CHEMICAL ENRICHMENT AT HIGH REDSHIFTS

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ABSTRACT

We have tried to understand the recent observations related to metallicity in Ly α forest clouds in the framework of the two component model suggested by Chiba & Nath (1997). The model consists of mini-halos having circular velocities smaller than $\sim$ 55 km s^{-1}, with no star formation and galactic halos with higher circular velocities $\leq$ 250 km s^{-1}, having clouds, star formation and consequent metal enrichment. The number of clouds in the galactic halos was determined from the observed redshift distribution of Ly α lines. We find that even if the mini-halos were chemically enriched by an earlier generation of stars, to have [C/H] $\simeq$ -2.5, the number of C IV lines with column density >10^{12} cm^{-2}, contributed by the mini-halos, at the redshift of 3, would be only about 10% of the total number of lines, for a chemical enrichment rate of $(1+z)^{-3}$ in the galaxies. Not much information about the degree of enrichment of the mini-halos can therefore, be obtained from observations of C IV lines with column density >10^{12} cm^{-2}. Recently reported absence of heavy element lines associated with most of the Ly α lines with H I column density between $10^{13.5}$ cm^{-2} and 10^{14} cm^{-2} by Lu et al (1998), if correct, gives an upper limit on [C/H]=-3.7, not only in the mini-halos, but also in the outer parts of galactic halos. This is consistent with the results of numerical simulations, according to which, the chemical elements associated with the Ly α clouds are formed in situ in clouds, rather than in an earlier generation of stars. However, the mean value of 7×10^{-3} for the column density ratio of C IV and H I, determined by Cowie and Songaila (1998) for low Lyman alpha optical depths, implies an abundance of [C/H] =-2.5 in mini-halos as well as most of the region in galactic halos, presumably enriched by an earlier generation of stars. The redshift and column density distribution of C IV has been shown to be in reasonable agreement with the observations.

Subject headings: galaxies: abundances – galaxies: halos – quasars: absorption lines

I. INTRODUCTION

In the past few years a wealth of information has been obtained, about the absorbers producing Ly α absorption lines in the QSO spectra, from the high resolution, high S/N observations obtained with the Keck telescope as well as observations obtained with the HST. Fernandez-Soto et al (1997) have used the luminosity function obtained with photometric redshift measurements of the Hubble deep field galaxies, to show that all the observed Ly α absorption lines with column densities $\geq 6 \times 10^{13}$ cm^{-2} can be accounted for by galaxies alone. Important information has come about the presence of heavy elements in the, till recently considered 'pristine', Ly α forest clouds (Tytler et al 1995, Cowie et al 1995). All the Ly α forest clouds with neutral hydrogen column density, $N_{\rm H\,I}$, larger than 10^{15} cm^{-2} and 75% of the clouds with $N_{\rm H\,I} > 3 \times 10^{14}$ cm^{-2} at z $\sim$ 3 have been found to show associated C IV absorption (Songaila & Cowie 1996). Carbon abundance in these clouds has been estimated to be between [C/H] $\sim$ -2 and -3. It has been suggested that a first generation of, Pop III, stars may have polluted the entire universe to a nearly uniform level of [C/H] $\simeq$ -2.5 (Songaila & Cowie, 1996, Miralda Escude & Rees, 1997). The presence of heavy elements in lower H I column density clouds has been addressed recently by Lu et al (1998). They tried to detect C IV in very high S/N ($\sim$ 1860:1) spectra, obtained for a rest frame composite spectrum of about 300 Ly α lines at redshifts between 2.2 and 3.6. In absence of any detection of C IV lines in the composite spectrum they concluded that the mean metallicity of the Ly α clouds with $10^{13.5}$<$N_{\rm H\,I}$<10^{14} cm^{-2} is [C/H] < -3.5, at least a factor of 10 lower than that for the higher $N_{\rm H\,I}$ (> 10^{14} cm^{-2}) clouds. Similar conclusion was drawn by Dave et al (1998) who tried and failed to detect O VI lines corresponding to weak Ly α lines. These observations are consistent with results of numerical hydrodynamical simulation studies of structure formation. According to these, most of the metals in Ly α clouds with $N_{\rm H\,I} > 10^{14}$ cm^{-2} are produced in situ by Pop II stars in the clouds themselves or in nearby galaxies, while the first generation of stars which probably formed around z $\sim$ 14 enriched the universe to a mean metallicity as small as 10^{-5} solar (Gnedin 1997).

