CHANDRA ACIS-S OBSERVATIONS OF THREE QUASARS WITH LOW-REDSHIFT DAMPED Lyα ABSORPTION: CONSTRAINTS ON THE COSMIC NEUTRAL GAS-PHASE METALLICITY AT REDSHIFT z ≈ 0.4

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Received 2002 August 8; accepted 2003 February 25

ABSTRACT

Chandra X-Ray Observatory ACIS-S spectra of three quasars that lie behind three foreground damped Lyα (DLA) absorbers are analyzed in order to attempt to determine the amount of photoelectric absorption due to metals present in their X-ray spectra. These absorbers are the three largest neutral hydrogen column density absorption-line systems known at low redshift (0.313 ≤ z_{abs} ≤ 0.524). They have H I column densities that lie in the range 3 \times 10^{21} ≤ N_{H I} ≤ 5 \times 10^{21} atoms cm^{-2}. At these redshifts the amount of photoelectric absorption at X-ray energies is primarily an indicator of the oxygen abundance. Since the column densities of these systems are so high, one would expect accurate metallicity measurements of them to yield a robust estimate of the column density–weighted cosmic neutral gas-phase metallicity at z ≈ 0.4. We consider cases in which the DLA gas has solar element abundance ratios and ones with the α group element abundance ratios enhanced. For the adopted assumptions, the column density–weighted cosmic neutral gas-phase metallicity of the nonenhanced elements (e.g., Zn) at z ≈ 0.4 likely lies in the range \approx 0.04–0.38 Z_{\odot}.

Subject headings: galaxies: abundances — galaxies: evolution — quasars: absorption lines — quasars: individual (AO 0235+164, PKS 1127−145, S4 0248+430)

1. INTRODUCTION

Observations of the chemical evolution of the universe provide independent constraints on the processes that govern cosmic nucleosynthesis and galaxy formation. This includes studies of the chemical makeup of the universe’s gaseous and stellar components with increasing redshift. With regard to the gaseous structures, it is widely recognized that intervening damped Lyα (DLA) absorption-line systems in quasar spectra are important probes of galaxy formation. They are not only the highest neutral hydrogen column density systems, with N_{H I} ≥ 2 \times 10^{20} atoms cm^{-2}, but consideration of them alone can be used to trace nearly all of the neutral gas in the universe out to at least redshift z = 3.5. The work on DLA systems has included studies of their cosmological incidence, mass density, and column density distribution (e.g., see Rao & Turnshek 2000, hereafter RT00, and references therein), the types and impact parameters of the luminous galaxies associated with them (e.g., Le Brun et al. 1997; Turnshek et al. 2001; Nestor et al. 2002; Turnshek, Rao, & Nestor 2002; Rao et al. 2003) and their kinematic properties along the sight lines to the background quasars (e.g., Prochaska & Wolfe 1999). Of special interest to the work presented here, Pettini and collaborators (e.g., Pettini et al. 1999 and references therein) have pioneered the method of using DLAs to measure the cosmic neutral gas-phase metallicity of the universe. However, it has not been possible to extend this work significantly below z ≈ 0.6 primarily due to the fact that, at these redshifts, the measurements must be done from space. This is because there are no suitable unsaturated heavy-element resonance lines in the optical, which can be used to reliably measure metallicities in high N_{H I} systems. For example, Zn ii λλ2026, 2062, which is a good tracer of the neutral gas and is relatively unaffected by depletion onto dust grains, is only visible in optical spectra at redshifts z > 0.6; and while Ca ii λλ3934, 3969 and Na i λλ5891, 5897 are visible in optical spectra, they are affected by complicated depletion processes and possible saturation effects. Moreover, although many measurements at z = 0 can be obtained from observations within the Galaxy, these measurements may not be representative of the universe as a whole. Therefore, given that neutral gas-phase metallicities have been measured for DLA systems at high redshifts, it would seem that the more appropriate way to empirically establish the mean metallicity of the universe at low redshift is to measure the asymptotic trend (and eventually the spread) in metallicity as one probes from high redshifts to low redshifts.

Here we report attempts to use Chandra X-Ray Observatory (CXO) ACIS-S observations of three quasars to measure the amount of photoelectric absorption due to metals in their spectra arising from three foreground low-redshift DLA systems. The three DLA systems studied here have 0.313 ≤ z_{abs} ≤ 0.524; they are the largest H i gas columns presently known at low redshifts (RT00), with 3 \times 10^{21} ≤ N_{H I} ≤ 5 \times 10^{21} atoms cm^{-2} as inferred from their DLA or 21 cm absorption lines. Since the K-shell ionization edge of oxygen occurs at a rest-frame energy of 0.53 keV and oxygen has relatively high absorptivity in comparison to the other heavy elements (Wilms, Allen, & McCray 2000), the amount of photoelectric absorption in the observed 0.3–8 keV energy range, where CXO ACIS-S is the most sensitive,
is primarily an indicator of a DLA system’s oxygen abundance. Furthermore, because the three systems are such high \( N_{\text{HI}} \) systems and the sum of their column densities are similar to those probed at higher redshifts, definitive measurements of the metal abundances in them would provide a robust determination of the cosmic neutral gas-phase metallicity at \( z \approx 0.4 \). This is an important constraint on the process of cosmic chemical evolution; specifically, it would be a measurement of the metallicity of the neutral gas, which is an important constituent of matter in the cyclic process of galaxy formation (e.g., collapse of gas to form large neutral gas structures, followed by the formation of molecular clouds and star formation, eventually leading to metal enrichment of the environment, and so on—but see Allen 2002 for a different perspective).

