A LOWER LIMIT TO THE UNIVERSAL DENSITY OF METALS AT \( z \sim 3 \)

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ABSTRACT

Column density distribution functions of C IV with 12.05 \( \leq \log(N) \leq 14.35 \) and Si IV with 11.70 \( \leq \log(N) \leq 13.93 \) have been obtained using 81 C IV absorbers and 35 Si IV absorbers redward of the Ly\( \alpha \) forest in the lines of sight to seven quasars with 2.518 \( \leq z_{\text{em}} \leq 3.78 \). These distribution functions have been directly integrated to yield ion densities at \( z = 3-3.5 \) of \( \Omega\text{C}_{\text{iv}} = (2.0 \pm 0.5) \times 10^{-8} \) and \( \Omega\text{Si}_{\text{iv}} = (7.0 \pm 2.6) \times 10^{-9} \) with \( H_0 = 65 \) km s\(^{-1}\) Mpc\(^{-1}\) and \( q_0 = 0.02 \) (1 σ errors). A larger sample of 11 quasar lines of sight was used to measure C II/C IV, Si III/Si IV, and N v/C IV ratios, which suggest that C IV and Si IV are the dominant ionization stages and that corrections to \( \Omega\text{C}_{\text{carbon}} \) and \( \Omega\text{Si}_{\text{silicon}} \) are no more than a factor of 2. Normalizing the \( \alpha \)-process elements to silicon and the Fe-coproduction elements to carbon gives a density of heavy elements in these forest clouds of \( \Omega\text{metals} = (3.3 \pm 0.8) \times 10^{-7} \) (\( H_0 = 65 \), \( q_0 = 0.02 \)). The implications for the amount of star formation and for the ionization of the intergalactic medium prior to \( z = 3 \) are discussed.

Subject headings: early universe — galaxies: formation — intergalactic medium — quasars: absorption lines

1. INTRODUCTION

In any cold dark matter (CDM) or CDM + \( \Lambda \) cosmology, the first generation of stars is expected to form at redshifts 10–30 in small (~ 10\(^8\) M\(_{\odot}\)) bound objects and is assumed to imprint the intergalactic medium (IGM) by both enriching and ionizing it. This enrichment may now have been detected in Keck spectra of the Lyman forest (Cowie et al. 1995; Tytler et al. 1995; Songaila & Cowie 1996, hereafter SC96), and various attempts have been made to use the first crude measurements of the forest metallicity (SC96; Haehnelt, Steinmetz, & Rauch 1996; Rauch, Haehnelt, & Steinmetz 1997a) to place upper limits on the amount of early star formation in small galaxies (SC96; Miralda-Escudé & Rees 1997; Gnedin & Ostriker 1997; Haiman & Loeb 1997) and to infer the rate of the high-redshift Type II supernovae that may be our best hope of detecting objects in these early stages of the galaxy formation era (Miralda-Escudé & Rees 1997).

The critical quantity for normalizing the amount of early star formation is the density of metals at early epochs. This has generally been obtained (e.g., Miralda-Escudé & Rees 1997; Haiman & Loeb 1997) by combining the rough estimates of metallicity in forest clouds with the total baryon density (\( \Omega_\text{b} \)) inferred from big bang nucleosynthesis (SBBN). Apart from the uncertainty in the value of \( \Omega_\text{b} \), from SBBN, this methodology assumes a uniform enrichment of metals in the IGM and also entails considerable uncertainty in the determination of individual cloud metallicities caused by poorly known ionization corrections and abundance patterns in the heavy elements.

It is possible to avoid many of these problems by directly integrating the observed ion column densities in the forest clouds to obtain \( \Omega_{\text{metals}} \) and, within plausible limits, \( \Omega_{\text{metals}} \). Carbon and silicon are both well suited to this approach: as discussed below, their dominant ionization stages in the IGM are C IV and Si IV, strong doublets that are easy to find and measure with 10 m class telescopes (§ 2); they both have strong accessible lines in other ionization stages with which to assess ionization corrections (§ 3); and the ratio of \( \alpha \)-process silicon to Fe-coproduction carbon is useful for determining the abundance pattern at early epochs and to give some idea of the nature of the initial mass function (§ 4). This Letter reports the results of such a direct integration.

