METAL LINES ASSOCIATED WITH Lyα ABSORBERS: A COMPARISON OF THEORY AND OBSERVATIONS

UFFE HELLSTEN, ROMEEL DAVÉ, AND LARS HERNQUIST
University of California, Lick Observatory, Santa Cruz, CA 95064

DAVID H. WEINBERG
Ohio State University, Department of Astronomy, Columbus, OH 43210

AND

NEAL KATZ
Department of Physics and Astronomy, University of Massachusetts, Amherst, MA 01003-4525

Received 1997 January 10; accepted 1997 May 12

ABSTRACT

We study the metal-line absorption of C IV, C II, Si IV, and N V at redshifts z = 3.5 to z = 2 within the framework of a cosmological model for the Lyα forest, comparing the results of numerical simulations to recent observations by Songaila & Cowie (SC). We find that the observed mean value of the C IV/H I ratio at z ≈ 3 is reproduced if a uniform metallicity of [C/H] ≈ −2.5 is assumed in our model, but that the observed scatter in this ratio is larger than predicted, implying a scatter of roughly an order of magnitude in the metallicity of the absorbing systems. The enrichment pattern that is required for our model to match SC’s C IV observations is very similar to that predicted by other simulations of reionization and early metal enrichment in this type of cosmological scenario.

Our model predicts no significant evolution in the mean values of metal-line column densities between z = 3.5 and z = 2. Comparison of the predicted and observed numbers of Si IV and N V systems suggests that the photoionizing background radiation field at z ≈ 3 is somewhat softer than that proposed earlier. Our model does not account for the increase in the Si IV/C IV ratio at z ≈ 3.2 found by SC. While the latter study suggested that the increase could be explained by a softening of the radiation field caused by He II absorption at z ≳ 3, such a modification does not raise the mean value of Si IV/C IV significantly in our simulation, because it shifts numerous weak Si IV systems to just above the detection limit, thus keeping the mean column density of observable Si IV systems low.

Subject headings: cosmology: theory — galaxies: abundances — galaxies: evolution — quasars: absorption lines

1. INTRODUCTION

Spectra of high-redshift quasi-stellar objects (QSOs) are densely populated with absorption lines blueward of the Lyα emission peak. This “Lyα forest” is interpreted as arising from absorption by neutral hydrogen that is cosmologically distributed along the line of sight to the QSO (e.g., Lynds 1971; Sargent et al. 1980). For more than a decade it was not known whether the gaseous systems responsible for the Lyα forest were chemically pristine. Meyer & York (1987) presented early evidence for metal lines in the forest, and within the last several years observations with improved spectral resolution and signal-to-noise ratio (S/N) have revealed the presence of heavy elements in a significant fraction of Lyα systems with moderate H I column densities (∼10¹⁴–10¹⁵ cm⁻²). Analyzing data from the HIRES spectrograph on the Keck 10 m telescope, Cowie et al. (1995) find that ∼50% of identified Lyα lines with log N_H I > 14.5 have associated C IV absorption. This finding is roughly consistent with that of Womble, Sargent, & Lyons (1995), who infer C IV absorption in 40%–45% of all Lyα systems with log N_H I > 14.3. More recently, Songaila & Cowie (1996, hereafter SC) presented an analysis of even higher S/N spectra and found C IV absorption in ∼75% of all systems with log N_H I > 14.5 and in ∼90%–100% of those with log N_H I > 15.2. In addition, they detected absorption from Si IV, C II, and N V in a number of these systems.