In principle, the use of photoelectric absorption to measure DLA metallicities has advantages. First, since atoms tied up in all states (e.g., including ionized species, molecules, and grains) contribute to photoelectric absorption, it can provide a more direct measurement of the total metallicity. Ionization corrections and depletion onto grains need not be considered. Second, due to shielding below the hydrogen Lyman limit in the absorber rest frame, the ionized hydrogen gas fraction is expected to be minimal relative to the total column, and searches for molecular hydrogen in DLA systems usually yield null results or very low molecular hydrogen fractions (e.g., Levshakov et al. 2002; Petitjean, Srianand, & Ledoux 2002 and references therein). Thus, the H i column densities inferred from the DLA or 21 cm absorption lines of these systems are indicative of the systems’ total column densities. One would therefore expect X-ray measurements of the DLA metallicities to be straightforward, in the sense that it would not be necessary to make corrections that depend on physical conditions. However, the main limitation of our \( CXO \) ACIS-S observations is that they are insufficient to readily resolve the oxygen K-shell ionization edge at a particular redshift. Instead, any photoelectric absorption signature is due to the cumulative effect of all the metals that may be present in objects at all intervening redshifts, and it is not possible to definitively determine the abundance of any individual element, or even isolate the amount of absorption due to metals at any particular redshift.

Our main aim here is to use \( CXO \) ACIS-S observations with reasonable assumptions to derive a preliminary measurement of the mean cosmic neutral gas-phase metallicity of the universe at redshift \( z \approx 0.4 \). We consider the measurement preliminary for three reasons. First, since absorption edges are not specifically identified, any detected absorption could arise from gas at some other redshift. However, since the probability of encountering a second strong X-ray absorber at \( z > 0 \) along any of these sight lines is small, we will simply assume that any detected absorption originates at the DLA redshifts. If this were not true, our measurements would then represent upper limits on the DLA systems’ metallicities. Second, it is possible that the absorbers we have studied here, while sampling the largest H i columns known at low redshift, are biased against including more chemically evolved systems that contain significant dust, thereby dimming background quasars and eliminating them from current samples that are being studied. This selection bias, if present, could cause us to underestimate the mean cosmic neutral gas-phase metallicity at \( z \approx 0.4 \). Third, \( CXO \) ACIS-S calibrations may change, especially at energies \( E < 0.4 \) keV. Nevertheless, we believe that the results reported here are valuable because they will, at the very least, provide some insight on attacking this problem in the future.

The organization of this paper is as follows. In § 2 we present the \( CXO \) ACIS-S quasar observations along the sight lines through three low-redshift DLA absorbers and the analyses and assumptions that lead to DLA metallicity determinations. In § 3 we combine our results with the DLA metallicity measurements of Pettini et al. (1999) at \( z > 0.6 \); this provides a preliminary estimate of the evolution of the column density–weighted cosmic neutral gas-phase metallicity at \( z < 3.5 \). A discussion of the limitations of these results and their implications is presented in § 4.

2. OBSERVATIONS, ANALYSES, AND NEUTRAL GAS-PHASE METALLICITY DETERMINATIONS

Observations of the three quasars were made with ACIS-S CCD 7 on \( CXO \). The journal of observations and other details are given in Table 1. First, we emphasize that an essential data processing step is to take into account the known decay of the ACIS quantum efficiency with time. Without this step, the derived metallicities for two of the DLA absorbers would have been about 0.3 dex higher. The final processing of each observation was performed using the XAssist software (Ptak 2001), which is a software package that assists in X-ray data reprocessing, initial source detection, and analysis. The data reductions were performed using CIAO version 2.2 and the data were reprocessed using CALDB version 2.9. Briefly, XAssist performs the basic data reduction steps recommended by the \( CXO \) X-Ray Center (\( CXC \)) “threads.” We also implemented an optional step, which removed the 0.5 pixel position randomization. Sources were detected using the WAVDETECT software, which detects sources using a wavelet procedure, and the background light curves were examined, which permitted removal of data taken during times of background flaring. Images of detected sources were fitted with elliptical Gaussian models in order to determine their spatial extent. The spectra were then binned to 20 counts per channel so that the \( \chi^2 \) statistic could be used to examine the goodness of each spectrum fit.

The DLA absorption redshifts and H i column densities for the three systems are included in Table 1. The H i column densities for the AO 0235+164 and PKS 1127–145 DLAs were derived by fitting Voigt damping profiles to the Ly\( \alpha \) absorption lines in their \( HST \) UV spectra (RT00). Unfortunately, the \( HST \) UV spectrum of S4 0248+430 has very low signal-to-noise ratio, so the H i column density of this system had to be derived from its 21 cm absorption profile (Lane & Briggs 2001) for an assumed spin temperature of 700 K. Adopting \( T_e = 700 \) K for this system is consistent with the measured spin temperatures of other DLA absorbers (Carilli et al. 1996; Lane et al. 1998).

