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ON THE ABUNDANCE OF METALS AND THE IONIZATION STATE IN ABSORBING CLOUDS TOWARD QSOs[1]

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ABSTRACT

We present photoionization models for clouds of material illuminated by the integrated radiation of QSOs over a range of epochs and predict the column densities of the most abundant ions for clouds with $N(\text{H I}) = 5 \times 10^{16}$ cm^{-2}. For a wide density range, C III is predicted to have the highest column density of all metallic ions, and we search for C III in the $z = 3.321$ absorption system toward S5 0014+81. Our observations set an upper limit of the metal-to-hydrogen ratio of $10^{-3.5}$ compared to the solar value, the lowest value yet inferred for any extragalactic material.

Since our conclusions depend on the assumption of photoionization by integrated QSO radiation, we discuss the likely ionization mechanism and ionization state of such clouds in light of a recent unified picture of the Lyman-α and metal line QSO absorption systems proposed by Tytler. We conclude that the ionization is high and due to photo-, rather than collisional, ionization. If this unified picture is correct, there must be a wide range in the metal abundances among clouds. We suggest that the metal-containing clouds may be more massive than previously realized.

Subject headings: abundances — quasars

I. INTRODUCTION

The suggestion originally put forth by Lynds (1971), that the majority of the numerous absorption lines below the Lyman-α emission line in QSOs are Lyman-α's arising in clouds of material taking part in the general Hubble flow, has been strongly corroborated by subsequent investigations. In their seminal paper on this subject, Sargent *et al.* (1980) showed that two classes of such clouds appear to exist: (1) the "metal line" clouds, in which metal lines (usually C IV λλ1548, 1550) could be detected; these exhibited a sharp peak in the two-point velocity correlation function at 140 km s^{-1}, suggesting that this material was contained in halos of galaxies through which our line of sight passes toward the QSO; and (2) the "metal-free," "Lyman-α forest," or "Lyman-α only" clouds, in which no metal lines could be detected. Lines of the latter class represent by far the majority of the lines below the QSO Lyman-α emission line and exhibited no peak in the velocity correlation function (although Webb, Carswell, and Irwin 1984 have recently reported evidence for such a peak at 150 km s^{-1} in this material as well). These characteristics led Sargent *et al.* to hypothesize that the latter clouds are not associated with galaxies and may represent primordial material.

A third class of Lyman-α clouds has been identified by Wolfe and his collaborators (see, e.g., Wolfe *et al.* 1984). These clouds exhibit strongly damped Lyman-α lines, corresponding low-ionization metal line absorption, and in some cases 21 cm absorption. Such clouds have many characteristics in common with interstellar clouds in the Galaxy and are referred to as "Lyman-α disk" systems.

Several investigators have searched for metal lines in Lyman-α forest clouds in order to set limits on the metal abundance in the candidate primordial material. This task is made difficult by the fact that most QSOs of sufficiently high redshift to allow detailed study of the forest are faint, and the column density of neutral hydrogen implied by most of the Lyman-α absorption lines is low. Carswell *et al.* (1984) have shown that the typical H I column density of lines in the forest is $\log N(\text{H I}) \approx 13.6$. At such a low H I column density, any metal line would be very difficult to detect with the present generation of telescopes, spectrographs, and detectors, unless the logarithmic metal-to-hydrogen ratio of the material with respect to the solar value, [M/H], were greater than -1.

Several attempts have been made to improve the detection limit. Norris, Hartwick, and Peterson (1983) formed a composite Lyman-α forest cloud spectrum by shifting the entire absorption line spectrum of 4C 5.34 and OQ 172 to the rest frame for every line in the forest and adding the resulting spectra together. This "average" Lyman-α forest spectrum showed not only Lyman-α and -β, but a suggestion of the O VI absorption doublet at 1031.9, 1037.6 Å. From this detection, Norris, Hartwick, and Peterson estimated the [M/H] of the average Lyman-α forest cloud to be -1.1. Application of this technique by other workers (Carswell, private communication; Roeser, private communication; Sargent and Boksenberg 1983) failed to detect O VI lines. Moreover, Sargent and Boksenberg (1983) report having failed to detect any O VI in a cloud with $\log N(\text{H I}) = 17.3$.

More recently, Chaffee *et al.* (1985, hereafter Paper I) studied an unusually high column density cloud toward S5 0014+81, a high-luminosity QSO with $z = 3.42$ (Kuehr *et al.* 1983). The cloud exhibits an extensive Lyman series and produces a measurable Lyman discontinuity. They inferred a neutral hydrogen

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[1] Observations reported here were obtained with the Multiple Mirror Telescope, a joint facility of the Smithsonian Institution and the University of Arizona.

density for the cloud which is high enough to allow a stringent upper limit to be set on [M/H]. In fact, they reported a marginal detection of absorption at the proper redshift to be the resonance line of Si III (λ1206) and used this detection to infer [M/H] = -2.7. If the feature is real, this implies a [M/H] value similar to that of Galactic Population II material.

However, this cloud, too, may not be representative of the material in the Lyman-α forest, because at 30 km s^{-1} resolution it was revealed to be a double Lyman system of $\Delta v \approx 110$ km s^{-1}, a signature characteristic of a metal line system. The column densities inferred in Paper I for the two components were log N(H I) = 16.3 and 16.7.

Whatever the nature of this material, an estimate of its metal-to-hydrogen ratio remains crucial to understanding its origin. In order to set the lowest possible [M/H] limit, we must know which ionization state of the metals whose absorption lines are likely to be detected dominates under the variety of physical conditions likely to exist at various epochs. To address this question, we calculated detailed photoionization models, from which we predict the column densities for the most abundant ions whose resonance lines are likely to be detectable, in clouds at various epochs.