In the present paper we analyze the predicted metal-line absorption from a hydrodynamic cosmological simulation of the high-redshift intergalactic medium (IGM), and we compare these predictions to the observations of SC. The analysis of such simulations during recent years (e.g., Miralda-Escudé et al. 1994; Zhang, Anninos, & Norman 1995; Pettitjean, Mück, & Kates 1996; Hernquist et al. 1996) has established a convincing general scenario in which the Lyα forest is produced by regions of moderate overdensity in a hierarchically clustering universe that is pervaded by an ionizing radiation field presumed to originate from the QSOs (for related semianalytic modeling see, e.g., Bi 1993; Bi & Davidsen 1997; Hui, Gnedin, & Zhang 1997). These cosmological Lyα forest models predict QSO absorption features that resemble those observed, and they reproduce the column density and Doppler parameter distributions down to the lowest observable column densities (Miralda-Escudé et al. 1996; Davé et al. 1997, hereafter DHWK; Zhang et al. 1997). The interpretation of the metal-line data within the framework of these models of the Lyα forest constitutes a further test of the validity of the models and provides potentially valuable insight into the physical conditions prevailing in the IGM, such as gas densities, temperatures, and the shape and intensity of the ionizing radiation field. It is even conceivable that comparisons between such models and the wealth of forthcoming observations will constrain the...
underlying cosmological parameters, although this possibility remains to be demonstrated.

Haehnelt, Steinmetz, & Rauch (1996) and Rauch, Haehnelt, & Steinmetz (1996) have pioneered the technique for incorporating metals into cosmological Lyα models. They endow the gas with a uniform metallicity, postulated to have arisen from a (Population III?) burst of star formation at a significantly earlier time; they then compute the ionization states based on the assumption of a uniform ionizing background of a given strength and spectral shape. By generating and analyzing artificial metal-line spectra along lines of sight (LOS) through cosmological hydrodynamical simulations, these authors compare their models to a number of observables, such as the Doppler parameter and column density distributions, C IV/H I and other metal-line ratios, and two-point correlation functions; they generally find acceptable agreement between their models and observations.

In the present work we adopt a similar approach, but whereas the gaseous regions studied in the above-mentioned works are overdense regions that eventually evolve into galaxies, we utilize a larger simulation that allows us to consider a random region of the universe and make quantitative predictions regarding the statistics of observable metal systems and their evolution in redshift. Through most of this paper we will assume that the simulation provides an adequate physical model of the IGM and will use comparison to observations to obtain information about the metal enrichment of the diffuse gas and the spectral shape of the ionizing radiation field. This assumption is supported by the previous successes of the model mentioned above, and we will argue in § 4 that the model’s success in predicting the relative numbers of observable metal-line systems provides further evidence in favor of this physical picture of the high-redshift IGM.

2. THE MODEL

The cosmological simulation analyzed here is identical to that described in DHWK. A 22.222 comoving Mpc box of baryonic and dark matter is evolved from z = 49 to z = 2 using TreeSPH (Hernquist & Katz 1989), assuming a cold dark matter (CDM) spectrum of density fluctuations and the parameters σ8 = 0.7, h = 0.5, and Ωc = 0.05, where h ≡ H_0/(100 km s⁻¹ Mpc⁻¹). The mass per gas and dark matter particle is m_p = 1.5 × 10⁸ M⊙ and m_DM = 2.8 × 10⁹ M⊙, respectively. A spatial uniform photoionizing background radiation field is imposed with the shape suggested by Haardt & Madau (1996); hereafter HM and an intensity chosen to reproduce the mean H I optical depth as observed by Press, Rybicki, & Schneider (1993). For further details concerning the simulation method, see Katz, Weinberg, & Hernquist (1996).

Artificial spectra were generated along 400 random LOS through the simulation box for each of the redshifts z = 2.0, 2.33, 2.66, 3.0, and 3.5 by binning the gas in distance along the LOS and calculating smoothed particle hydrodynamics (SPH) estimates of density, temperature, and velocity v = v_Hubble + v_pec of the relevant species. The mass of a given species, such as C IV, in each SPH particle is evaluated prior to smoothing using

\[ m_{C IV} = m_p Z_C f_{C IV}(\rho, T, J), \]

where \( Z_C \) is the mass fraction of the metal (here carbon) in the gas, and \( f_{C IV} \) is the fraction of the total carbon atoms that are found in the ionization stage C IV. Assuming the ionization to be in or near equilibrium, \( f_{C IV} \) is a function of the local gas density \( \rho \), temperature \( T \), and the properties of the photoionizing background \( J \). We evaluate \( f_{\text{species}} \) using the code CLOUDY 90 (Ferland 1996), creating a lookup table in \( \rho \) and \( T \) given the adopted \( J \), and interpolating within this table.