Absorption of these quasars’ X-ray spectra is due to hydrogen, helium, and metals in the Milky Way Galaxy’s

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6 See http://cxc.harvard.edu.
7 See http://cxc.harvard.edu/cal/Links/Acis/acis/Cal_prods/qeDeg/index.html.
8 See also http://www.xassist.org.
| Quasar        | $z_{\text{em}}$ | $N_{\text{H}I}^{\text{GAL}}$ ($10^{21}$ cm$^{-2}$) | DLA  | $N_{\text{H}I}^{\text{DLA}}$ ($10^{21}$ cm$^{-2}$) | Redshifted DLA Oxygen K Edge (keV) | Observation Date | Cleaned Exposure Time (ks) | Total Counts 2–8 keV | Program ID | PI  |
|--------------|-----------------|---------------------------------|------|---------------------------------|---------------------------------|------------------|--------------------------|---------------------|------------|-----|
| AO 0235+164  | 0.94            | 0.87                            | 0.524| 4.5 ± 0.4                       | 0.35                            | 2000 Sep 20      | 27.5                     | 3577                | 1.61 ± 0.10 | 884 |
| S4 0248+430  | 1.31            | 0.89                            | 0.394| 3.9 ± 0.6                       | 0.38                            | 2000 Sep 27      | 22.8                     | 2570                | 1.60 ± 0.12 | 885 |
| PKS 1127–145 | 1.19            | 0.33                            | 0.313| 5.1 ± 0.9                       | 0.40                            | 2000 May 28      | 27.3                     | 15,818              | 1.20 ± 0.05 | 866 |

$^a$ Galactic H I column density derived from the 21 cm emission map of Hartmann & Burton 1997. Uncertainties are on the order of 2%.

$^b$ The quoted error is approximately a 1 σ error derived from the χ² statistics of the fit.

$^c$ The H I column density is derived using the 21 cm data reported in Lane & Briggs 2001 and is slightly revised from the W. Lane (2002, private communication) result reported in RT00.
interstellar medium (ISM) and in other intervening systems. To derive DLA metallicities we used the publicly available XSPEC software package (Arnaud 1996), which is often used for analysis of X-ray spectra. We have limited our analysis to the $0.4 < E < 8$ keV region because of calibration uncertainties outside this range, especially below 0.4 keV. We proceeded as follows. We assumed that a power law with index $\Gamma$ fitted to each quasar’s spectrum at energies $2 < E < 8$ keV could be extrapolated to lower energies to provide a reliable indication of the unabsorbed quasar X-ray spectrum. This is a reasonable assumption, since in no case is the absorbing column large enough to affect the continuum at $E > 2$ keV. Thus, the $2 < E < 8$ keV range fixes both the slope and normalization of the X-ray spectrum. Our tests using other quasars with similar emission redshifts in the CXO archives, which are not in environments where absorption at the emission redshift may be prevalent and that have no known DLA absorption, show that such extrapolations are generally consistent with quasar spectra in the $0.4 < E < 2$ keV range after accounting for Galactic absorption. For the three quasars considered here, the best-fit derived $\Gamma$s over this energy range are reported in Table 1. We assumed that the most accurate $\HI$ column densities of Galactic ISM gas along the sight lines to the three quasars are those derived from the 21 cm all-sky emission map of Hartmann & Burton (1997). These Galactic $\HI$ column densities are specified in Table 1. However, it should be noted that the $0.5 \times 0.5$ angular resolution of the $\HI$ map is much larger than the pencil beam of a quasar line of sight. Therefore, the $\HI$ column density derived from a 21 cm emission observation may only be approximate since the measured value is an average over the size of the beam. We also assumed that the metallicity of the Galactic gas is given by the ISM metallicity model of Wilms et al. (2000). Wilms et al. (2000) present a good justification for the metallicities they adopt. The oxygen abundance in their model is 0.58 $Z_\odot$, while the metallicities of nitrogen and carbon are 0.76 and 0.60 $Z_\odot$, respectively. The Wilms et al. (2000) ISM metallicity model is one of the options incorporated into the XSPEC software package. At the same time, in order to assess how our final results on DLA metallicities depend on Galactic gas metallicity, we also derived DLA metallicities under the assumptions of zero and solar Galactic gas metallicity, where the solar metallicity is that specified by Feldman (1992). We note that recent investigations generally indicate that the Galactic gas metallicity is demonstrably sub-solar, i.e., $\approx 0.65 Z_\odot$ (e.g., Sembach et al. 1995; Roth & Blades 1995; Meyer, Jura, & Cardelli 1998). For one Galactic sight line, Meyer et al. (1994) reported a Galactic gas metallicity of 0.4 $Z_\odot$.