The conclusions of Lu et al (1998) have been contradicted by Cowie and Songaila (1998). They have used a new, robust method for analyzing the carbon and oxygen absorption lines in the QSO spectra, based on the measurement of optical depths. They conclude that the ratio $N_{\rm C\,IV}/N_{\rm H\,I}$ roughly remains constant over a wide range of over-densities and suggest that a substantial metallicity is present even in the regions of the intergalactic medium with only slight over-densities. They determine a mean and median value of 7×10^{-3} and 3×10^{-3} respectively for $N_{\rm C\,IV}/N_{\rm H\,I}$, for optical depths between 2 and 5 which is close to the range of H I column densities considered by Lu et al (1998). The mean value of $N_{\rm C\,IV}/N_{\rm H\,I}$ was earlier found to be 3.5×10^{-4} for $N_{\rm H\,I}$ between 10^{15} and 10^{17} cm^{-2} (Songaila and Cowie 1996).

In the simulation studies, Ly α absorption with $N_{\rm H\,I} > 10^{14}$ cm^{-2} mostly occurs in continuous filaments of gas surrounding and connecting collapsed objects, while clouds with $N_{\rm H\,I} < 10^{14}$ cm^{-2} are preferentially found in voids which are far away from the collapsed objects. As a result, a large variation is to be found in the heavy element abundances of Ly α clouds. Clouds with low column densities will have practically no heavy elements, while the higher column density clouds would have been enriched by heavy elements from Pop II stars mostly through galaxy mergers (Gnedin 1997; Gnedin & Ostriker 1997; Ostriker & Gnedin 1996). A similar model was recently considered, analytically, by Chiba & Nath (1997, hereafter CN97). Their model, based on CDM models of structure formation, assumes that the Ly α absorption lines are produced by virialized gas clouds. They have argued that gas confined to mini-halos (with circular velocities $\leq$ 55 km s^{-1}) will not have heavy elements as the star formation in these may be inhibited by the suppression of radiative cooling due to photoionization. These mini-halos will contribute more to the lower H I column density Ly α lines which are not accompanied by lines of heavy elements. Gas in the galactic halos ($55\leq V_c\leq250$ km s^{-1}), on the other hand, would probably cool and form clouds and stars and would contribute more to the higher H I column density Ly α lines which will be accompanied by lines of heavy elements. It is however, possible that the mini-halos may have been chemically enriched by an earlier generation of stars. In this paper we reconsider this two component model of the Ly α lines and compare its predictions with the above mentioned observational results. In section 2 we briefly describe the model while in section 3 we compare the model results with observations. Conclusions are presented in section 4.

II. DESCRIPTION OF THE BASIC MODEL

Our treatment of mini-halos and galactic halos is essentially same as, and differs only in some details from, that of CN97. We therefore describe the basic scenario very briefly here, the reader is requested to refer to CN97 for further details, in particular about the justification of the values assumed for various quantities entering the calculation.

We assume the radial distribution of baryonic matter, the density of which is assumed to be 0.05 times the total matter density in the mini and galactic halos, as given by

$$\rho(r) \ = \frac{\mathrm{V_c^2}}{4\ \pi\ \mathrm{G}\ (\mathrm{r}^2 + \mathrm{r_c^2})}\ (\frac{\mathrm{x_v}}{\mathrm{x_v} - \mathrm{arc\ tan\ x_v}}) \qquad (1)$$

where V_c is the circular velocity at the virial radius, $\mathrm{r_{vir}}$, G is the universal gravitational constant, $\mathrm{r_c}$ is the core radius, taken to be 10 and 100 kpc for the mini and galactic halos respectively and $\mathrm{x_v} = \frac{\mathrm{r_{vir}}}{\mathrm{r_c}}$. The limits on $\mathrm{V_c}$ pertaining to the two types of halos are based on various physical reasons. The lower limit on V_c ($\sim$ 15 km $\mathrm{s^{-1}}$) is roughly the value below which the perturbations in baryonic mass are suppressed. The upper limit on $\mathrm{V_c}$ ($\sim$ 55 km $\mathrm{s^{-1}}$) for mini-halos is roughly the value below which photoionization suppresses cooling and formation of clouds. Upper limit on $\mathrm{V_c}$ for galactic halos is taken to be 250 km $\mathrm{s^{-1}}$. Our treatment of galactic halos differs somewhat from that of CN97. While CN97 have assumed that the column density along a line of sight with impact parameter b through a galactic halo is equal to the column density of hydrogen in a single cloud at a radial distance equal to the impact parameter from the centre of the galaxy, we consider the distribution of clouds and calculate the total column density along a given line of sight as the sum of column densities in all the clouds that may lie along the line of sight. This is likely to be more appropriate in view of the covering factors obtained in our model as will be discussed below. Thus the column density of a particular ion along a line of sight with impact parameter b is given by