The spatial bins are projected into their corresponding velocity bins, their velocities convolved with a thermal Doppler broadening function. This procedure yields the redshift–space density profile \( n(z) \) along the LOS; \( n(v)dv/H(z) \) is the column density of a species with observed radial velocity in the interval \( v \) to \( v + dv \). The optical depth at velocity \( v \) is

\[ \tau_v = \frac{\pi v^2}{m_p c} \int n(z) n(v) dz, \]

where \( \tau_v \) is the product of the oscillator strength and the rest transition wavelength \( \lambda \) for the particular absorption line (Gunn & Peterson 1965). The observed wavelength is \( \lambda_o = \lambda(1 + \nu/c)(1 + \tau_v) \).

The resulting artificial spectra (e⁻ν vs. v) are degraded to Keck HIRES resolution (Δλ = 0.06 Å), and noise is added with a S/N comparable to that in the HIRES spectrum of Q1422+231 (SC), i.e., a S/N of roughly 60 in the forest region and upward of 150 in the region redward of the Lyα emission peak where C IV is observed. Voigt profiles are fitted to the resulting artificial spectra using the automated fitter AUTOVP (DHWK) in order to obtain the column densities and b-parameters of individual lines.

Given the ionizing background we have employed, we find that the observed mean metallicity as measured by [C IV/H I] is best reproduced for a uniform metallicity of [C/H] = −2.5. We will later vary the spectrum of the background to match observations of various metals, and when this is done we will vary [C/H] to match the observed mean column density of C IV. We further assume [C/Fe] = 0, [Si/C] = 0.4, and [N/C] = −0.7. This relative abundance pattern is similar to that observed in halo stars, low-metallicity H II regions, and damped Lyα systems (e.g., Tomkin et al. 1992; Pettini, Lipman, & Hunstead 1995; Wheeler, Sneden, & Truran 1989), although the nitrogen abundance is somewhat uncertain.

3. C IV/H I AT z = 3

Figure 1 shows an example of artificial spectra for Lyα (H λ1216), Lyβ (H λ1026), and C IV (λ = 1548 Å) absorption along one of the more peculiar LOS in the sample at z = 3, fitted using AUTOVP. At v ≈ 600 km s⁻¹, a feature saturated in both Lyα and Lyβ is present, possessing a column density \( N_{H I} = 1.3 \times 10^{16} \) cm⁻². The corresponding unsaturated C IV lines reveal the presence of several velocity components in the system, as is often observed in high column density Lyα absorbers. A weaker, more typical absorption feature is seen at v = 1300 km s⁻¹. For that system, \( N_{H I} = 7 \times 10^{14} \) cm⁻², which is too low to be saturated in Lyβ, and \( N_{C IV} = 1.6 \times 10^{13} \) cm⁻², which is close to the limit of detectability. The third system, around \( v \approx 1850 \) km s⁻¹, has \( N_{H I} = 3 \times 10^{15} \) cm⁻². This absorber also has several associated C IV lines and distinguishable individual subcomponents in Lyβ. When computing the column densities of H I and metals, we fit the Lyβ spectrum to obtain the column densities in each H I line, then we sum
over all components for each species that lie within the region where the Ly\(\beta\) transmission is below 0.7. This technique is similar to that used by SC, and it avoids the ambiguous and often physically meaningless task of associating each metal line with a subcomponent in H I. The metal-line absorption in systems where the Ly\(\beta\) transmission does not fall below 0.7 is too weak to be detected at the SC limits.

The C IV/H I column density ratios for all such systems detectable in Ly\(\alpha\) and C IV in the 400 random LOS at \(z = 3\) are plotted as circles in Figure 2. Observed values from SC (with \(\log N_{\text{HI}} > 5 \times 10^{14}\)) are shown as solid triangles. The crosses will be discussed below. The modest scatter in C IV/H I predicted by our uniform-metallicity model arises from a scatter in physical densities and temperatures of the absorbing regions. Because there exists a fairly tight correlation between H I column density and physical density and temperature in the model (Miralda-Escudé et al. 1996, 1997), this scatter is small. The scatter in the observational data is seen to be at least an order of magnitude higher. We thus confirm the finding of Rauch, et al. (1996) that significant spatial variations in metallicity are required in order to explain the observations of C IV/H I in the high-redshift universe in the context of this model for the Ly\(\alpha\) forest.