For the assumptions given above, and for two different cases of relative DLA metal abundances, we then used XSPEC to determine the best-fit overall metallicities for the three DLA systems. For one case we assumed that the relative DLA metal abundances had solar ratios as specified by Feldman (1992), and for the other case we assumed that the $\alpha$ group element relative abundances (specifically O, Ne, Mg, Si, S, Ar, and Ca) were enhanced by a factor of 2.5 relative to the Feldman (1992) solar metal ratios. Consideration of the enhanced $\alpha$ group element case seems appropriate since the X-ray measurements should be most affected by the oxygen abundance, whereas at higher redshift the most reliable measurements of the overall DLA metallicity come from studies of zinc, which tracks iron but shows little or no evidence for depletion onto grains. The need to consider the possible effects of $\alpha$ group abundance enhancements is clearly evident from studies of a variety of stellar populations (e.g., see Prochaska et al. 2000 and references therein). The degree of $\alpha$ group metals enhancement generally depends on the overall metallicity, with $\Omega/\text{Fe} = -0.4\text{[Fe/H]}$ being close to the general trend. For example, $\text{[Fe/H]} = -1$ (i.e., a metallicity of $0.1 Z_\odot$) is indicative of an enhancement of $\alpha$ group metals by a factor of 2.5 times solar. Since the higher redshift DLA measurements of Pettini et al. (1999) indicate that zinc metallicities are typically $<0.1 Z_\odot$, considering a case where $\alpha$ group element abundances are enhanced by a factor of 2.5 seems appropriate.

The derived overall DLA metallicities and errors are reported in Table 2 for the six combinations of assumptions about Galactic-gas metal ratios (three different cases) and DLA-gas metal ratios (two different cases), which were outlined above. Also, because the error source was quite different, the error in photon index was not propagated to arrive at the quoted errors; but this is an insignificant component to the error budget. This is especially true given the various interpretive assumptions we have made (i.e., the six combinations of assumptions mentioned above plus assumptions put forth in § 1). Uncertainties in the Galactic and DLA $\HI$ column densities have also not been propagated, but again, these contributions to the error budget are small relative to the interpretive assumptions. The $\chi^2$ statistic per number of degrees of freedom is listed in Table 2 for each fit. This fit refers to the entire $0.4 < E < 8$ keV range. These statistics show all of the fits to be fairly reasonable, so this is an indication that X-ray observations at such low resolution are unable to distinguish between the six cases. Because of the overwhelming evidence that the Galactic gas ISM metallicity is likely to be close to that specified by Wilms et al. (2000), we adopt these results in the remainder of the paper.

The left and right panels of Figures 1, 2, and 3 show the effect of DLA gas absorption on the quasar X-ray spectrum. Both panels include a power-law fit in the 2–8 keV range that is extrapolated to 0.4 keV to obtain the unabsorbed quasar X-ray spectrum and absorption by Galactic gas according to the Wilms et al. (2000) ISM metallicity model. The right panel shows the best-fit model with DLA gas absorption also included. The results indicate that, for the AO 0235+164 and S4 0248+430 absorbers, the overall DLA metallicities may be substantial, i.e., greater than 0.1 $Z_\odot$, and metallicities only a factor of $\approx 2$ less than Galactic ISM values cannot be ruled out. In § 4.1.2 we do, however, discuss the possibility that another significant absorber may be present in the S4 0248+430 spectrum. As for the PKS 1127−145 DLA absorber, for our adopted assumptions we find that there is no evidence for absorption due to metals at the DLA redshift. In fact, our analysis underpredicts the X-ray flux in the $0.4 < E < 2$ keV region even when the DLA gas metallicity is zero. This can be seen by inspecting the right panel of Figure 3, where the X-ray spectrum is seen to lie slightly above the model with zero DLA metallicity. This may indicate a problem with our assumptions in the PKS 1127−145 analysis, which is further discussed in § 4.1.3.

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9 See also http://xspec.gsfc.nasa.gov.
### TABLE 2
**Derived Neutral Gas-Phase Metal Abundances for Three Low-\(z\) Damped Ly\(\alpha\)/C11 Systems**

| Quasar      | \(N_{\text{H}_1}\)^\(a\) (10\(^2\) atoms cm\(^{-2}\)) | Galactic Metallicity Model\(^a\) | \(z_{\text{abs}}\) | \(N_{\text{DLA}}\)^\(a\) (10\(^2\) atoms cm\(^{-2}\)) | Solar Ratio Metals\(^b\) | Enhanced \(\alpha\) Metals\(^b\) | Solar Ratio Metals | Enhanced \(\alpha\) Metals |
|-------------|-----------------------------------------------------|---------------------------------|-------------------|-----------------------------------------------------|--------------------------|--------------------------|---------------------|--------------------------|
| AO 0235+164 | 0.87                                                | 0                               | 0.524             | 4.5 ± 0.4                                            | 0.61 ± 0.07              | 0.29\(^{+0.04}_{-0.03}\) | 150/131             | 149/131                  |
|             |                                                     | ISM                             |                   |                                                     | 0.37 ± 0.06               | 0.19 ± 0.03              | 143/131             | 143/131                  |
|             |                                                     | Solar                            |                   |                                                     | 0.24 ± 0.06               | 0.11 ± 0.03              | 142/131             | 142/131                  |
| S4 0248+430 | 0.89                                                | 0                               | 0.394             | 3.9 ± 0.6                                            | 0.46 ± 0.08               | 0.22 ± 0.04              | 84/100              | 84/100                   |
|             |                                                     | ISM                             |                   |                                                     | 0.23 ± 0.07               | 0.11 ± 0.04              | 83/100              | 83/100                   |
|             |                                                     | Solar                            |                   |                                                     | 0.10\(^{+0.08}_{-0.07}\)  | 0.04\(^{+0.04}_{-0.03}\) | 367/300             | 367/300                  |
| PKS 1127−145\(^d\) | 0.33                                          | 0                               | 0.313             | 5.1 ± 0.9                                            | (0 < 0.0035)             | (0 < 0.0024)             | 389/300             | 389/300                  |
|             |                                                     | ISM                             |                   |                                                     | (0 < 0.0032)             | (0 < 0.0022)             | 367/300             | 367/300                  |
|             |                                                     | Solar                            |                   |                                                     | (0 < 0.0029)             | (0 < 0.0020)             | 475/300             | 371/300                  |

