongly suggests that chemical evolution through stellar nucleosynthesis is still at an early stage in this high-redshift galaxy.

This conclusion is *qualitatively* consistent with the underabundance of C by a factor of ~100 reported by Black, Chaffee, and Foltz (1987). While we cannot exclude the possibility that C may be overdeficient by a factor of 4 relative to Zn, there is no need to invoke such an effect, because the determination of the abundance of C in the $z_{abs} = 2.3091$ system is highly uncertain, for the reasons outlined in § II. Specifically, Black, Chaffee, and Foltz deduced $N(C^+) = 7.7 \times 10^{15}$ cm^{-2} from the strongly saturated (W_0 = 0.48 Å) C II λ1334 line, *assuming* $b = 25$ km s^{-1}. However, even a small change in *b*, from 25 to 20 km s^{-1} for example, would change the deduced value of $N(C^+)$ by one order of magnitude. Thus, the data presented here quantify the underabundance of

TABLE 4

COMPARISON OF Zn AND Cr ABUNDANCES

Object (1)	N(H) (10^{21} cm^{-2}) (2)	Zn/H (10^{-9}) (3)	Cr/H (10^{-9}) (4)	Cr/Zn (5)	References (6)
Sun	...	38 ± 7	580 ± 200	15 ± 6	Aller 1987
ζ Oph (Milky Way ISM)	1.35 ± 0.05	14 ± 1.5	2.3 ± 0.2	0.16 ± 0.02	Morton 1975; Snow, Weiler, and Oegerle 1979
R136 (LMC ISM)	6.5 ± 2	20 ± 10	18 ± 3	0.40 ± 0.25	de Boer *et al.* 1985
$z_{abs} = 2.3091$ in PHL 957	2.5 ± 0.3	1.6 ± 0.3	5.9 ± 0.9	3.7 ± 0.9	This work

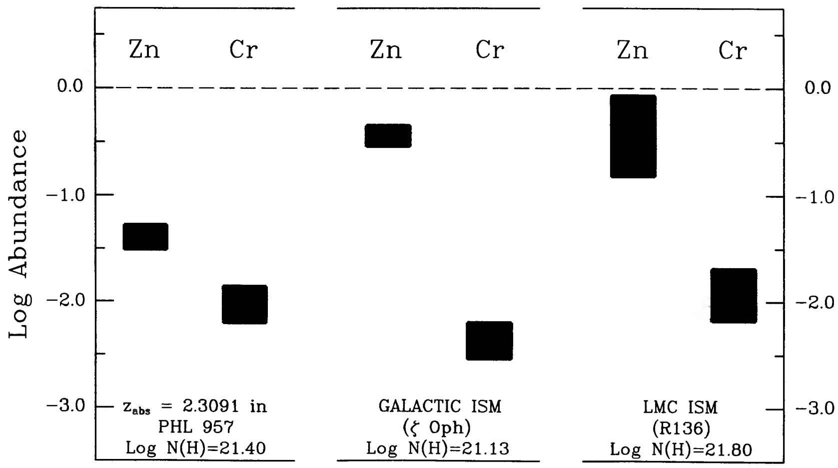

FIG. 4.—Comparison of the abundances of Zn and Cr in the $z_{abs} = 2.3091$ absorption system in PHL 957 with those measured in diffuse interstellar clouds in the solar neighborhood and in the Large Magellanic Cloud. The height of each box reflects the range of uncertainty in the measurements. The broken line at 0.0 corresponds to solar abundances.

metals in the $z_{abs} = 2.3091$ system more accurately than has been possible so far.

b) Dust Content

It is also evident from the results in Table 4 and Figure 4 that the depletion of Cr is far less extreme in the $z_{abs} = 2.3091$ system than in diffuse interstellar clouds in the Galaxy and the LMC. If we adopt an average metallicity $Z = -1.4$ from the Zn abundance, we see that Cr is further depleted by only a factor of ~ 4, rather than by ~ 100 and ~ 40 as toward ζ Oph and R136, respectively (col. [5] of Table 4). Presumably, a smaller proportion of Cr is locked up in interstellar grains in the high-redshift system than in nearby interstellar clouds, suggesting a much reduced dust-to-gas ratio. Unfortunately, the degree of depletion of Cr cannot be readily transformed to a quantitative estimate of dust content. Qualitatively, however, the presence of at least some dust is required to account for the finding that the Cr-to-Zn ratio is ~ 4 times below solar. [The alternative explanation—that this is an intrinsic abundance difference—seems unlikely in view of the fact that these two elements track each other closely in metal-poor stars down to metallicities $Z \simeq -2.5$ (Lambert 1989; Wheeler, Sneden, and Truran 1989)]. The inferred low dust content may be taken as another indication—together with the low metallicity—that the cycling of interstellar gas through stars has not proceeded very far in the galaxy at $z_{abs} = 2.3091$, since the atmospheres of low- and intermediate-mass giants are regarded as major sources of interstellar dust.