The model data points scale directly with the carbon abundance, and with [C/H] \(\sim -2.5\), the mean value of C IV/H I of the points from the simulation above the SC detection limit (dashed line) matches that of the observational data points. Essentially all systems with \(\log N_{\text{HI}} \gtrsim 15.2\) (the Ly\(\beta\)-selected sample of SC) have detectable C IV absorption. For lower values of \(N_{\text{HI}}\), we expect an increasing fraction of the C IV lines to lie below the detection limit.

Gnedin & Ostriker (1997), simulating the reionization and metal enrichment of the universe by early generations of stars, predict (at \(z = 4\)) a pattern of metal enrichment consistent with our requirements. They predict a mean metallicity of [C/H] \(\sim -2.3\) with a large scatter, which is similar to what we infer in comparing our simulation to the SC data. They further predict a dependence of metallicity on volume density (and hence on column density, because of the correlation mentioned above), since most of the star formation and subsequent enrichment of the surrounding IGM take place within relatively dense regions, while regions with low densities, corresponding to column densities \(N_{\text{HI}} \lesssim 10^{13.5}\) cm\(^{-2}\), have essentially no metals. This latter prediction cannot be tested observationally at this stage; the metal lines would be far below the detection limit.

Figure 2 also shows a sample of high column density systems (log \(N_{\text{HI}} > 16\)) with their C IV/H I ratios shown as crosses. These LOS were preselected to have high total H I column density in order that they provide better statistics on the absorption properties of the relatively uncommon high column density systems. It is seen that the model predicts a value of C IV/H I systematically decreasing with \(N_{\text{HI}}\). This trend is consistent with the observations of SC, who find that Lyman limit systems with \(17 \lesssim \log N_{\text{HI}} \lesssim 18\) have a mean log (C IV/H I) \(\sim -4\) and show that the trend cannot be explained by radiative shielding effects alone. The physical reason for this trend in the model is the correlation between the H I column density and the physical gas density. For a homogeneous radiation field, the photoionization parameter, defined as the ratio of ionizing photons to free electrons, will be a decreasing function of \(N_{\text{HI}}\). For relatively low values of \(N_{\text{HI}}\), the C IV column density increases slightly faster than \(N_{\text{HI}}\), so the C IV/H I ratio is a weakly increasing function. When \(N_{\text{HI}}\) exceeds a value of \(\sim 10^{16}\) cm\(^{-2}\), \(N_{\text{CIV}}\) begins to drop, as the C IV...
recombines to lower ionization states, causing the observed decrease in C IV/H I. Rauch et al. (1996) find a similar trend of C IV/H I with $N_{\text{HI}}$. For Lyman limit systems ($\log N_{\text{HI}} \gtrsim 17.2$), the ionization parameter will decrease even faster with $N_{\text{HI}}$, since the systems become increasingly opaque to the Lyman limit photons of the background radiation.

4. REDSHIFT EVOLUTION AND OBSERVED FRACTIONS OF METAL LINES AT $z = 3$

Figures 3a–3d show the magnitude and scatter of the column densities in C IV, C II, Si IV, and N V at five different redshifts. The systems studied here are chosen to mimic the Lyβ-selected sample of SC: only systems that are Lyβ saturated ($\log N_{\text{HI}} > 15.2$) are included, and of those, only systems with metal column densities larger than the detection limits of SC ($10^{12}$ for C II, C IV, N V, and $5 \times 10^{11}$ for Si IV) are plotted. At $z = 3$, 98 of our 400 random LOS had absorbers with $\log N_{\text{HI}} > 15.2$. We have adjusted the metallicity of our model of this high column density sample to $[\text{C/H}] = -2.3$, which reproduces the observed mean value $\log N_{\text{CIV}} = 13.2$. As expected from the discussion of Figure 2, the scatter in column density is less than observed, presumably because the model assumes a homogeneous metallicity distribution.