**Note.**—The derived DLA metallicities hold for the specified values of Galactic \((z = 0)\) \(N_{\text{H}_1}\) and metallicity. If additional absorption is present, these results represent upper limits on DLA metallicity (see text for assumptions and discussion).

\(^a\) Three Galactic gas metallicity models were considered: zero metallicity, the ISM metallicity model of Wilms et al. 2000, and the solar metallicity model of Feldman 1992. The ISM metallicity model used to construct Fig. 5 has an oxygen abundance of 0.58 \(Z_{\odot}\), a nitrogen abundance of 0.76 \(Z_{\odot}\), and a carbon abundance of 0.60 \(Z_{\odot}\). (see § 3).

\(^b\) The DLA metallicities quoted here were inferred from the XSPEC results so that they could be compared with the zinc metallicity results at high redshift (e.g., Pettini et al. 1999), where the DLA zinc abundance is given relative to the solar zinc abundance. In the case of DLA gas with \(\alpha\) group elements enhanced by a factor of 2.5, one sees that the inferred equivalent zinc metallicity is lower; this is because the abundance of elements such as oxygen are enhanced in the gas, allowing the abundance of elements like zinc to be lower and yet produce the best fit to the X-ray spectrum. The quoted errors are approximately 1 \(\sigma\) for the assumptions made.

\(^d\) Spectrum corrected for pileup. However, the inferred low metallicity may be an artifact of assuming that the unabsorbed X-ray spectrum can be described by a single power law.

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**Fig. 1.**—Chandra ACIS-S spectrum of the quasar AO 0235+164. **Left:** Power-law fit to the 2–8 keV region of the spectrum, extrapolated to 0.4 keV while only accounting for Galactic ISM absorption. **Right:** Same power-law fit extrapolated to 0.4 keV but including the effects of both Galactic ISM absorption and DLA absorption. Details are reported in the text and tables.

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Fig. 2.—*Chandra* ACIS-S spectrum of the quasar S4 0248+430. *Left:* Power-law fit to the 2–8 keV region of the spectrum, extrapolated to 0.4 keV while only accounting for Galactic ISM absorption. *Right:* Same power-law fit extrapolated to 0.4 keV but including the effects of both Galactic ISM absorption and DLA absorption. Details are reported in the text and tables.

Fig. 3.—*Chandra* ACIS-S spectrum of the quasar PKS 1127–145. *Left:* Power-law fit to the 2–8 keV region of the spectrum, extrapolated to 0.4 keV while only accounting for Galactic ISM absorption. *Right:* Same power-law fit extrapolated to 0.4 keV but including the effects of both Galactic ISM absorption and DLA absorption. Note that fixing $N_H$ in the DLA system to the value derived from the fit to the DLA line in the HST UV spectrum and assuming zero DLA metallicity causes us to underpredict the flux in the X-ray spectrum in the $0.4 < E < 1$ keV range. Details are reported in the text and tables.
We note that Bechtold et al. (2001) also recently performed an XSPEC analysis to study the metallicity of the DLA absorber in PKS 1127−145 (see both our Fig. 3 and Fig. 3 in Bechtold et al. 2001). However, pileup, which is a problem with the data (G. Chartas 2002, private communication), was not considered in their analysis. We attempted to model and remove this effect. While the effects of pileup can be mitigated by going off-axis, one would have needed to be greater than 5° off-axis to begin to obtain a significant reduction in pileup (G. Chartas 2002, private communication).

In the Bechtold et al. (2001) analysis, some emphasis was placed on exploring the parameter spaces of X-ray spectrum fits, including the possibility of absorption at other redshifts. Ignoring the fact that pileup was not considered in their analysis, their work indicated that, indeed, the most plausible redshift for X-ray absorption was the DLA redshift ($z_{abs} = 0.313$). For Galactic absorption along the PKS 1127−145 sight line they used the observations of Murphy et al. (1996) and adopted an H i column density of $3.8 \times 10^{20}$ atoms cm$^{-2}$, which is about 16% larger than what we used based on the observations of Hartmann & Burton (1997). The metallicity they adopted for the Galactic ISM gas was presumably solar. However, when making fits to any DLA X-ray absorption, they chose to fix the DLA gas metallicity to be either zero (primordial) or solar (processed), and then they determined best-fit $N_{H_1}$ values for absorption of the X-ray spectrum. They found that solar metallicity gas with $N_{H_1} = 1.2 \times 10^{21}$ atoms cm$^{-2}$ provided the best fit to the DLA-absorbed X-ray spectrum. Since this is 23% of the H i column indicated by the fit to the DLA line in the HST UV spectrum (RT00), they inferred a metallicity of 0.23 $Z_\odot$ for the PKS 1127−145 DLA absorber. However, they also showed that zero-metallicity DLA gas at $z_{abs} = 0.313$ with $N_{H_1} = 3.3 \times 10^{21}$ atoms cm$^{-2}$ can adequately absorb and explain the X-ray spectrum. But in this case the required $N_{H_1}$ value is still only 63% of the H i column derived from the HST spectrum. This conclusion is implausible since (as Bechtold et al. 2001 also note) metal absorption lines are observed in the quasar spectrum at the DLA redshift and the H i column density is greater than $N_{H_1} = 3.3 \times 10^{21}$ atoms cm$^{-2}$. It would then follow that DLA gas with the known column density, i.e., $N_{H_1} = 5.1 \times 10^{21}$ atoms cm$^{-2}$, cannot have a metallicity of 23% solar and still be consistent with the X-ray spectrum.