II. THE PHOTOIONIZATION MODELS

Photoionization and thermal equilibrium models of the clouds were calculated using CLOUDY, a program by Gary Ferland. For details of the calculations, see Ferland and Netzer (1983), and Ferland and Truran (1981). The clouds considered here were modeled under the following assumptions:

a) All energy input into the absorbing clouds is from photoionization. That is, we neglect any input via conduction from a hot intercloud medium, such as is discussed by Ostriker and Ikeuchi (1983).

b) The clouds are plane-parallel slabs illuminated on one face.

c) All clouds are at constant pressure.

d) The clouds have a metallicity of [M/H] = -1.7, where the adopted logarithmic solar abundance with respect to hydrogen is He:C:N:O:Mg:Si = -1.0: -3.33: -4.01: -3.08: -4.59: -4.40. The resulting models can then be scaled to any lower metallicity since, at the densities believed to exist in such clouds, the thermodynamic structure of the cloud is only weakly dependent on the metallicity.

e) The clouds have a neutral hydrogen column density of 5×10^{16} cm^{-2}. This value for N(H I) is characteristic of the very thickest Lyman-α–only systems and is approximately the optical thickness of the individual components of the system studied in Paper I.

The adopted radiation field was calculated by Weymann and Malkan (1985), assuming that all ionizing quanta are produced by background QSOs. The radiation field is calculated using the QSO luminosity function of Schmidt and Green (1983) and is corrected for absorption by Lyman-α forest systems and the very optically thick Lyman-α disk systems. The radiation field is specified between 1 and 16 ryd as a function of the redshift of the absorbing cloud.

We assume in all our models that the radiation field between 16 and 10,000 ryd follows a power law with index -0.7. This is consistent with observations of the X-ray background at $z = 0$, which can be characterized by a power law of index -0.62 from 2 to 40 keV, which steepens to a power law of index -1.67 from 60 to 400 keV (Rothschild *et al.* 1983). The results of our model calculations are completely insensitive to the shape of the X-ray spectrum beyond 40 keV and are changed by $\sim$10% if the spectral index softer than 40 keV is varied between -0.5 and -1.0.

A grid of models was calculated for redshifts in the range $0.25 \leq z \leq 3.50$, in steps of 0.25. At each redshift, models were run for total hydrogen density $n_{\mathrm{H_{tot}}}$ over the range $-4.5 \leq \log n_{\mathrm{H_{tot}}} \leq -2.5$ in steps of 0.5 dex. In addition to the models with log N(H I) = 16.5, a grid with more tightly spaced density points was calculated assuming log N(H I) = 15.0, using the radiation field appropriate for $z = 2.0$. For each density, the size of the cloud was compared to the upper and lower limits for Lyman-α forest clouds at $z \approx 2$. The upper limit was determined by Sargent, Young, and Schneider (1982) to be of order 1 Mpc. The lower limit adopted was 5 kpc, as determined by Foltz *et al.* (1984) from observations of the gravitationally lensed QSO 2345+007 A, B. This leads to a minimum and maximum total hydrogen density at that epoch of $-4.4 \leq \log n_{\mathrm{H_{tot}}} \leq -3.3$. These density limits imply pressures which can be used to constrain the models at other redshifts. If we assume that the clouds are pressure-confined by a medium which evolves adiabatically (in which case the pressure scales as $[1 + z]^5$), the pressure limits can then be scaled to any redshift and compared to the pressure calculated as a function of density at that redshift (see § III).

The models also provide us with a value of the temperature of the absorbing gas as a function of density, redshift, and position in the cloud. This could, in principle, be used to further constrain the models of the absorbing cloud. Carswell *et al.* (1984) demonstrate that the Doppler parameters for Lyman-α forest clouds lie in the range $10 \leq b \leq 45$ km s^{-1}. These limits imply temperature constraints of $6070 \leq T \leq 123{,}000$ K, assuming that the line widths are thermal. Unfortunately, this does not provide a very powerful constraint, as all the photoionization models calculated have temperatures which lie within this range. We discuss further properties of these clouds in §§ V and VI.

III. IONIC COLUMN DENSITIES

Figure 1 presents the column densities of various ions at $z = 2.0$. The horizontal bars along the x-axes present the upper and lower density limits implied by the size constraints discussed in § II for adiabatically evolving clouds in pressure equilibrium with the intergalactic medium at $z = 1.0$, 2.0, and 3.0.

We adopt an equivalent width W_λ of 100 mÅ in the observer's frame as representative of the detection limit achievable with the best data currently available. if we assume the metal lines are thermally broadened to a temperature of 55,000 K (corresponding to the typical Lyman-α Doppler width of 30 km s^{-1}), we can predict the column density limit thus implied for the dominant ions at each epoch. These results are given in Table 1, where the difference between these values and the predicted column densities for each ion in Figure 1 is a direct measure of how stringent a [M/H] upper limit can be set with observations of each ion. We see that for $\log n_{\mathrm{H_{tot}}} \geq -3.5$, C III provides the most stringent upper limit on [M/H] at all epochs, while at lower densities, O VI sets that limit.