The model shows no significant evolution in the mean column densities with redshift. This is consistent with what is seen observationally (see Figs. 4a–4d of SC). For C IV, there is a hint of evolution with the mean value of $N_{\text{CIV}}$: at $z = 2, 2.3, and 2.7$ it is around $10^{13}$, while at $z = 3$ and $3.5$, it is around $10^{13.2}$; but the scatter is consistent with no evolution. For the other species, the observational detection limits combined with small numbers of detections make it difficult to draw conclusions about the redshift evolution of their mean column densities, but again the results are consistent with no evolution. The model also shows, at face value, that the number of detectable metal systems increases dramatically with redshift (the larger number of points in Figs. 3a–3d with increasing $z$), an effect that is not nearly so

![Fig. 3.—Metal-line column densities of systems identified in 400 random LOS at $z = 2, 2.3, 2.7, 3.0$, and 3.5. Only systems above the detection limits of Songaila & Cowie (1996) are included. The error bars next to the points indicate the mean value and $1\sigma$ scatter of the data. Also shown are the numbers of such systems identified at each redshift. While this number increases with $z$ there is no significant evolution in the mean column densities over this redshift range.](image-url)
pronounced in observations. The increase arises partly as an artifact of our simulation volume's representing a larger redshift interval at earlier times $[\Delta z \propto (1 + z)^{3/7}]$ and partly because the universe is physically denser at higher redshifts, causing an increase in the number of Ly$\alpha$ and weak metal absorption lines per unit wavelength.

Both the model and the data show that while essentially all systems in the Ly$\beta$-selected sample have detectable C IV absorption, only a fraction of the absorbers have column densities in Si IV, C II, and N V that are above the detection limit. To check our model quantitatively, we have taken the output at $z = 3$ as representative for the sample observed by SC and have added an additional Gaussian scatter of $\sigma([C/H]) = 0.8$ in metallicity, so the observed scatter in $N_{C IV}$ is crudely reproduced.

The column densities with and without this added scatter are displayed as triangles in Figures 4 and 5, respectively, and the corresponding fractions of the systems above the detection limit (Fig. 5) are shown in column (1) of Table 1. This model predicts too few Si IV systems and too many N V systems, compared to what is observed (column 3 of Table 1). No reasonable changes in the relative abundances [Si/C] and [N/C] can remove this discrepancy. If, however, the ionizing radiation field is softer than the HM spectrum, we expect to see less N V (more N IV) and more Si IV (less Si V) and C IV for the relevant ionization conditions in the Ly$\alpha$ absorbers, while C II has an ionization potential that is too low to be affected significantly. The model column densities, after our modifying the HM spectrum by reducing the intensity by a factor of 10 above 4 ryd, are shown as circles in Figure 4 and are seen to follow the expected trends. Most dramatically, the many Si IV systems that have a column density that is below the detection limit with the background are seen to have column densities close to or above the detection limits after the removal of the energetic photons.

The predicted distributions of column densities above the detection limit for the normal HM spectrum versus the softened background spectrum are plotted in Figure 5. Gaussian scatter of $\sigma([C/H]) = 0.8$ has been added to both distributions, and the mean $[C/H]$ in the softened model has been adjusted to fit the observed mean value of $N_{C IV}$, requiring $[C/H] = -2.85$ (note the lower mean C IV, com-

| Line     | HM   | HM + Cut | Observed |
|----------|------|----------|----------|
| C II     | 24%  | 15%      | 24%      |
| C IV     | 90%  | 96%      | 95%      |
| Si IV    | 17%  | 43%      | 38%      |
| N V      | 45%  | 14%      | 17%      |
| C II     | 1.5  | 3.6      | ~2       |

Fig. 4.—Column densities of C IV, C II, Si IV, and N V at $z = 3$ for an HM radiation spectrum (left columns, triangles) and a spectrum softened by cutting the intensity above 4 ryd by a factor of 10 (right columns, circles). Extremely weak lines below the detection limit have been included here to clarify the effects of softening the radiation field. Detection limits inferred by SC are indicated as horizontal lines in the figure.