Our results add to a growing body of evidence suggesting that the damped Lyα systems *in general* exhibit a low dust-to-gas ratio. Meyer and York (1987) found both Ni and Cr to be much less depleted in two damped systems toward PKS 0528−250—at $z_{abs} = 2.811$ and 2.142, respectively—than in local interstellar clouds, consistent with the results presented here. However, in that case, the lack of Zn II data prevented a measure of the metallicity of the gas and, consequently, an estimate of the residual depletions of Ni and Cr. A low concentration of dust in the $z_{abs} = 2.3091$ system in PHL 957 has been suspected for a number of years from the absence of the 2175 Å extinction feature (Jura 1977). However, dust in high-redshift galaxies may have quite different extinction properties from Galactic dust and lack the 2175 Å bump, particularly if metal abundances are low. A trend of decreasing strength of the bump with metallicity is seen, for example, in the Galaxy–LMC–SMC sequence. Observational approaches to the detection of dust in QSO absorption systems have been reviewed recently by Boissé and Bergeron (1988) and by Ostriker, Vogeley, and York (1989). Of these, a statistical test for differences in spectral slope between QSOs with and without damped systems has so far given the best estimate of dust-to-gas ratio at high redshifts (Fall, Pei, and McMahon 1989). These authors concluded that damped Lyα galaxies have *on average* a dust-to-gas ratio one-tenth of the local value and extinction curves closer to those of the Magellanic Clouds than that produced by Milky Way dust.

Returning to PHL 957, the low dust content we infer for the $z_{abs} = 2.3091$ system is qualitatively consistent with the absence of both molecular hydrogen and neutral carbon reported by Black, Chaffee, and Foltz (1987), since interstellar grains act as catalysts for the production of H_2 and provide the shielding of UV radiation necessary to maintain an observable fraction of C in neutral form. The low abundance of H_2 is particularly striking with $f = 2N(H_2)/N(H) = 4 \times 10^{-6}$, which is $\sim 1.25 \times 10^5$ times lower than the value expected for a Galactic interstellar cloud of comparable N(H I). Black, Chaffee, and Foltz attributed the low concentrations of H_2 and C I to an enhanced interstellar radiation field, which they estimated to be ~ 100 times more intense than in our Galaxy. This result, however, rests primarily on the observed $N(C^{3+})/N(C^+)$ ratio, which is highly uncertain, as explained above. While the diffuse radiation field in the galaxy producing the $z_{abs} = 2.3091$ system may well be higher than that in the solar neighborhood, we see no evidence of an excessively high star formation rate in Lyα emission (§ V*c*). Possibly both effects—a higher density of ionizing radiation and a lower concentration of dust—combine to produce much reduced abundances of H_2 and C I in the high-redshift damped Lyα systems relative to the interstellar medium near the Sun.

c) Star Formation Rate

The upper limit on the Lyα luminosity determined above (§ IV*c*) corresponds to an Hα luminosity $L(\mathrm{H}\alpha) \lesssim 3.5 \times 10^{41}$

ergs s^{-1}, assuming case B recombination. However, even small amounts of dust mixed with extended H I can be very effective in reducing the Lyα flux, because multiple scattering in neutral hydrogen selectively increases the path length of Lyα photons. Indeed, *IUE* observations of extragalactic H II regions and H II galaxies (Meier and Terlevich 1981; Hartmann, Huchra, and Geller 1984; Deharveng, Joubert, and Kunth 1985; Hartmann *et al.* 1988) typically show Lyα-to-Hβ ratios 20–30 times smaller than predicted, with a tendency toward larger values (i.e., *less* Lyα suppression) with decreasing metallicity of the gas. Thus, on the basis of our results for the degree of metal enrichment and the dust content of the $z_{abs} = 2.3091$ system, we adopt 3.5×10^{42} ergs s^{-1} as an upper limit to the Hα luminosity of this high-redshift galaxy, corresponding to a reduction of Lyα by a factor of ~10. For comparison, the brightest H II regions in nearby spiral and irregular galaxies have $L(\mathrm{H}\alpha) \lesssim 2 \times 10^{40}$ ergs s^{-1} (Kennicutt 1988; Kennicutt, Edgar, and Hodge 1989), while the integrated Hα luminosities of the galaxies can be as high as $\sim 2 \times 10^{42}$ ergs s^{-1} (Kennicutt 1983).