2. OBSERVATIONS

The data used comprise high-resolution observations of 11 quasars with 2.518 \( \leq z_{\text{em}} \leq 3.78 \) made with the HIRES spectrometer on the Keck I telescope, for a variety of programs, between 1994 November and 1997 April. All spectra have a resolution \( R = 36,000 \) and have variable wavelength coverage in the range 3500–7000 Å. Full details of the extraction and processing of these spectra are given in a companion paper (Songaila 1997). Seven of the spectra have complete wavelength coverage between the quasar’s Ly\( \alpha \) and C IV emission lines, whereas the remainder have only partial coverage redward of Ly\( \alpha \) emission or have remaining interorder gaps from HIRES’s incomplete coverage above 5000 Å.

The sample used to construct the C IV column density distribution consists of all C IV doublets detected redward of Ly\( \alpha \) emission in those spectra with complete coverage. The doublets were found by inspection of the spectra and were confirmed by consistency of the column density and velocity structure in the two members of the doublet. Systems with 5000 km s\(^{-1}\) of the quasar’s emission redshift were excluded from the sample to avoid including proximate systems that have ion ratios dominated by photoionization from the quasars themselves. Also excluded were 10 specifically targeted partial Lyman limit systems (PLLSs) in nine quasars that were chosen to be observed in a program to look for suitable systems in which to measure the primordial ratio of deuterium to hydrogen. The final sample consists of 81 C IV doublets, with 2.02 \( \leq z \leq 3.54 \) and 12.05 \( \leq \log (N_{\text{c iv}}) \leq 14.35 \), free from proximity or observational selection bias.

The Si IV column density distribution was similarly determined from all Si IV doublets detected in the same subsample of quasar spectra as used for the C IV distribution. Only systems blueward of the quasars’ rest frame Si IV but redward of the Lyman forest were included, again excluding proximate systems and targeted PLLSs. This resulted in 35 systems in seven lines of sight between \( z = 2.16 \) and \( z = 3.54 \), with 11.70 \( \leq \log (N_{\text{si iv}}) \leq 13.93 \).

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In all cases, ion column densities were determined by fitting up to 10 Voigt profiles to each redshift system, defined in this context to be all absorption near a given fiducial redshift with gaps in velocity space of no more than 50 km s\(^{-1}\). The column density at a given redshift is then the total column density of all such components. In all but a few systems, individual lines were unsaturated, so fitted column densities are insensitive to v value.

With these samples, the column density distribution function \(f(N)\) was determined for each ion. The function \(f(N)\) is defined as the number of absorbing systems per unit redshift path per unit column density, where at a given redshift \(z\) the redshift path, \(X(z)\), is defined as \(X(z) = \frac{1}{2} [(1 + z)^2 - 1] \) for \(q_0 = 0\) or by \(X(z) = \frac{1}{2} [(1 + z)^{3/2} - 1] \) for \(q_0 = 0.5\) (Tytler 1982). The C\(\text{iv}\) and Si\(\text{iv}\) distribution functions are shown in Figure 1, over the redshift ranges, 2.02 \(\leq z \leq 3\) and 3 \(\leq z \leq 3.54\) for C\(\text{iv}\), and 2.16 \(\leq z \leq 3\) and 3 \(\leq z \leq 3.54\) for Si\(\text{iv}\). The data were calculated with \(q_0 = 0\) and are plotted with 1 \(\sigma\) error bars calculated from the Poisson errors based on the number of systems in each bin.

Because of the somewhat heterogeneous nature of the parent observations, the signal-to-noise ratio of the full sample is quite variable, in some cases because the low quasar emission redshift entailed observing below 4000 \(\AA\), where the CCD efficiency drop-off is quite severe, in others because of variable coverage at the red end of the spectrum to fill in interorder gaps. Exposure times were also variable for the usual observational reasons. The amount of incompleteness at low column density was assessed by recalculating the column density distributions using only systems drawn from the highest signal-to-noise ratio spectrum, toward Q1422+231, which has an exposure time of 580 minutes and reaches a 1 \(\sigma\) limiting column density of 1.3 \(\times\) 10\(^{11}\) cm\(^{-2}\) for C\(\text{iv}\) and 5 \(\times\) 10\(^{10}\) cm\(^{-2}\) for Si\(\text{iv}\) for \(b = 6\) km s\(^{-1}\). Comparing this with the distributions obtained from the full sample, it is found that the turnover at low column density \((N_{\text{CIV}} < 2.8 \times 10^{12} \, \text{cm}^{-2})\) in the full sample is almost entirely a result of incompleteness. To take this into account, power laws were fitted only above 5.6 \(\times\) 10\(^{12}\) cm\(^{-2}\) for C\(\text{iv}\) and 10\(^{12}\) cm\(^{-2}\) for Si\(\text{iv}\), with best-fit indices of \(-1.5\) for both low- and high-redshift C\(\text{iv}\), and \(-1.8\) for low-redshift Si\(\text{iv}\) and \(-2.0\) for high-redshift Si\(\text{iv}\). These values are quite similar to those measured in H\(\text{I}\) in the forest at these redshifts (Petitjean et al. 1993; Hu et al. 1995; Kim et al. 1997) and in higher column density C\(\text{iv}\) samples (Petitjean & Bergeron 1994).