$$N_{ion}(b) = 2\int_b^\infty \frac{n_H(r) f_{ion}(r) r dr}{\sqrt{r^2 - b^2}}, \qquad \text{for mini - halos} \tag{2}$$

and

$$N_{ion}(b) = 2\int_b^\infty \frac{N_H(r) f_{ion}(r) \sigma(r) \eta_{cl}(r) r dr}{\sqrt{r^2 - b^2}} + 2\int_b^\infty \frac{n_H(r) f_{ion}(r) r dr}{\sqrt{r^2 - b^2}}, \qquad \text{for galactic halos,} \tag{3}$$

where the first term is the contribution from the galactic clouds while the second term is the contribution from the intercloud medium along the line of sight. Here n_H is the number density of hydrogen, $f_{ion}(r)$ is the ratio of the number density of the ion to hydrogen number density in a cloud at a radial distance r. $\sigma(r)$ is the area of crosssection of the clouds and $\eta_{cl}(r)$ is the number of clouds per unit volume at a radial distance r. We assume all the clouds to have a uniform mass, M_{cl}, of $\sim 10^6$ $M_\odot$. The clouds are assumed to be in pressure equilibrium with the hot intercloud medium. The clouds, being photoionized, have a temperature $\sim 3 \times 10^4$ K. The radius of a cloud, R_{cl}, at a radial distance r from the centre of the galaxy, in a halo with circular velocity V_c, is given by

$$R_{cl} = \left(\frac{3M_{cl}}{4\,\pi n_{cl} m_p}\right)^{1/3} = 5.2 \times 10^7 M_{cl}^{1/3} T_{cl}^{1/3} T^{-1/3} n^{-1/3} \tag{4}$$

T, n and T_{cl}, n_{cl} being the temperatures and the particle densities in the hot medium and the cloud respectively. For the hot inter cloud medium associated with galactic halos, T for $V_c \geq 55$ km s^{-1} is given by, $T \simeq 10^5 (\frac{V_c}{55 kms^{-1}})^2$ K while for $V_c \leq 55$ km s^{-1} it is taken to be $\sim 3 \times 10^4$ K. $N_H(r)$, the column density of hydrogen through the cloud at a radial distance r, is taken to be $n_{cl} R_{cl}$.

While CN97 have made the assumption of unit covering factor by the clouds of the galactic halo projected on to the sky, we assume the number density of clouds, $\eta_{cl}(r)$, to have the same radial dependence as the total density, so that

$$\eta_{cl}(r) = \frac{\eta_{cl}(0)}{1 + r^2/r_c^2} \tag{5}$$

The number of lines of a particular ion per unit redshift interval per unit column density interval per line of sight is given by (assuming $q_o = 0.5$)

$$\frac{d^2N(z, N_{ion})}{dN_{ion}dz} = \frac{c}{H_o} (1+z)^{1/2} \int_{V_l}^{V_u} n(V_c, z)\, 2\, \pi\, b\, \frac{db}{dN_{ion}}\, \epsilon\, dV_c, \tag{6}$$

where b is the impact parameter for a halo of circular velocity V_c, for which the column density N_{ion} will be obtained for the particular ion. ϵ is the fraction of halos that give rise to absorption lines, for the galactic halos it is the fraction of halos having sufficient gas to produce absorption lines. For these, ϵ is taken to be 0.69, which is the fraction of late type galaxies (Postman & Geller 1984). For mini-halos $\epsilon = 1$. From the CDM models of structure formation (Mo, Miralda-Escude & Rees 1993) the mass and circular velocity of a halo are related to the comoving radius r_o and redshift z by,

$$M = \frac{4\,\pi}{3}\, \rho_o\, r_o^3, \quad V_c = 1.67\, (1+z)^{1/2}\, H_o\, r_o \tag{7}$$

where ρ_o and H_o, are respectively, the mean density of the universe and the Hubble constant at the present time. $n(V_c,z)dV_c$ is the number of halos per unit volume with circular velocity between V_c and $V_c + dV_c$ being given by

$$n(V_c, z)dV_c = \frac{-3(1.67)^3 \delta_c H_o^3 (1+z)^{5/2}}{(2\pi)^{3/2} V_c^4 \Delta(r_o)} \frac{d\ln\Delta}{d\ln V_c} \times \exp\left(\frac{-\delta_c^2 (1+z)^2}{2\,\Delta^2(r_o)}\right) dV_c \tag{8}$$

Here $\delta_c = 1.68$ and the functional form of $\Delta(r_o)$ for the CDM power spectrum of density perturbation is

$$\Delta(r_o) = 16.3\, b_g^{-1}\, (1 - 0.3909\, r_o^{0.1} + 0.4814\, r_o^{0.2})^{-10} \tag{9}$$

where b_g is the bias parameter taken to be 1.