The appropriate way to proceed, which is the approach we took in our analysis, is to run the XSPEC software by fixing the DLA H i column density (since it is known) while allowing the overall DLA absorber metallicity to be a free parameter. This takes advantage of the fact that fitting a Voigt profile to the UV DLA absorption line provides a metallicity independent method of determining the H i column density.

### 3. COLUMN DENSITY–WEIGHTED COSMIC NEUTRAL GAS-PHASE METALLICITY

The integrated H i column densities of 42 high-redshift DLA systems in five arbitrary redshift bins (e.g., see Pettini et al. 1999) is comparable to the integrated H i column density of the three systems we have studied here at $z \approx 0.4$. This is illustrated in Figure 4. The distinguishing difference of the summed H i column densities illustrated in Figure 4 is that the lowest redshift bin (this work) pertains to metallicity measurements at X-ray energies, while the higher redshift bins pertain to metallicity measurements made at UV/optical wavelengths. From this figure it is clear that if metallicity determinations of sufficient accuracy existed for the three individual low-redshift DLA systems studied here, a very interesting result could be inferred on the mean column density–weighted cosmic neutral gas-phase metallicity at $z \approx 0.4$. For this work, we adopt a definition analogous to the one used by Pettini et al. (1999) to determine the mean column density–weighted metallicity of Zn. In the absence of an effect that would bias our sample (see §1), such a measurement would represent the actual cosmic neutral gas-phase metallicity. Moreover, such a determination would be robust in the sense that future metallicity measurements of many lower $N_{H_1}$ systems would only slightly modify the result because of their low weight.

For the assumption of Galactic ISM gas with the metallicity specified by Wilms et al. (2001), we have determined the following from the XSPEC fits. If DLA gas has solar ratio metals, the column density–weighted neutral gas-phase metallicity at $z \approx 0.4$ is 0.19 ± 0.11 $Z_\odot$. Alternatively, if the DLA gas has $\alpha$ group metals that are enhanced by a factor of 2.5 over solar ratios, we find a metallicity of 0.10 ± 0.06 $Z_\odot$ for the nonenhanced elements (e.g., Zn). In addition, if one were to take the view that the PKS 1127−145 DLA metallicity results should be excluded from this analysis (see §2 and §4.1.3), the results become 0.31 ± 0.07 $Z_\odot$ (for solar ratio metals) and 0.15 ± 0.04 $Z_\odot$ (for nonenhanced metals mixed with enhanced $\alpha$ group metals).

As discussed earlier, depletion onto grains is not a concern for X-ray–derived metallicities. Thus, it is possible to make a comparison between the X-ray–derived low-redshift DLA metallicity results and those derived from the Zn ionic...
lines in high-redshift DLAs. This is because Zn is not significantly depleted onto grains and the columns of Zn not in the singly ionized state are expected to be relatively small, especially for the large H I column densities involved here (e.g., Vladilo et al. 2001). Since we quote metallicities for the non-enhanced elements in both cases in the preceding paragraph, the results can be directly compared with the DLA [Zn/H] metallicities considered by Pettini et al. (1999) at high redshift. These comparisons are made in Figure 5 (all three DLA absorbers) and Figure 6 (excluding the PKS 1127–145 DLA absorber). The effect of using a Galactic gas metallicity other than the ISM values of Wilms et al. (2000) can be judged from the range of results presented in Table 2. Figures 5 and 6 show that the X-ray observations cannot be used to rule out a significant increase in the column density–weighted neutral gas phase metallicity with decreasing redshift by \( z \approx 0.4 \). However, given the various assumptions we have made, and the formal errors in our metallicity determinations for these assumptions, the results should also not be interpreted as evidence for an increase in metallicity with decreasing redshift.