Finally, adopting an extended Miller-Scalo initial mass function (IMF), as proposed by Kennicutt (1983), we deduce a star formation rate SFR $\leq 30\ M_{\odot}\ \mathrm{yr}^{-1}$. This is a strict upper limit in the sense that a lower SFR would obtain if, as a result of its low metallicity, the galaxy at $z_{abs} = 2.3091$ has an IMF with a higher cutoff mass, or a shallower slope at the high-mass end (Terlevich and Melnick 1981; Melnick 1987).

VI. CONCLUDING REMARKS

Table 5 summarizes the properties of the galaxy presumed to give rise to the $z_{abs} = 2.3091$ absorption system in the spectrum of the QSO PHL 957, as determined in this study. The similarity with present-day H II galaxies is striking. Taking each point in turn:

1. H II galaxies are generally H I rich, and sight lines with $N(\mathrm{H\ I}) > 10^{21}\ \mathrm{cm}^{-2}$ are not uncommon in 21 cm emission (see Viallefond, Lequeux, and Comte 1987 and Axon *et al.* 1988 for recent examples).

2. H II galaxies are low-metallicity systems. A survey of oxygen abundance in 102 galaxies by Terlevich and collaborators found $-1.65 \leq [\mathrm{O/H}] \leq -0.2$ (Terlevich 1987).

3. The dust content of H II galaxies is low, as indicated by the strengths of the blue and ultraviolet continua (Hartmann *et al.* 1988) and, for three cases observed with *IRAS*, by the low far-infrared luminosities (Gondhalekar *et al.* 1986).

4. Lyα luminosities of H II galaxies detected with *IUE*, as references in § V*c*, are $L(\mathrm{Ly}\alpha) \leq 2 \times 10^{42}$ ergs s^{-1}, consistent

TABLE 5

PROPERTIES OF THE GALAXY AT $z_{abs} = 2.3091$ IN LINE TO PHL 957

Parameter	Value
N(H I)	$2.5 \times 10^{21}\ \mathrm{cm}^{-2}$
Z	-1.4
Dust-to-gas ratio	~0.1[a]
L(Lyα)	$\leq 3.5 \times 10^{42}$ ergs s^{-1}[b]
SFR	$\leq 30\ M_{\odot}\ \mathrm{yr}^{-1}$[c]

[a] Relative to the interstellar medium in the solar neighborhood.

[b] Assuming $H_0 = 50\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$, $q_0 = 0.5$.

[c] Assuming that dust absorption has reduced the Lyα flux by a factor of 10.

with the upper limit determined here for the system at $z_{abs} = 2.3091$.

5. The star formation activity of H II galaxies—SFR $\lesssim 50\ M_{\odot}\ \mathrm{yr}^{-1}$, as deduced from the Hβ luminosity (Terlevich 1987)—is also consistent with the upper limit in Table 5. Furthermore, in Q0836+113, where Lyα emission associated with a damped system *has* been detected (Hunstead, Pettini, and Fletcher 1990), the implied SFR $\simeq 1\ M_{\odot}\ \mathrm{yr}^{-1}$ is near the average value for H II galaxies, and the width of the emission conforms to the empirical relationship between luminosity and velocity dispersion for H II galaxies determined by Melnick, Terlevich, and Moles (1988).

The similarity in metallicity, dust content, and star formation rate between the $z_{abs} = 2.3091$ system in PHL 957 and present-day H II galaxies may be an indication that the damped Lyα sample is dominant by dwarf galaxies whose properties have not changed significantly from $z \simeq 2.5$ to the present epoch. Alternatively, if the damped systems arise predominantly in extended galactic disks as proposed by Wolfe *et al.* (1986), our results would suggest that the progenitors of spiral galaxies resembled in several ways the H II galaxies we see today.