Fig. 5.—Column densities of metal-line systems in the model with HM spectrum (triangles) and softened spectrum (circles) after adding an additional Gaussian scatter of $\sigma([C/H]) = 0.8$ and adjusting the mean metallicity to reproduce the observed mean C IV column density of $10^{13.2}$. Only systems with column densities above the SC detection limits are plotted. Notice the increase in detections of Si IV, and the decrease in detections of N V due to softening the spectrum. The resulting statistics (see Table 1) agree better with observed values.

TABLE 1

| Line     | HM   | HM + Cut | Observed |
|----------|------|----------|----------|
| C II     | 24%  | 15%      | 24%      |
| C IV     | 90%  | 96%      | 95%      |
| Si IV    | 17%  | 43%      | 38%      |
| N V      | 45%  | 14%      | 17%      |
| C II     | 1.5  | 3.6      | ~2       |
pared with the circles in Fig. 4). The fractions above the detection limits for the softened model are shown in column 2 of Table 1. For this choice of background radiation, there is much better agreement between the predicted and observed metal-line fractions for N v and Si iv. Because of the reduction in metallicity, however, slightly too few C ii detections are now seen.

Also shown in Table 1 is the mean He ii optical depth in the models. Cutting the number of He ii ionizing photons by a factor of 10 increases $\tau_{\text{He}^\ast}$ from 1.6 to 3.6. Observational results by Hogan, Anderson, & Rugers (1996) indicate that $1.5 < \tau_{\text{He}^\ast} < 3$ (95% confidence level) at $z \approx 3.3$, and at $z = 3$ we would expect it to be slightly less. A cut by a factor of 10 thus seems barely acceptable, and the spectrum giving the best fit to the observational data is probably somewhere between the two extremes considered. Alternatively, the observations could be accommodated if the ionizing background were inhomogeneous and softer in some regions than in others because of varying distances from the nearest ionizing source. Given the crudity of the approach made in producing Figure 5 and Table 1 and the still sparse amount of observational data, we will not attempt to infer any further details of the radiation field. We simply suggest, based on the above results, that the ionizing background photon field around $z = 3$ is somewhat softer than the HM spectrum.

We now consider the Si iv/C iv ratio as a signature for He ii reionization. SC suggest that this ratio increases rather abruptly by a factor of a few around $z = 3.2$ and that this effect could be explained if the He ii reionization redshift is around this value. While it is true that the Si iv/C iv ratio in a uniform-density, one-phase medium will increase as high-energy photons are removed from the spectrum by He ii absorption, the effect is different in our models. As can be seen from Figure 4, the mean column density of the observable Si iv systems will not increase if the radiation field is softened, because the numerous Si iv systems are shifted upward to just above the detection limit. Meanwhile, $N_{\text{C}^\text{IV}}$ is seen to increase if the radiation field is softened, so the net effect is actually to decrease the Si iv/C iv ratio. If the observed increase in Si iv/C iv is real, we are seeing the first clear example of a failure of the model to reproduce observations. It should be remarked, however, that our model predicts optical depths for He ii absorption that are consistent with observations without the need to assume He ii reionization at $z = 3.2$ (Croft et al. 1996).

5. CONCLUSIONS

We have compared a cosmological simulation of the Lyα forest and associated metal lines to recent observations of C iv, C ii, Si iv, and N v absorption in high-redshift QSO spectra. Our simulated spectra have signal-to-noise properties similar to those of the observed spectra, and we analyze them by a Voigt-profile fitting procedure that is similar to that used in the observational analyses. We can examine our results from two different points of view. First, we can assume that our theoretical model provides an accurate description of physical conditions in the absorbing gas, and we can use the comparison to the observations to draw inferences about the metal enrichment of the IGM and the spectral shape of the ionizing radiation background. Second, we can ask whether the predicted properties of the IGM are consistent with the metal-line observations, within the uncertainties of the observations and the theoretical modeling. Adopting the first point of view, we conclude the following:

1. The mean metallicity of the IGM at $z \approx 3$ corresponds to $[\text{C}/\text{H}] \approx -2.5$. More specifically, for the Lyβ-selected sample of SC (log $N_{\text{HI}} \geq 15.2$), the inferred mean metallicity ranges from $[\text{C}/\text{H}] \approx -2.8$ to $[\text{C}/\text{H}] \approx -2.3$, depending on the assumed spectral shape of the ionizing background.