Unfortunately, the strongest line from both these ions lies below Lyman-α and hence will suffer severe Lyman-α forest blending. However, ions such as C II, C IV, Si II, Si IV, and Mg II, whose lines are clear of such blending, never provide as stringent a [M/H] limit as either C III or O VI, unless the density is

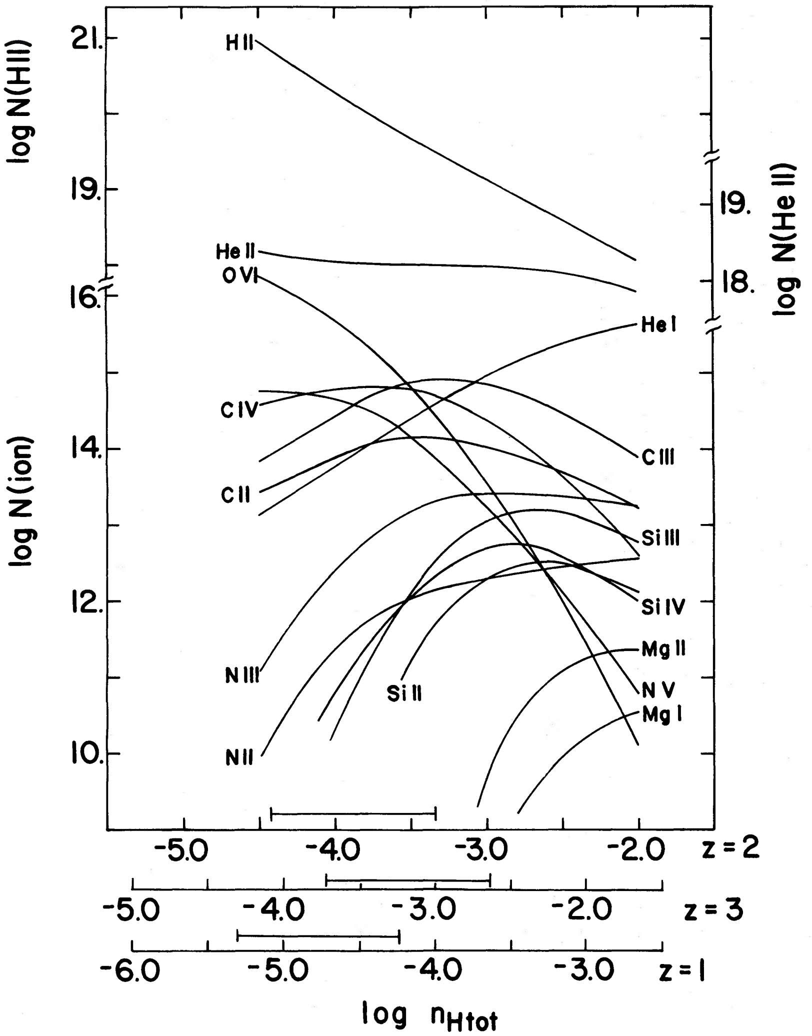

FIG. 1.—Column densities for the dominant ions as a function of the total hydrogen density predicted by the photoionization models for the Weymann-Malkan input spectrum. The results are presented for a plane-parallel slab with log N(H I) = 16.5 and [M/H] = −1.7. Since the radiation field does not change its shape dramatically, the results can be applied to any epoch by a horizontal shift of the density axis, as is seen for the three epochs z = 1.0, 2.0, and 3.0. The horizontal bars on each density axis show the limits implied by the observed size constraints on the clouds at z = 2 and the assumption that the clouds are in pressure equilibrium with an adiabatically evolving confining medium. Note the scale changes for the H II and He II column densities.

TABLE 1

COLUMN DENSITIES OF COMMON IONS IN LYMAN-α FOREST CLOUDS WHEN W_λ OBSERVED = 100 mÅ

ION	λ_{rest}	f	log N (cm^{-2}) z = 1.0, W_{rest} = 50 mÅ	 z = 2.0, W_{rest} = 33 mÅ	 z = 3.0, W_{rest} = 25 mÅ
He I	584.330	0.276	13.98	13.72	13.56
He II	303.790	0.416	14.87	14.28	14.06
C II	1334.530	0.118	13.57	13.34	13.19
C III	977.026	0.810	13.08	12.81	12.65
C IV	1548.188	0.190	13.21	12.99	12.85
N II	1083.990	0.101	13.88	13.62	13.46
N III	989.790	0.107	13.97	13.69	13.53
N V	1238.808	0.152	13.55	13.31	13.16
O VI	1031.928	0.130	13.85	13.57	13.41
Mg I	2852.965	1.770	11.68	11.47	11.33
Mg II	2796.352	0.592	12.17	11.97	11.83
Si II	1260.421	1.122	12.78	12.48	12.31
Si III	1206.510	1.660	12.67	12.35	12.18
Si IV	1393.755	0.528	12.98	12.70	12.53

significantly greater than that allowed by the results of Foltz *et al.*

In light of these results, it seems profitable to search for C III and O VI in absorption toward high column density QSO clouds despite the associated Lyman-α forest blending. It would be interesting to conduct a search for C III absorption using the same QSO spectra and method Norris, Hartwick, and Peterson (1983) used for their reported O VI detection.

IV. FURTHER OBSERVATIONS AND ANALYSIS OF 0014+81

Our models predict that at no epoch or plausible density will Si III produce a line of strength comparable to that of C III. If the value reported in Paper I of $N(\mathrm{Si\ III}) = 2 \times 10^{12}$ cm^{-2} toward S5 0014+81 is correct, our models imply that $N(\mathrm{C\ III}) = 4.2 \times 10^{13}$ cm^{-2} when $\log n_{\mathrm{H}} = -2.3$, the lowest density at which Si III is detectable and C IV is not. Such a C III column density would produce a line with W_λ (observed) = 360 mÅ, assuming thermal broadening and a temperature of 55,000 K. In order to search for such a feature, we obtained a 33 km s^{-1} resolution spectrum of S5 0014+81 with the MMT spectrograph in the echellette mode (see Paper I for system description).