In this context, a metallicity $Z = -1.4$ at an epoch when the universe was ~0.17 of its present age ($q_0 = 0.5$) is broadly consistent with the age-metallicity relation for the solar neighborhood (e.g., Nissen, Edvardsson, and Gustafsson 1985; Tosi 1988). On the other hand, Wheeler, Sneden, and Truran (1989) have recently reexamined the age-metallicity relation and concluded that its interpretation is not unequivocal. These authors put forward the possibility that the Glactic disk may have maintained an approximately constant $[\mathrm{Fe/H}] = 0.0 \pm 0.3$ since its formation 10–15 Gyr ago, with metal-deficient stars belonging mostly to a halo population. This interpretation is consistent with models in which there is a considerable gap in time between the formation of the halo and the first burst of star formation in the disk. If the chemical evolution of galaxies generally proceeded along these lines, the low metal abundance deduced here for the $z_{abs} = 2.3091$ system in PHL 957 may be inconsistent with the hypothesis that this is a galactic *disk* at high redshift.

While our observations have shown that the $z_{abs} = 2.3091$ system can be plausibly identified with a galaxy in its early stages of evolution, it will be necessary to extend this work to a number of other cases in order to elucidate further the nature of the damped Lyα systems. In particular, it will be of interest to determine the *spread* in chemical abundances, dust-to-gas ratios, and Lyα luminosities found at redshifts $z \simeq 2$–3. If future work showed that metallicities $Z < -1.4$ are common at these epochs, it would be difficult to escape the conclusion that galaxies have evolved significantly since then, because $Z = -1.4$ is near the lower limit of the range for present-day H II galaxies (Kunth and Sargent 1986; Skillman *et al.* 1988; Skillman, Kennicutt, and Hodge 1990).

As a final remark, we draw attention to the fact that high-resolution observations of high-order Lyman lines in damped systems of low metallicity are one of the most promising avenues for measuring the primordial abundance of deuterium, a key parameter for testing the prediction of big bang nucleosynthesis and determining the baryonic density of the universe (e.g., Pagel 1986). The main advantages of searching for deuterium in the high-redshift galaxies giving rise to the damped Lyα systems, rather than in the intergalactic clouds producing the Lyα forest, are twofold: (i) N(H I) is both high and well determined, facilitating the detection of deuterium absorption lines and the subsequent measurement of the D-to-H ratio, and (ii) the metallicity of the damped systems can be determined directly, as shown here, while that of the Lyα forest clouds is dependent on large and uncertain ionization corrections (Chaffee *et al.* 1986). Comparison of D/H in the damped Lyα systems with that in the local interstellar medium would then give a measure of the degree of astration of deuterium and allow extrapolation to the primordial abundance.

It is a pleasure to thank the night assistants of the AAT and the Hale telescope for the help they provided with the observations, the time assignment committees of both telescopes for their support of this program, and Wal Sargent for generously sharing his observing time with us. We are grateful to Dave King for help with the production of the figures and to Lawrence Cram for his critical reading of the manuscript. R. W. H. acknowledges financial support from the Australian Research Council.