2. Significant spatial variations of $[\text{C}/\text{H}]$ with an rms scatter of roughly one order of magnitude are required to match the observed scatter in C iv/H i.

3. The ionizing background spectrum at $z \approx 3$ must be somewhat softer than the spectrum predicted by HM to explain the observed number of Si iv systems. However, if the spectrum is too much softer than the HM spectrum, it will conflict with the observed He ii optical depth (see Croft et al. 1996; Davidsen, Kriss, & Zheng 1996; Hogan et al. 1996).

The required metallicity pattern of the IGM is very similar to that predicted by Gnedin & Ostriker's (1997) numerical simulations of metal enrichment and reionization by stars. The required scatter in metallicity is also plausible on observational grounds, since it is similar to that seen in halo stars in our own Galaxy (e.g., Ryan & Norris 1991). However, some of the observed scatter in C iv/H i could also be contributed by inhomogeneities in the ionizing background instead of by metallicity variations.

Within the current uncertainties of the observational data and the theoretical modeling, we expect the predictions presented here to be generic to cosmological models that have similar amounts of small-scale power at $z \sim 2-3.5$. Several results of our comparison support the adopted physical model of the high-redshift IGM:

1. With plausible assumptions about enrichment and the ionizing background, the model reproduces the observed abundances of C iv, C ii, Si iv, and N v in Lyα forest systems fairly well. This agreement suggests that the predicted densities and temperatures of the absorbing gas are at least approximately correct.

2. Consistent with SC's observations, the model predicts no substantial evolution in the mean value of $N_{\text{C}^\text{IV}}$ for Lyβ-selected H i lines over the redshift range 2.5 $\lesssim z \lesssim 3.5$.

3. The model successfully explains the observed trend towards lower C iv/H i ratios in high column density systems ($N_{\text{HI}} \sim 10^{16}-10^{17}$ cm$^{-2}$). This trend arises because of the correlation between column density and physical density, which causes the stronger absorbers to have more of their carbon in lower ionization states.

4. Qualitatively, the model reproduces observations that show multiple C iv components associated with strongly saturated Lyα lines (see Fig. 1). We will explore the model predictions more quantitatively in future work.

The observation that is most difficult to explain in this model is the jump in the mean Si iv/C iv ratio at $z \approx 3$, which SC suggest is due to a rapid change in the shape of the ionizing background spectrum associated with He ii reionization. In our model, there are many weak Si iv systems below the SC detection threshold. Softening the background spectrum moves these systems above the threshold, keeping the mean Si iv column density low.

To the extent that the analyses overlap, our conclusions agree well with those of Haehnelt et al. (1996) and Rauch et
al. (1996), despite differences in numerical techniques, in the mass resolution of the simulations, and in the type of simulations (a single, large box representing a randomly selected volume vs. multiple, higher resolution simulations focused on collapsing regions). Many potential improvements in future modeling are plausible, including higher resolution of the gas dynamics (in order to describe better the structures giving rise to the moderate column density systems where metals are detected), a nonequilibrium treatment of the ionization of all species, and explicit incorporation of spatial variations in the metallicity of the gas and the intensity and shape of the background radiation field. Future studies can also examine alternative reionization scenarios and other cosmological models in order to see which theories of cosmic structure formation can account for metal-line absorption in the high-redshift universe.

We have benefited from discussions with Len Cowie, Gary Ferland, and Bernard Pagel. We also thank the referee, Matthias Steinmetz, for his useful comments and suggestions. This work was supported by the NSF under grants AST 90-18256 and ASC 93-18185, and the Presidential Faculty Fellows Program. U. H. acknowledges support from a postdoctoral research grant from the Danish Natural Science Research Council. D. H. W. acknowledges support from NASA grants NAG 5-3111 and NAG 5-3525. Computing support was provided by the San Diego Supercomputer Center.

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