Figure 2 presents a 4 hr exposure of the region where C III λ977 lies in the $z = 3.321$ system. We have plotted the predicted profile of a double C III line with a velocity splitting of 110 km s^{-1} given by the Lyman lines, each C III line having $\bar{W}_\lambda =$ 360 mÅ as predicted above. The strong line at the predicted position of the longer wavelength C III line is probably Lyman-α at $z = 2.474$, since a line of the proper wavelength to be its corresponding Lyman-β appears in lower resolution data. Since the shorter wavelength line is predicted to fall on the steep wing of a nearby strong line (of unknown intrinsic shape), it is difficult to measure a limit on its strength directly. We estimate an upper limit on its equivalent width by isolating a neighboring line-free continuum region, measuring the equivalent width of a window 90 km s^{-1} wide and estimating the error in the equivalent width assuming all uncertainties arise from counting statistics alone. The result is that a 3 σ upper limit on the observed equivalent width is 170 mÅ, implying a column density of $\log N(\mathrm{C\ III}) \leq 12.9$, a factor of roughly 5 less than we predict from the strength of Si III reported in Paper I.

If carbon were significantly depleted with respect to silicon in the $z = 3.321$ cloud, it would still be possible to have detected Si III and not C III. However, if such depletion occurs onto grains as in Galactic interstellar clouds, then we would expect silicon to be more depleted than carbon (see Morton 1975).

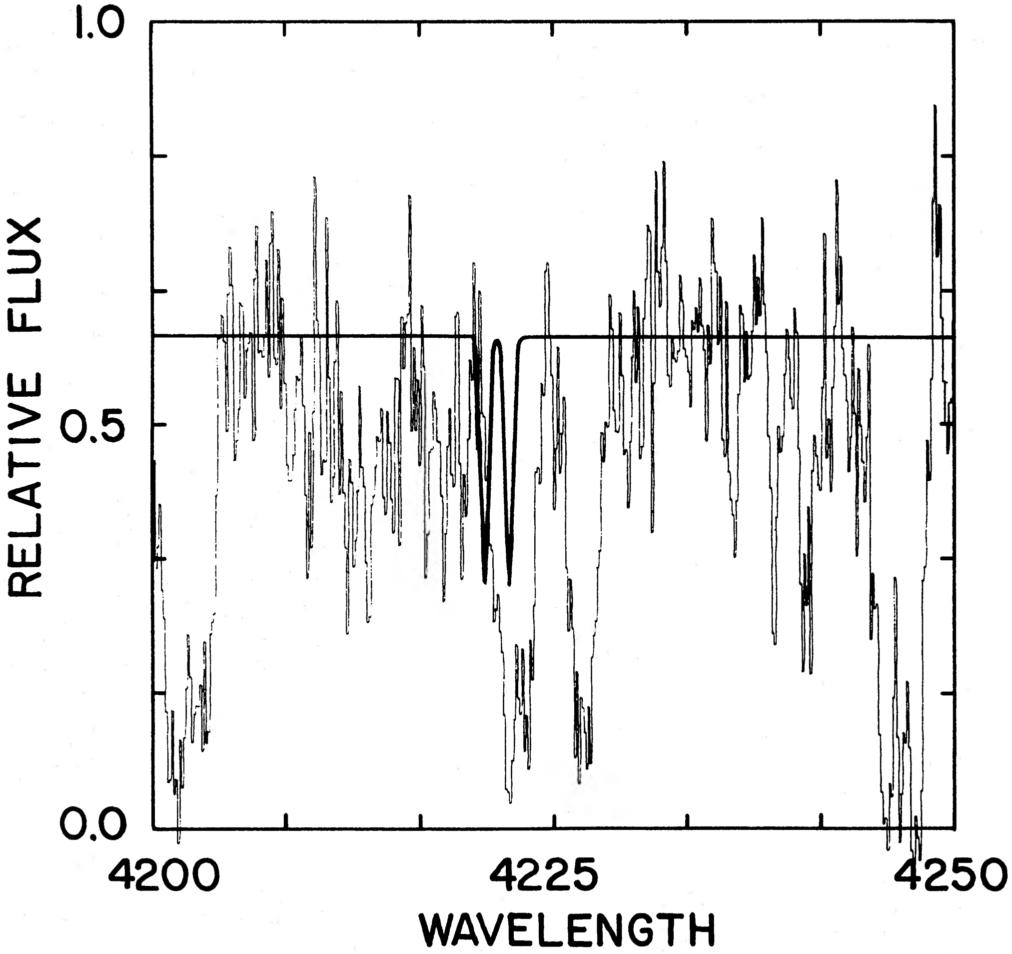

FIG. 2.—A 4 hr integration of the QSO S5 0014+81 obtained with the MMT spectrograph. The bold curve shows the predicted C III λ977 lines for the system described in Paper I, assuming $\log N(\mathrm{H\ I}) = 16.5$ and $[\mathrm{M/H}] = -2.7$. These values lead to a predicted C III column density of 4.2×10^{13} cm^{-2} and an observed equivalent width of 360 mÅ. Our estimate of the 3 σ upper limit on the strength of the C III absorption is 170 mÅ, yielding $N(\mathrm{C\ III}) \leq 7.9 \times 10^{12}$ and $[\mathrm{M/H}] \leq -3.5$.

We therefore conclude that the features identified in Paper I as Si III either are not real or are due to Lyman-α absorption. The N(C III) upper limit then sets [M/H] ≤ -3.5 at $\log n_{\rm H_{tot}} = -2.5$, the highest number density allowed by the pressure constraints. At lower densities, the limit on N(C IV) sets even lower limits on the metallicity. The O VI/H I limit reported by Sargent and Boksenberg (1983) in the cloud toward Q 2126−158 gives [M/H] ≤ -3.0 when analyzed by our models at $\log n_{\rm H_{tot}} = -4.42$, the lowest density allowed by the pressure constraints applied to that epoch. In either case, the question of whether such clouds are primordial remains open.