We have used the code 'cloudy 90' for calculation of f_{ion}. For the range of column densities that we are interested in this paper, the values of f_{ion} for C IV and H I are independent of the hydrogen column density as well as the particle density for the range of values expected in the clouds and intercloud medium. $\frac{f_{ion}}{Z}$ is also independent of Z, the chemical abundance of carbon. We have therefore stored the results of several runs of cloudy in the form of a table of $\frac{f_{ion}}{Z}$ vs. the ionizing parameter Γ. The ionization parameter at a radial distance r from the centre is given by

$$\Gamma(\mathrm{r}) \;= \frac{4\;\pi\;10^{-21}\mathrm{J}_{21}}{\mathrm{c}\;\alpha_{\mathrm{Q}}\;\mathrm{h}\;\mathrm{n}_{\mathrm{H}}} \tag{10}$$

where J_{-21} is the intensity of the UV background radiation in units of 10^{-21} ergs cm^{-2} s^{-1} Hz^{-1} str^{-1}. c and h are velocity of light and Planck's constant and α_Q is the slope of the spectrum of the UV background radiation (assumed to be a power law). $\mathrm{n_H}$ is replaced by $\mathrm{n_{cl}}$, the density of the particles in the clouds at a radial distance r for clouds in galactic halos. The table is searched and the value of $\mathrm{f_{ion}}$ obtained by interpolation, at every point during the evaluation of the integrals in equation (2) and (3). J_ν is assumed to be independent of z for z>2.5 as suggested by the proximity effect analysis of Ly α lines, while for z<2.5, J_ν varies with z as $\mathrm{J}_\nu(\frac{1+z}{3.5})^\alpha$. The index α gives the rate of decrease of J_ν for z<2.5 and we have considered two cases (i) $\alpha = 0$ (ii) $\alpha = 2.0$.

The number of clouds per unit volume at the centre of the galaxy, $\eta_{\mathrm{cl}}(0)$, is an unknown factor. We take $\eta_{\mathrm{cl}}(0) = \mathrm{f}\ \frac{3}{4\,\pi\,\mathrm{r}^3_{\mathrm{cl}}(0)}$, where f≤1. The value of f is obtained by making the predicted redshift distribution for Ly α lines match with the observed values. These distributions are plotted in Figure 1 for two values of α, for $\alpha_Q = 1.5$. The straight line fit to the observed data from Keck and HST is from Kim et al (1998). A good match between theoretical and observed distributions is obtained for f=0.0035. The Figure also shows the distribution for f = 0.001 and f = 0.01 for comparison. f = 0.0035 gives the total number of clouds in the galactic halos with V_c = 55 & 250 km s^{-1} to be about 380 and 161544 respectively, thus giving total halo mass $\simeq 3.8 \times 10^8$ and 1.6×10^{11} $\mathrm{M}_\odot$ which is close to 10 % of the total masses of these halos. The total covering factor presented by the clouds on the projected plane of the galaxy being 0.16 and 1.15 for V_c = 55 & 250 km s^{-1} respectively. In the following analysis we take the value of f to be 0.0035. Note that CN97 have assumed a unit covering factor by clouds in the galactic halos, while we get lower values for low V_c clouds and higher values for high V_c clouds. As a result, their assumption of the H I column density at an impact parameter b being equal to the column density in a cloud at a radial distance b is not valid in our case.

III. COMPARISON WITH OBSERVATIONS

A. Column density distribution of neutral hydrogen

The column density distribution function, f($N_{\rm H\,I}$), is defined as the number of absorbing systems per unit column density per unit redshift path which is defined by X(z) $= \frac{2}{3}[(1+z)^{3/2}-1]$ for $q_o = 0.5$. Recently Kim et al (1998) have analyzed the properties of low column density (between $10^{12.8}$ and 10^{16} cm^{-2}) Ly α lines towards 5 QSOs at different redshifts, between 2.1 and 3.5, using the Keck data. They find that the density distribution function fits a power law with a slope between -1.35 and -1.55. The slope changes slowly with redshift, the distribution becoming steeper with increasing redshift. For $N_{\rm H\,I} > 10^{14}$ cm^{-2}, they find a departure from the power law, the observed number of lines being smaller than that given by the power law. A comparison of the observations with the predictions of our model is presented in Figure 2. The slope of the predicted distribution is $\sim$ -1.5 and it is almost independent of redshift. The distribution function also shows an increase in the slope at higher $N_{\rm H\,I}$, which is, however, less than the observed departure from the power law.