REFERENCES

Aller, L. H. 1987, in *Spectroscopy of Astrophysical Plasmas*, ed. A. Dalgarno and D. Layzer (Cambridge: Cambridge University Press), p. 89.
Axon, D. J., Staveley-Smith, L., Fosbury, R. A. E., Danziger, J., Boksenberg, A., and Davies, R. D. 1988, *M.N.R.A.S.*, **231**, 1077.
Black, J. H., Chaffee, F. H., and Foltz, C. B. 1987, *Ap. J.*, **317**, 442.
Boissé, P., and Bergeron, J. 1988, *Astr. Ap.*, **192**, 1.
Briggs, F. H., Wolfe, A. M., Liszt, H. S., Davis, M. M., and Turner, K. L. 1989, *Ap. J.*, **341**, 650.
Brinks, E., and Klein, V. 1989, in *Evolutionary Phenomena in Galaxies*, ed. J. Beckman and B. E. J. Pagel (Cambridge: Cambridge University Press), in press.
Cameron, A. G. W. 1982, in *Essays in Nuclear Astrophysics*, ed. C. A. Barnes, D. D. Clayton, and D. N. Schramm (Cambridge: Cambridge University Press), p. 23.
Carignan, C., and Freeman, K. C. 1988, *Ap. J. (Letters)*, **332**, L33.
Chaffee, F. H., Foltz, C. B., Bechtold, J., and Weymann, R. J. 1986, *Ap. J.*, **301**, 116.
Coleman, G., Carswell, R. F., Strittmatter, P. A., Williams, R. E., Baldwin, J., Robinson, L. B., and Wampler, E. J. 1976, *Ap. J.*, **207**, 1.
de Boer, K. S., Fitzpatrick, E. L., and Savage, B. D. 1985, *M.N.R.A.S.*, **217**, 115.
Deharveng, J. M., Joubert, M., and Kunth, D. 1985, in *Star-forming Dwarf Galaxies and Related Objects*, ed. D. Kunth, T. X. Thuan, and J. Tran Thanh Van (Paris: Ed. Frontières), p. 431.
Fall, S. M., Pei, Y. C., and McMahon, R. 1989, *Ap. J. (Letters)*, **341**, L5.
Feast, M. W. 1989, in *Proc. Le Monde Des Galaxies*, ed. H. Corwin, Jr. (New York: Springer), in press.
Foltz, C. B., Chaffee, F. H., and Weymann, R. J. 1986, *A.J.*, **92**, 247.
Gilbert, G. R., Angel, J. R. P., Grandi, S. A., Coleman, G. D., Strittmatter, P. A., Cromwell, R. H., and Jensen, E. B. 1976, *Ap. J. (Letters)*, **206**, L129.
Gómez-Gonzàlez, J., and Lequeux, J. 1975, *Astr. Ap.*, **38**, 29.
Gondhalekar, P. M., Morgan, D. H., Dopita, M., and Ellis, R. S. 1986, *M.N.R.A.S.*, **219**, 505.
Hartmann, L. W., Huchra, J. P., and Geller, M. J. 1984, *Ap. J.*, **287**, 487.
Hartmann, L. W., Huchra, J. P., Geller, M. J., O'Brien, P., and Wilson, R. 1988, *Ap. J.*, **326**, 101.
Hewitt, A., and Burbidge, G. 1987, *Ap. J. Suppl.*, **63**, 1.
Holmberg, E. 1975, in *Stars and Stellar Systems, Vol.* **9**, *Galaxies and the Universe*, ed. A. Sandage, M. Sandage, and J. Kristian (Chicago: University of Chicago Press), p. 123.
Hunstead, R. W., Pettini, M., and Fletcher, A. 1990, *Ap. J.*, submitted.
Impey, C., and Bothun, G. 1989, *Ap. J.*, **341**, 89.
Jenkins, E. B. 1987, in *Interstellar Processes*, ed. D. J. Hollenbach and H. A. Thronson (Dordrecht: Reidel), p. 533.
Jura, M. 1977, *Nature*, **266**, 702.
Kennicutt, R. C. 1983, *Ap. J.*, **272**, 54.
———. 1988, *Ap. J.*, **334**, 144.
Kennicutt, R. C., Edgar, B. K., and Hodge, P. W. 1989, *Ap. J.*, **337**, 761.
Kunth, D., and Sargent, W. L. W. 1985, *Ap. J.*, **300**, 496.
Lambert, D. L. 1989, *Proc. AIP Conf. 183, Cosmic Abundances of Matter*, ed. C. J. Waddington (New York: American Institute of Physics), p. 168.
Lilly, S. J. 1988, *Ap. J.*, **333**, 161.
Luck, R. E., and Bond, H. E. 1985, *Ap. J.*, **292**, 559.
Meier, D., and Terlevich, R. 1981, *Ap. J. (Letters)*, **246**, L109.