V. THE IONIZATION STATE OF LYMAN-α FOREST AND METAL-CONTAINING CLOUDS

A number of critical assumptions have entered into the conclusions described above concerning the level of ionization and the metal deficiency in the $z = 3.321$ absorption system:

i) The Lyman alpha clouds at $z \approx 2$ toward 2345+00 are roughly spherical objects in pressure equilibrium with a confining medium.

ii) The confining pressure behaved adiabatically between $z \approx 2.0$ and $z = 3.321$.

iii) The cloud with $\log N(\mathrm{H\ I}) \approx 16.7$ in 0014+81, except for its larger column density, is similar in physical properties and abundance to the much lower column density cloud in 2345+00.

Recently, however, Tytler (1985) has made the remarkable discovery that a single featureless power law can be used to describe the distribution of N(H I), as inferred from observed Lyman-α equivalent widths and a reasonable estimate of the Doppler parameter, for narrow QSO absorption line systems over the range $13.0 \leq \log N(\mathrm{H\ I}) \leq 20.0$. From this, he infers that both types of systems are really representatives of a single population. In particular, it would follow that there were no clouds of "primordial" composition, since the metal-containing systems are manifestly not of primordial composition, and, as discussed below, we estimate the metal depletion in a typical high-z metal-containing system to be not more than about 30. By contrast, our results above imply upper limits to the metal content which are about 100 times lower than this.

Since our result is obviously sensitive to our assumptions concerning the physical conditions in the cloud, and especially the ionization state, we reexamine them in light of Tytler's recent suggestion.

a) The Level of Ionization in a Typical Metal-containing System

We first consider fairly typical metal line systems whose neutral hydrogen column density appears to be comparable to that in the 0014+81 cloud discussed above. These systems typically have C IV much stronger than C II. An example of such a system is the $z = 2.12$ cloud toward B2 1225+31 (Bechtold *et al.* 1985). These authors estimate N(C IV) to be 8×10^{13} cm^{-2} and place a 3 σ upper limit of 3×10^{13} cm^{-2} on N(C II). There is a saturated Lyman-α line in this system, but N(H I) cannot be accurately determined without comparable data on Lyman β or a reliable estimate of the Doppler parameter (including any structure on scales of order 10 km s^{-1}) or both. The Doppler parameter is not well determined from the C IV data because the lines are relatively unsaturated, and at the resolution used (40 km s^{-1} FWHM), profile-fitting does not provide useful limits. The log N(H I) is unlikely to exceed 16.7 because, according to the spectrum presented by Snijders, Pettini, and Boksenberg (1981), $\tau_{1\,\rm ryd} \leq 0.34$. The Lyman-$\alpha$ profile is consistent with a value of log N(H I) even less than 16.0, but only if unusually large Doppler parameters are assumed. For a typical value of 35 km s^{-1}, $\log N(\mathrm{H\ I}) \approx 16.7$. We adopt this value in the discussion below.

Independent of the value of N(H I) in this system, we find it impossible to explain the observed N(C II)/N(C IV) upper limit of about 0.4 unless hydrogen is mostly ionized. Given this limit, the hydrogen ionization is dependent only on the *shape* of the radiation field. If we adopt the shape of the Weymann-Malkan radiation field at $z = 2.25$, then we find that $N(\mathrm{C\ II})/N(\mathrm{C\ IV}) < 0.4$ implies $N(\mathrm{H\ I})/N(\mathrm{H\ II}) < 10^{-3}$, where about 15% of the carbon is present as C IV. This level of ionization together with the H I and C IV column densities implies a value of [M/H] of -1.5. As discussed above, it is unlikely that we have underestimated N(H I) in this system, but if we have overestimated it, then the metal abundance is even more nearly solar. A "hard" power law in the range 1–10 ryd with a spectral index of -1.0 increases the value of H I/H II by about 5. Alternatively, if we consider the case where the radiation field is dominated by blackbody radiation (as might be the case if starlight from nearby galaxies with hot stars provides the photoionization), then we find that even for blackbody temperatures as low as 40,000 K, hydrogen is very highly ionized, with H I/H II $= 6 \times 10^{-5}$.

b) Is the B2 1225+31 System Collisionally Ionized?

We next consider the possibility that the densities and temperatures in the B2 1225+31 cloud are sufficiently high that collisional ionization dominates photoionization. High-energy particles or conduction from surrounding very hot gas might provide the energy input; alternatively, the cloud might be a thin sheet which has cooled following the passage of a strong shock. If the material is in thermal and ionization equilibrium then the C II/C IV limit implies that the electron temperature is in excess of 90,000 K (Shull and Van Steenberg 1982). At such temperatures hydrogen is very highly ionized. In fact, we find that the temperature regime above ~60,000 K is thermally unstable. Thus, time-dependent calculations such as those of Shapiro and Moore (1976) are probably more appropriate. These models follow the ionization of the cloud shock-heated to 10^6 K followed by radiative cooling. Since the time scales for recombination are longer than those for cooling, C IV (and even C V) remains fairly abundant at temperatures less than 90,000 K. Nonetheless, in the context of these calculations, the C II/C IV limit implies that $T \geq 80{,}000$ K, with the hydrogen, of course, still highly ionized. There are at least two problems with such an interpretation of systems such as the one in B2 1225+31. First, this temperature implies Doppler widths somewhat larger than some of those observed. Second, it is difficult to understand why there should not be material which has cooled well below 80,000 K, since the cooling rate is very high over the range $30{,}000 \leq T \leq 80{,}000$ K, and this should produce a large amount of C II in the majority of the metal-containing systems. Our estimates of the radiation produced by isobaric cooling of the shocked gas also suggest that such radiation cannot maintain the gas in a highly ionized state. In summary, we consider that the moderate–column density metal-containing clouds, of which the $z = 2.12$ cloud toward B2 1225+31 is typical, are highly ionized, low-density clouds in which photo- rather than collisional ionization is dominant.