![Graph](image)

**Fig. 5.** — Log of the column density–weighted cosmic neutral gas-phase metallicity derived from DLA systems vs. cosmic time (bottom horizontal axis) and redshift (top horizontal axis) for a cosmology with \( H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_m = 0.5 \), and \( \Lambda = 0 \). The low-redshift metallicity determination was derived from XSPEC analysis of the Chandra ACIS-S X-ray spectra of three quasars containing DLA systems (Tables 1 and 2). The horizontal "error bars" represent the redshift intervals covered (e.g., \( 0.313 < \zabs < 0.524 \) for the low-redshift point). The high-redshift metallicity determinations, shown as open squares, are those for zinc (a non-\( \alpha \)-group element) as reported by Pettini et al. (1999). The two low-redshift metallicity determinations shown here (which are slightly displaced in redshift so that they can be distinguished in the figure) are those derived under the assumption that Galactic (\( z = 0 \)) ISM gas absorption follows the metallicity model recommended by Wilms et al. (2000). Other assumptions are discussed in \( \S \) 2 of the text. The point plotted with an open triangle was derived under the assumption that the DLA gas has solar ratio metals as specified by Feldman (1992). The low-redshift point plotted with an open circle was derived under the assumption that DLA \( \alpha \) group metals were enhanced by a factor of 2.5 over solar ratio metals. By considering these two cases (\( \alpha \) group elements not enhanced and \( \alpha \) group elements enhanced), a fair comparison can be made with the higher redshift metallicity determinations based on zinc. The horizontal dashed line indicates solar metallicity; the horizontal dotted line indicates Galactic ISM gas metallicity.

4. DISCUSSION

4.1. Comments on Individual Damped Ly \( \alpha \) Systems

Of course, analysis of the Chandra data is not limited to results on DLA absorption in these quasars. Additional analysis on the fields containing these quasars can be found in the XAssist output. With regard to individual DLA systems, various details should be noted here for each of the objects studied. These are discussed below.

4.1.1. AO 0235+164 (\( \zabs = 0.524 \))

AO 0235+164 is a well-known object that has properties of so-called optically violent variables (OVVs). It has been described as a blazar, a BL Lac object, and a high-polarization quasi-stellar object (QSO) (e.g., see Burbidge et al. 1996 and references therein). The high column density absorption system at \( \zabs = 0.524 \) was first discovered in redshifted 21 cm absorption by Roberts et al. (1976). Subsequently, Wolfe, Briggs, & Davis (1982) showed the 21 cm absorption to be variable, and Briggs (1983) proposed a kinematic model for the absorption.

Cohen et al. (1999) used their HST UV spectrum of AO 0235+164 to study the DLA line associated with the 21 cm absorption and deduce the H I column density and other properties of the absorber. They found \( N_{H_1} = 5 \times 10^{21} \text{ atoms cm}^{-2} \); they also reported evidence for dust at the absorption redshift, but at a significantly lower level than what would be expected for a Galactic line of sight at similar H I column density. Our independent analysis of the HST UV spectrum of AO 0235+164 yielded \( N_{H_1} = 4.5 \times 10^{21} \text{ atoms cm}^{-2} \) for the DLA absorber, which is the value adopted in our analysis (Tables 1 and 2).

Using data taken with the Einstein Observatory Imaging Proportional Counter in 1980 August, Madejski (1994)
performed an analysis that showed the metallicity of the DLA absorber to be $2 \pm 1 \, Z_{\odot}$ for the assumptions he made. This is a higher metallicity than what we infer from the superior Chandra data.

Finally, HST imaging and follow-up spectroscopy of the field by Burbidge et al. (1996) has led to a rather surprising serendipitous discovery about the environment surrounding the AO 0235+164 DLA absorber. There are two optical identifications of objects (called “A1” and “A2”) at redshift $z \approx 0.524$ that lie within $2''$ of the AO 0235+164 sight line. The nearer object, A1, is separated by $1''08$ from the sight line and has a WFPC2 instrumental magnitude of $m_{F702W} = 21.3$. It is a resolved emission-line galaxy, appearing as a structure that is elongated $2''$, with a brighter inner region that has an extent of $0'15$. Object A is separated by $1''96$ from the sight line and has $m_{F702W} = 20.6$. It appears as an unresolved point source surrounded by faint nebulosity. Its spectrum exhibits broad emission lines as well as broad absorption lines (BALs), which have a maximum outflow velocity ($6000 \, \text{km s}^{-1}$); this maximum velocity is on the low side of what is normally observed in BAL QSOs. However, Burbidge et al. (1996) note that, based on object A’s magnitude and the surrounding faint nebulosity, it might best be classified as a Seyfert 1 active galactic nucleus (AGN), in which case the outflow velocities are rather large in comparison with those sometimes seen in AGN. In any case, the presence of both an emission-line galaxy (object A1) and a BAL QSO/AGN (object A) in the vicinity of the AO 0235+164 DLA absorber is suggestive of a chemically evolved environment.

4.1.2. S4 0248+430 ($z_{\text{abs}} = 0.394$)

The identification of the DLA absorber in S4 0248+430 is based on 21 cm absorption (Lane & Briggs 2001). As such, a DLA absorption line was not used to derive its H I column density. Instead, a reasonable value of the spin temperature was assumed for the H I column density derivation ($\S$ 2). The fact that the continuum was too faint to observe the DLA line in S4 0248+430’s HST UV spectrum (RT00) may be an indication that significant dust is present along the sight line. This sight line also represents a case in which significant metal-line absorption from objects other than the DLA system are clearly present. However, it is unclear whether the column densities of these other absorption systems are sufficient to give rise to X-ray absorption. In particular, in addition to the DLA system at $z_{\text{abs}} = 0.394$, Womble et al. (1990) identify two other distinct low-ionization systems at $z_{\text{abs}} = 0.452$ and 0.452. The rest equivalent widths of the Mg II lines at $z_{\text{abs}} = 0.452$ (Womble et al. 1990) are small enough that this system is not likely to be in the DLA regime (RT00). Indeed, our HST spectrum of the Lyα line at $z_{\text{abs}} = 0.452$ (RT00) indicates that this system is not damped. Thus, we conclude that the $z_{\text{abs}} = 0.452$ does not give rise to any appreciable X-ray absorption. However, as discussed below, X-ray absorption from the $z_{\text{abs}} = 0.052$ is a possibility.