Melnick, J. 1987, in *Starbursts and Galaxy Evolution*, ed. T. X. Thuan, T. Montemerle, and J. Tran Thanh Van (Paris: Ed. Frontières), p. 215.
Melnick, J., Terlevich, R., and Moles, M. 1988, *M.N.R.A.S.*, **235**, 297.
Meyer, D. M., and York, D. G. 1987, *Ap. J.*, **319**, L45.
Morton, D. C. 1975, *Ap. J.*, **197**, 85.
———. 1978, *Ap. J.*, **222**, 863.
Morton, D. C., York, D. G., and Jenkins, E. B. 1988, *Ap. J. Suppl.*, **68**, 449.
Nachman, P., and Hobbs, L. M. 1973, *Ap. J.*, **182**, 481.
Nissen, P. E., Edvardsson, B., and Gustafsson, B. 1985, in *Production and Distribution of C, N, O, Elements*, ed. I. J. Danziger, F. Matteucci, and K. Kjär (ESO Conf. and Workshop Proc. No. 21), p. 131.
Oke, J. B. 1974, *Ap. J. Suppl.*, **27**, 21.
Ostriker, J. P., Vogeley, M. S., and York, D. G. 1989, Princeton Observatory preprint No. 279.
Pagel, B. E. J. 1986, *Phil. Trans. Roy. Soc. London A*, **320**, 557.
Pettini, M. 1978, Ph.D. thesis, University of London.
———. 1985, in *Productions and Distribution of C, N, O Elements*, ed. I. J. Danziger, F. Matteucci, and K. Kjär (ESO Conf. Workshop Proc. No. 21), p. 355.
Pettini, M., Hunstead, R. W., Murdoch, H. S., and Blades, J. C. 1983, *Ap. J.*, **273**, 436.
Russell, S. C., and Bessell, M. S. 1989, *Ap. J. Suppl.*, **70**, 865.
Sadakane, K., Jugaku, J., and Takada-Hidai, M. 1988, *Ap. J.*, **325**, 776.
Sargent, W. L. W., Steidel, C. C., and Boksenberg, A. 1989, *Ap. J. Suppl.*, **69**, 703.
Skillman, E. D., Kennicutt, R. C., and Hodge, P. W. 1990, *Ap. J.*, in press.
Skillman, E. D., Melnick, J., Terlevich, R., and Moles, M. 1988, *Astr. Ap.*, **196**, 31.
Sneden, C., and Crocker, D. A. 1988, *Ap. J.*, **335**, 406.
Snow, T. P., Weiler, E. J., and Oegerle, W. R. 1979, *Ap. J.*, **234**, 506.
Spinrad, H. 1987, in *High Redshift and Primeval Galaxies*, ed. J. Bergeron, D. Kunth, B. Rocca-Volmerange, and J. Tran Thanh Van (Paris: Ed. Frontières), p. 59.
Steidel, C. C., Sargent, W. L. W., and Boksenberg, A. 1988, *Ap. J. (Letters)*, **333**, L5.
Terlevich, R. 1987, in *High Redshift and Primeval Galaxies*, ed. J. Bergeron, D. Kunth, B. Rocca-Volmerange, and J. Tran Thanh Van (Paris: Ed. Frontières), p. 281.
Terlevich, R., and Melnick, J. 1981, *M.N.R.A.S.*, **195**, 839.
Tosi, M. 1988, *Astr. Ap.*, **197**, 33.
Tyson, N. D. 1988, *Ap. J. (Letters)*, **329**, L57.
Van Steenberg, M. E., and Shull, J. M. 1988, *Ap. J.*, **330**, 942.
Viallefond, F., Lequeux, J., and Comte, G. 1987, in *Starbursts and Galaxy Evolution*, ed. T. X. Thuan, T. Montemerle, and J. Tran Thanh Van (Paris: Ed. Frontières), p. 139.
Wheeler, J. C., Sneden, C., and Truran, J. W. 1989, *Ann. Rev. Astr. Ap.*, **27**, in press.
Wolfe, A. M. 1988, in *QSO Absorption Lines: Probing the Universe*, ed. J. C. Blades, D. A. Turnshek, and C. A. Norman (Cambridge: Cambridge University Press), p. 297.
Wolfe, A. M., Briggs, F. H., Turnshek, D. A., Davis, M. M., Smith, H. E., and Cohen, R. D. 1985, *Ap. J. (Letters)*, **294**, L67.
Wolfe, A. M., Turnshek, D. A., Smith, H. E., and Cohen, R. D. 1986, *Ap. J. Suppl.*, **61**, 249.

ALEC BOKSENBERG: Royal Greenwich Observatory, Herstmonceux Castle, Hailsham, East Sussex, BN27 1RP, England, UK

RICHARD W. HUNSTEAD: School of Physics, University of Sydney, N.S.W. 2006, Australia

MAX PETTINI: Anglo-Australian Observatory, P.O. Box 296, Epping, N.S.W. 2121, Australia