In light of this discussion, we now reconsider further the abundances in the 3.321 cloud toward 0014+81.

c) Can Metals in the 0014+81 Cloud Be Hidden if the Cloud Is Highly Ionized?

As shown in Figure 3, at $z = 3.25$, N(C IV) is high enough that metal abundances in the 0014+81 cloud comparable to those deduced in that toward B2 1225+31 should be easily detectable even if the ionization parameter is approximately three orders of magnitude higher than predicted on the basis of the spherical pressure equilibrium models; in addition, O VI would be extremely strong, even at this ionization parameter. Such high ionization seems extremely unlikely. If the strength of the radiation field is even approximately that estimated by Weymann and Malkan, the hydrogen ionization is so high and the corresponding neutral hydrogen density so low that absurdly large clouds (10^{28} cm!) would be required to produce the observed neutral hydrogen column density. Conversely, if the size of the clouds is not to greatly exceed 10 kpc (if they do, then such entities could no longer be considered coherent individual clouds in pressure equilibrium—see § VI), then the total density must be quite high, and to maintain such a very high level of ionization, the radiation field would have to be at least five orders of magnitude higher than the Weymann-Malkan estimate.

d) Can Metals in the 0014+81 Cloud Be Hidden if the Cloud Is Nearly Neutral?

In order for the 0014+81 cloud to have a metal deficiency which is similar to that in the B2 1225+31 cloud, we deduce from Figure 3 that the observational limit on N(C II) in the 0014+81 cloud implies $[\mathrm{M/H}]_{0014} \approx [\mathrm{M/H}]_{1225} \approx -1.5$ only if the density in the 0014+81 cloud is about two orders of magnitude higher than our nominal photoionization value. The thickness of such a cloud which will produce the observed N(H I) is only about a parsec. This is in strong conflict with the Foltz *et al.* (1984) estimate of a lower limit of ~10 kpc for such clouds, unless the common absorption is really due to a large ensemble of clouds or unless the clouds are thin sheets (for a discussion of this latter possibility see Chaffee *et al.* 1983). Such sheets could conceivably arise behind a cooling shock, and in contrast to the situation in B2 1225+31, such a possibility seems difficult to exclude with current observations (see also § VI)).

Such thin sheets would be a very different kind of structure than what we have argued is appropriate for the cloud toward B2 1225+31, and it would be difficult to understand how these two clouds could be members of a common population.

Alternatively, and we think more likely, if metal-containing and metal-free clouds belong to the same basic population, then the clouds could have the same basic structure but must have metal abundances differing by more than a factor of 100. Such a situation is encountered in other objects generally considered to be members of a common population (e.g., globular clusters).

VI. PHYSICAL PROPERTIES OF THE LYMAN-α AND METAL-CONTAINING CLOUDS

In the previous section we discussed the ionization state and metal abundance of two absorption systems: an apparently very low abundance or "primordial" system showing only Lyman lines, and a system in B2 1225+31 exhibiting a C IV doublet and only moderate metal depletion. In this section we comment on additional physical properties of the Lyman-α only and metal line clouds and the possible differences and similarities between them.

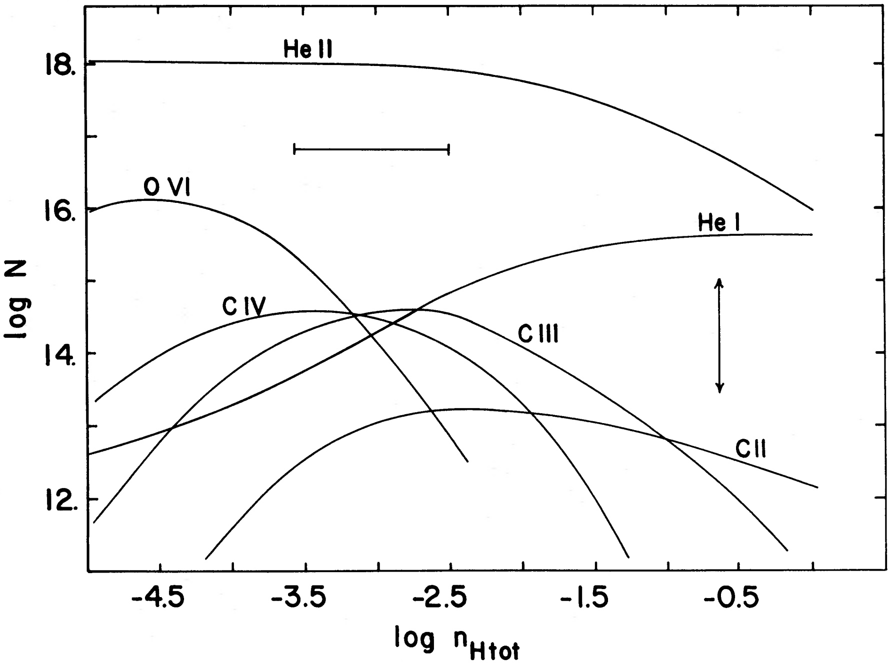

FIG. 3.—Column densities of dominant species as a function of total hydrogen density for the $z = 3.321$ cloud in the direction of the QSO S5 0014+81. The assumed parameters of the model are the same as in Fig. 1. The position marked with an arrow is that where the 0014+81 cloud would have the same C II/C IV ratio as the limit on the $z = 2.25$ cloud in the direction of B2 1225+31. The range of allowed densities constrained by the observations of limits on the Lyman-α cloud sizes is shown by a horizontal bar.