\(\Omega_{\text{CIV}}\) and \(\Omega_{\text{SiIV}}\) were calculated from the column density distributions of Figure 1 according to

\[
\Omega_{\text{ion}} = \frac{H_0}{\rho_{\text{crit}}} \sum N_{\text{ion}} \Delta X m_{\text{ion}},
\]

where \(\rho_{\text{crit}} = 1.89 \times 10^{-29} \, h^2 \, \text{g cm}^{-3}\) is the cosmological closure density, \(m_{\text{ion}}\) is the ion’s mass, and \(H_0 = 100 \, h \, \text{km s}^{-1} \, \text{Mpc}^{-1}\) (e.g., Lanzetta et al. 1991). Values of \(\Omega_{\text{CIV}}\) and \(\Omega_{\text{SiIV}}\) were calculated for \(z > 3\) in individual lines of sight to the five quasars in the sample with \(z_{\text{em}} > 3\) and complete spectral coverage between the quasar’s Ly\(\alpha\) and C\(\text{iv}\) emission lines. The results are tabulated in Table 1 for \(H_0 = 65 \, h \, \text{km s}^{-1} \, \text{Mpc}^{-1}\) and \(q_0 = 0.02\) (\(\Omega_{\text{ion}}\) scales as \(h^{-1} (1 + 2q_0 z)^{1/2}\)) and give some idea of the uncertainty in calculating \(\Omega_{\text{ion}}\). Formal mean values, weighted by \(\Delta X\), are \(\Omega_{\text{CIV}} = (1.2 \pm 0.3) \times 10^{-4} \, h^{-1} (1 + 2q_0 z)^{1/2}\) and \(\Omega_{\text{SiIV}} = (4.3 \pm 1.6) \times 10^{-5} \, h^{-1} (1 + 2q_0 z)^{1/2}\), where the errors are 1 \(\sigma\). The mean redshift of the sample is \(\bar{z} = 3.18\). A similar procedure applied to the \(z < 3\) systems gives \(\Omega_{\text{CIV}} = 9.3 \times 10^{-9} \, h^{-1} (1 + 2q_0 z)^{1/2}\) and \(\Omega_{\text{SiIV}} = 5.0 \times 10^{-9} \, h^{-1} (1 + 2q_0 z)^{1/2}\).

Because of the rarity of high column density systems \((N_{\text{CIV}} \gg 3 \times 10^{16} \, \text{cm}^{-2})\), considerably longer path lengths are required to determine the number density of such systems, and the present data measure \(\Omega_{\text{ion}}\) only for absorption with column density less than this value. (This corresponds roughly to \(N_{\text{HI}} < 10^{17} \, \text{cm}^{-2}\), from SC96.) The metal densities of the stronger systems are addressed in a companion paper (Songaila 1997). The contribution of systems to \(\Omega_{\text{CIV}}\) and \(\Omega_{\text{SiIV}}\) converges at the low column density end, and systems weaker than those observed will not contribute significantly to the density unless there is a very rapid upturn below the observed range.

3. IONIZATION BALANCE

A less restricted sample was used to assess the ionization balance correction to be applied to the C\(\text{iv}\) and Si\(\text{iv}\) sample. This was drawn from the full set of 11 quasar spectra, excluding proximate systems. In cases where there was no apparent ab-
sorption at the C IV redshift in the other ionic species, an upper limit to the absorption in other ions was found by formally fitting the C IV component model to the local continuum. This approach results in conservative upper limits, especially to lower ionization species, since C IV absorption is likely to be more widespread in velocity space than lower ionization absorption.

As is shown in Figure 2, C II is a trace ion relative to C IV, with nearly all systems having C II \( \ll 0.1 \) C IV. An additional direct search in the spectra for C II systems with no strong C IV yielded no additional systems. For photoionization models, this in turn yields a high photoionization parameter (\( \log \Gamma \gg -2 \)), which, for a wide range of photoionizing spectra, implies that Si III \( \approx \) Si IV and C III \( \approx \) C IV (e.g., Steidel 1990; Giroux \\
& Shull 1997). For Si III this can be directly verified from observations (Fig. 2, middle), which show that, even with Ly\( \alpha \) forest contamination, the upper limits on the Si III column density are generally compatible with Si IV measurements. Ionization by a starburst galaxy spectrum with no high-energy photons could result in a much higher ratio of C III to C IV while maintaining the low C III/C IV and Si III/Si IV ratios, but it would also produce Si IV much in excess of C IV, which is not observed: at \( z > 3 \) Si IV/C IV has an average value of about 0.2 (SC96; Songaila 1997).