The system at $z_{\text{abs}} = 0.052$ is likely associated with a luminous spiral galaxy at redshift $z = 0.052$, which is offset $14''7$ from the sight line to S4 0248+430 (Womble et al. 1990; Sargent & Steidel 1990). At such low redshift, light from this extended luminous galaxy overlaps and contaminates the image of the background quasar. Both Womble et al. (1990) and Sargent & Steidel (1990) detected Ca ii and Na i absorption at this redshift in the quasar’s spectrum. The high-resolution spectrum of Womble et al. (1990) shows two primary absorption components at this redshift. Their curve-of-growth analysis indicates that the total Ca ii column density of both components is $\approx 5.3 \times 10^{15}$ atoms cm$^{-2}$. If there were no calcium depletion onto grains and this was indicative of a neutral gas column with solar abundances, the total H i column density would be $\approx 2.3 \times 10^{19}$ atoms cm$^{-2}$, which would not be large enough to cause significant X-ray absorption. However, the curve-of-growth error analysis of Womble et al. (1990) admits the possibility that the Ca ii column density is significantly higher. Moreover, calcium is easily depleted onto grains and, as discussed above, there is evidence for dust reddening along this sight line. Thus, we cannot rule out the possibility that some of the X-ray absorption seen in the S4 0248+430 spectrum comes from this system.

4.1.3. PKS 1127−145 ($z_{\text{abs}} = 0.313$)

The properties of the various emission-line galaxies near redshift $z = 0.313$ along the sight line toward PKS 1127−145 are described by Lane et al. (1998), Nestor et al. (2002), and Rao et al. (2003). Most notably, there is a large patchy/irregular low surface brightness structure that is very extended in the north-south direction and $\approx 3'5$ to the west of the sight line.

As discussed in $\S$ 2, Bechtold et al. (2001) originally studied the possibility of X-ray absorption from this DLA system. This same group has also made a detailed study of the Chandra X-ray images of the field (Siemiginowska et al. 2002). Recall that the main problem we encountered in our analysis of X-ray absorption from this DLA absorber ($\S$ 2) was that, even with zero-metallicity DLA gas, after Galactic absorption was taken into account the DLA absorption column required to explain the X-ray spectrum at energies below 2 keV was less than what was measured in the RT00 HST UV spectrum. This suggests that extrapolation of the power-law fit to the 2–8 keV region to lower energies under-predicts the X-ray flux in the 0.4–2 keV region, indicating that there may be, for example, a significant soft X-ray energy excess in PKS 1127−145. Siemiginowska et al. (2002) present some evidence for this; however, the flux from an X-ray jet identified by Siemiginowska et al. (2002) in the X-ray image appears to be negligible. In any case, estimating the metallicity of this object is problematic. We can only conclude that in this DLA system there is presently no evidence for relatively high metallicity, unlike the evidence in the other two DLA absorbers.

4.2. Limitations of the Results and Implications

The details of the objects studied ($\S$ 4.1) and the spectral resolution of the Cxo ACIS-S observations present limitations to the direct detection of metals at the DLA redshifts. Thus, our results and interpretation depend on the reliability of the assumptions we have made. For now, we believe that our assumptions represent the most probable case. This leads to the conclusion that we cannot rule out the possibility of significant evolution of the cosmic neutral gas-phase metallicity in the form of increasing metallicity with decreasing redshift. In fact, Figure 6 suggests this trend, but the results are also consistent with no evolution (Fig. 5).
The statistics of low-redshift DLAs (RT00) support the assumption that the identified DLA system in each quasar spectrum is the dominant large column density system along the sight line to the quasar. Except in the case of S4 0248+430, the possibility of other significant absorption can be ruled out with some degree of certainty (§ 4.1). Also, because our sample is a radio-selected one, it probably does not suffer from the bias mentioned in § 1, namely, that chemically evolved DLA systems with significant dust are excluded from the sample because of optical dimming of background quasars. If present, this selection bias would cause an underestimate of the mean cosmic neutral gas-phase metallicity at $z \approx 0.4$.

The results reported here show that CXO ACIS-S observations can be used to investigate some important issues involving the X-ray absorption properties of DLA gas. However, our present results on the objects considered here indicate that X-ray grating observations are required in order to definitively make DLA metallicity measurements at X-ray energies. Such observations would not only permit individual features from redshifted metals to be observed, it would also eliminate the simplifying assumption that the unabsorbed X-ray spectrum can be modeled with a simple power law.

We want to thank those involved with the CXO for making it a user-friendly facility. In addition, we want to especially thank the referee, George Chartas, for an excellent report that allowed us to substantially improve the paper.

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