a) Characteristic Sizes and Masses of the Clouds and Cloud Ensembles

Three different methods have been used to estimate, or set limits on, the characteristic size of an absorbing region. A direct estimate comes from studies of "common" absorption systems in close pairs of QSOs or gravitationally split images of a QSO (Weymann and Foltz 1983; Foltz *et al.* 1984; Boksenberg and Sargent 1983). A second, indirect method involves estimates of the electron density required to produce the observed or inferred degree of ionization for some assumed radiation field together with an observed column density. A third, indirect, limit involves consideration of the central intensity or equivalent width of lines whose optical depths can be estimated. This line of argument establishes limits on the cross section of the absorbing region compared to the effective continuum source size (e.g., continuum source or broad-line emitting region). (See Boksenberg and Sargent for further discussion and a review of the properties of the metal line clouds). *In none of these techniques is it entirely clear whether we are measuring the size of an individual cloud or the size of a region containing several (or very many) separate clouds.* In the following discussion we consider only the first two of these techniques.

Boksenberg and Sargent (1983) review the observational material pertaining to common metal line systems seen in pairs. In particular, they present data on the C IV doublet seen in 0957+56 A, B, where the separation of the beams was estimated to be of order 8 kpc ($q_0 = 0.5$, $H_0 = 50$ is assumed in the rest of this discussion). Since there is evidence of structure in one of the lines of sight, the inference is that the 8 kpc is to be interpreted as a lower limit on the cloud ensemble size, rather than the size of an individual cloud. From the line profiles themselves, though, it is not clear whether there are one or two or a large number of clouds in the line of sight.

By contrast, the observations of Foltz *et al.* of the Lyman-α absorption systems in common to the spectra of 2345+00 A, B have been generally assumed to set lower limits on (or possibly characteristic sizes of) *individual* clouds. To a large extent the different interpretation of the two different observations represents the widely held preconception concerning the different nature of the Lyman-α–only and metal-containing systems. However, if separate clouds are involved, the rather small velocity difference between the members of the 13 pairs of common lines in 2345+00 suggests that the gravitational potential is remarkably small—but the velocity difference between the two lines of sight toward 0957+56 is also remarkably small! Additionally, the general lack of structure on scales of 30–100 km s^{-1} and the low Doppler parameter measured for some of the Lyman lines is more suggestive of a single cloud than a large ensemble of clouds.

Turning to the second method of estimating cloud sizes, Sargent *et al.* (1979) estimated sizes of order 100 pc for their so-called S_1 systems—systems showing both high and low ionization states. Letting ξ be the ionization parameter ($\xi \equiv n_{\gamma 0}/n_{\mathrm{H_{tot}}}$), $n_{\gamma 0}$ the photon number density at the Lyman limit, η the number of individual clouds along the line of sight, and N(H I) the neutral hydrogen column density, the characteristic cloud size d is given by:

$$d \approx \xi^2 N(\mathrm{H\ I})/\eta n_{\gamma 0} . \qquad (1)$$

In the case of the B2 1225+31 cloud, the C II/C IV upper limit sets a lower limit on ξ. Using the Weymann-Malkan estimate for the radiation field and our estimate of $\sim 5 \times 10^{16}$ cm^{-2} for N(H I) in the B2 1225+31 cloud, we find $d\eta > 5$ kpc. No structure is evident at the 40 km s^{-1} resolution used, and it seems unlikely that $\eta \gg 1$. The corresponding mass is greater than 10^6–10^7 $M_\odot$—in the range of globular cluster masses. Thus, it may be that some of the individual high-ionization metal line systems are larger and more massive than previously thought.

b) Physical Conditions in the Lyman-α Clouds in the Pressure-confined Model

The total hydrogen density limits given in Figure 1 are set, as noted in § II above, by upper and lower limits for the Lyman-α cloud size given by Sargent, Young, and Schneider (1982) and by Foltz *et al.* (1984), together with the assumption that the absorption arises in single clouds in pressure equilibrium with an adiabatically cooling confining medium. In the observations of Foltz *et al.* at $z = 2.0$, there was evidence (not yet adequately confirmed) that this lower limit may be close to the characteristic size of the cloud.

In this case, the pressure-confined model leads to a unique pressure at this and all other redshifts, and, if we assume that the clouds are in thermal and ionization equilibrium with the Weymann-Malkan radiation field, the total density, ionization, and temperature can be uniquely specified at all redshifts. Since both the neutral hydrogen column densities and the characteristic size of the clouds are very uncertain, we leave these two quantities as free parameters. Using Ferland's CLOUDY code, we then find that, for optically thin clouds at $z = 2$,

$$\log (n_{\mathrm{H_{tot}}})_{z=2} \approx 0.45[\log (N_{\mathrm{H}\,15}/D_{10})] - 3.50 , \qquad (2)$$

$$\log (T_0)_{z=2} \approx -0.10[\log (N_{\mathrm{H}\,15}/D_{10})] + 4.53 , \qquad (3)$$

while at $z = 3.321$,

$$\log (n_{\mathrm{H_{tot}}})_{z=3.321} \approx 0.45[\log (N_{\mathrm{H}\,15}/D_{10})] - 2.55 , \qquad (4)$$

$$\log (T_0)_{z=3.321} \approx -0.10[\log (N_{\mathrm{H}\,15}/D_{10})] + 4.40 , \qquad (5)$$

where $N_{\mathrm{H}\,15}$ and D_{10} are the neutral hydrogen column density and sizes of the $z = 2$ 2345 A, B clouds in units of 10^{15} cm^{-2} and 10 kpc respectively.