Finally, neither N V nor O VI is strong in the C IV-selected systems. Figure 2 (right) shows that N V \( < 0.05 \) C IV in the small number of systems measured. The high observed ratio of Si IV to C IV combined with the low observed values of C III/C IV and N V/C IV suggests that forest clouds at \( z > 3 \) are ionized by a broken power-law spectrum with relatively few high-energy photons and that it is unlikely that there is much material above the C IV and Si IV levels (SC96; Giroux \\
& Shull 1997). The best guess, therefore, would give \( \Omega_{\text{carbon}} \leq 2\Omega_{\text{C IV}} \) and \( \Omega_{\text{silicon}} \leq 2\Omega_{\text{Si IV}} \) in these clouds.

4. DISCUSSION

Converting \( \Omega_{\text{carbon}} \) and \( \Omega_{\text{silicon}} \) to the \( \Omega_{\text{metals}} \) of all metals requires an assumption of an abundance pattern in the \( z > 3 \) forest. As in the old metal-poor halo stars, silicon is overabundant with respect to carbon relative to solar. However, assuming that the carbon and silicon abundances trace the universal abundances of iron coproduction and \( \alpha \)-process elements, respectively (e.g., Timmes, Lauroesch, \\
& Truran 1995), then for the Fe-coproduction elements (C, N, Fe), \( \Omega = 1.75 \times \Omega_C \), and for the \( \alpha \)-process elements (O, Ne, Si, Mg, S), \( \Omega = 18.5 \times \Omega_S \), and setting \( \Omega_C = 2\Omega_{\text{C IV}} \) and \( \Omega_S = 2\Omega_{\text{Si IV}} \) gives \( \Omega_{\text{metals}} = (2.1 \pm 0.6) \times 10^{-5} h^{-1} (1 + 2q_0)^{3/2} \) (relative abundances from Anders & Grevesse 1989). Assuming a value of \( \Omega \) from SBBN of \( 0.005 \leq \Omega, h^2 \leq 0.016 \) (Songaila, Wampler, \\
& Cowie 1997)
gives \( \Omega_{\text{metals}}/\Omega_\nu = (1.3 \pm 0.4 \rightarrow 4.2 \pm 1.2) \times 10^{-3} h (1 + 2q_0z)^{1/2} \). With \( H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( q_0 = 0.02 \), and a solar metallicity of 0.019, this implies a minimum universal metallicity relative to solar, at \( z \sim 3 \), in the range \([-3.3]\) to \([-2.8]\). (The value of \( D/H = 2.3 \times 10^{-5} \pm 3 \times 10^{-6} \) (statistical) \( \pm 1 \times 10^{-5} \) (systematic) given in Tytler, Fan, & Burles 1996 has now been revised upward to \( 3.3 \times 10^{-5} \) [Tytler 1997], which would imply \( \Omega_{\nu}h^2 = 0.016 \) and a metallicity of \([-3.3]\), while the value of \( 2 \times 10^{-4} \) obtained by Webb et al. 1997 would give a metallicity of \([-2.9]\) [\( H_0 = 65, q_0 = 0.02 \)].) This is a minimum range of metallicity, since there may be additional metals in higher column density clouds or galaxies as well as in ionization states that were not sampled by these observations. Furthermore, adoption of \( q_0 = 0.5 \) would roughly double the metallicity. However, much of \( \Omega_{\nu} \) inferred from SBBN is believed to reside in the forest clouds at this time (Rauch et al. 1997b; Kim et al. 1997), suggesting that this calculated metal density should be a good estimate of the total metals. Interestingly, since a metallicity of \( 10^{-5} \) gives rise to one ionizing photon per baryon (e.g., Miralda-Escudé \& Rees 1997), the metallicity measured here is just sufficient to preionize the IGM. However, this metallicity range is substantially lower than the value of \( 2.4 \times 10^{-4} \) assumed by Miralda-Escudé \& Rees (1997) and Haiman \& Loeb (1997) and implies that their predicted rate of very high-\( z \) Type II supernovae could be lowered by as much as an order of magnitude, to a value of around one supernova per 10 arcmin\(^2\) per year.

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