As noted by many authors (cf. Ostriker and Ikeuchi 1983), such clouds will not be in pressure equilibrium if the sound crossing time is long compared to the time for the confining pressure to drop significantly due to the expansion of the universe. For $q_0 = \frac{1}{2}$ cosmological models, this leads to the condition

$$(R_{\mathrm{cloud}})_{z=2} < 8/h_0 \quad \text{and} \quad (R_{\mathrm{cloud}})_{z=3.321} < 4.5/h_0 ,$$

where $h_0 = H_0/50$.
We may also estimate the gravitational scale length

$$R_{\mathrm{grav}} = [kT/(a\mu m_{\mathrm{H}}{}^2 4\pi G n_{\mathrm{H_{tot}}})]^{1/2} , \qquad (6)$$

which, evaluated at the two epochs, leads to

$$(R_{\mathrm{grav}})_{z=2} \approx 30(N_{15}/D_{10})^{-1/3/} \text{ kpc} ,$$

$$(R_{\mathrm{grav}})_{z=3.32} \approx 7(N_{15}/D_{10})^{-1/3} \text{ kpc} .$$

Associated with this characteristic gravitational scale length is a characteristic neutral hydrogen column density, $N_{\mathrm{grav}}(\mathrm{H\ I}) = R_{\mathrm{grav}}\, n_{\mathrm{H\ I}}$, which evaluated at the two epochs gives

$$[N_{\mathrm{grav}}(\mathrm{H\ I})]_{z=2} \approx 3 \times 10^{15}(N_{15}/D_{10})^{2/3} ,$$

$$[N_{\mathrm{grav}}(\mathrm{H\ I})]_{z=3.32} \approx 3 \times 10^{16}(N_{15}/D_{10})^{2/3} ,$$

and a characteristic mass

$$[M_{\rm grav}({\rm H\,I})]_{z=2} \approx 8 \times 10^8 (N_{15}/D_{10})^{-0.55}\, M_\odot\,,$$
$$[M_{\rm grav}({\rm H\,I})]_{z=3.32} \approx 9 \times 10^7 (N_{15}/D_{10})^{-0.55}\, M_\odot\,.$$

For $N({\rm H\,I}) \gg [(N_{\rm grav}({\rm H\,I})]$, the clouds should be distinctly centrally condensed and possibly unstable with a density higher (and the ionization lower) then those given by equations (2) and (4). The "metal-free" clouds in 0014+81 discussed here and the one in 2126−15 discussed by Sargent and Boksenberg are possibly examples of such clouds, and this mechanism could set an upper limit on N(H I) in the metal-free clouds if they are unstable to gravitational collapse.

A different point of view recently presented by Ikeuchi and Ostriker (1985) yields similar upper limits to the sizes, masses, and H I column densities of the Lyman-α–only clouds. In their picture, shocks resulting from various pregalactic events at an earlier epoch ($z > 10$) propagate through the intergalactic medium (IGM), forming dense shells. High-energy events produce shells which are gravitationally unstable and fragment into galaxies; low-energy events produce shells which are gravitationally stable but suffer a Rayleigh-Taylor–type instability (Vishniac 1983; Vishniac, Ostriker, and Bertschinger 1985) and form Lyman-α clouds. The resulting fragments may be in pressure equilibrium with the IGM by $z \approx 3$, and have masses $\sim 10^6$–$10^9\ M_\odot$ and $N({\rm H\,I}) \approx 10^{13}$–$10^{14.5}$ cm^{-2}. Fragments experiencing higher pressure, e.g., the ram pressure resulting from the shell advancing into the IGM, might develop neutral cores and $N({\rm H\,I}) \approx 10^{16}$–$10^{18}$ cm^{-2}.

Finally, we remark on the helium ionization in clouds at $z = 3.3$ with log $n_{\rm H_{tot}}$ varying between the canonical pressure equilibrium value of −2.55 and the "thin sheet" value of ~ −0.65 required for the 0014+81 cloud to have the same metallicity as that toward B2 1225+31. As shown in Figure 3, the CLOUDY code and the Weymann-Malkan radiation field predict that $N({\rm He\,II})/N({\rm H\,I}) \approx 27$ and $N({\rm He\,I})/N({\rm H\,I}) \approx 0.02$ for the pressure equilibrium model, while for the thin sheet limit, $N({\rm He\,II})/N({\rm H\,I}) \approx 1.6$ and $N({\rm He\,I})/N({\rm H\,I}) \approx 0.12$. Considering the uncertainties in both the observations and the models, we believe that a definitive test requires the measurement of both He I and He II lines, which will be difficult.

VII. SUMMARY

We have presented photoionization models which predict the expected column densities of various observable ions in low-density clouds whose radiation environment is dominated by QSOs. These models suggest that at all epochs, for a fixed equivalent width limit in the observer's frame, C III λ977 will be the strongest observable line over the range $-1.0 \leq \log n_{\rm H_{tot}} \leq -3.5$. At lower and higher densities, O VI λλ1031, 1037 and C II λ1334 will dominate, respectively.

We apply these models to the data of Chaffee *et al.* (1985) of S5 0014+81 to show that their reported Si III detection is probably incorrect, since a cloud having the proposed Si III column density would have produced a detectable C III λ977 line.

We argue that the metal-containing clouds must be highly photoionized, as must the Lyman-α–only clouds if all physical properties except metal abundance are similar. If this is so, then the "Lyman-α–only" and "metal-containing" systems must span a wide range of metal abundances. The question of the lower limit to the [M/H] value in Lyman-α–only clouds remains open, and their primordial nature thus remains a possibility.

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