B. Redshift distribution of C IV lines

In trying to determine the redshift distribution of heavy element lines, one has to consider the change in abundance of heavy elements with redshift. Direct observational evidence for increase in chemical abundance with redshift has been obtained, for damped Ly α systems, by Pettini et al (1995, 1997) and Lu et al (1996). Lu et al (1996) have shown that the mean metallicity of these systems increases with decreasing redshift. They find that most systems with z $>$ 3 have [Fe/H] $<$ -2 while at z $<$ 3 a large fraction of the systems have [Fe/H] $\simeq$ -1.

It thus seems that the abundance in galactic disks (of which the damped Ly α are believed to be progenitors (Prochaska & Wolfe 1997, however, see Pettini et al 1997)) has been increasing with time. The abundance of carbon in Ly α forest clouds with $N_{\rm H\,I} > 10^{14}$ cm^{-2} at z $\sim$ 3 has been found to be between 10^{-2} and 10^{-3} of solar abundance. Though the abundance of silicon w.r.t. carbon in Ly α clouds appears to have changed with redshift (Songaila & Cowie 1996), there is, as yet, no definite evidence for a change in abundance of carbon with redshift in the forest clouds. However, it seems possible that the abundance in the galactic halos has been increasing continuously with time due to in situ star formation (Khare & Rana 1993; CN97). We, therefore, assume the abundance of carbon to depend on the redshift as $Z(z) = Z(0)(1+z)^{-\delta}$ in the galactic halos. For mini-halos we have assumed a constant abundance of [C/H]$\simeq$-2.5, assumed to be produced by the Pop III stars. In Figure 3 we have plotted the results of calculation for the redshift distribution of C IV lines for both galactic halos and mini-halos together for $N_{\rm C\,IV} > 10^{13}$ cm^{-2}.

In order to obtain observed value of dN/dz, we have collected data from the literature and performed a maximum likelihood analysis. The results of this analysis along with the references for the data used are given in Table 1. The data include components of damped Ly α systems also. We have included these in the data as most of the components are likely to arise in the galactic halos. Inclusion of the few pure DLA components will change the values of $\frac{dN}{dz}$ only by a very small amount. We have also considered a poissonian sample constructed for the data, obtained by counting lines within 200 km s^{-1} of each other as one line. This is to count the lines formed by various clouds in a single galaxy as one line. The results for this data set are given in the last two lines in Table 1. The value of the evolutionary index γ ($\frac{dN}{dz}$ α $(1+z)^{\gamma}$) is positive if lines with smaller column densities are included. The index is negative for higher column density lines, indicating an increase in the number of such lines with decreasing redshift, similar to that found with low resolution observations (Steidel 1990). The values of dN/dz for $N_{\rm C\,IV} > 10^{13}$ cm^{-2} are plotted in Figure 3. Songaila (1998) has reported observations of C IV towards 13 QSOs. The value of dN/dz calculated for her data with an average redshift of 2.87 is also plotted in the figure.

As seen from the Figure, high values of δ, $\simeq$ 4, are indicated by the observations which are probably consistent with the observations of damped Ly α systems. The distribution shows negative values of the index of redshift distribution, γ, for redshifts > 1. The values of γ for $N_{\rm C\,IV} > 10^{13}$ cm^{-2} in Table 1 are positive. However, γ is negative for higher column density cutoffs, the values though, are higher than the values obtained here for δ = 4.

One important result that emerges from this is that the contribution of mini-halos, assuming the abundance in these halos to be [C/H]=-2.5, produced by an earlier generation of stars, to the C IV lines with column density $>10^{13}$ cm^{-2} is completely negligible, being $< 5\%$ at z=3. Even for C IV lines with column density $> 10^{12}$ cm^{-2} mini-halos contribute only about 10 % to the total number of C IV lines at z=3. In the galactic halos, the contribution to the C IV column densities comes mostly from the clouds, the hot intercloud medium contributing insignificantly to the total C IV column density due to its lower particle density. Thus even if mini-halos had a chemical enrichment of [C/H]=-2.5 due to Pop III stars, they would not contribute significantly to the observed number of carbon lines with column density $> 10^{12}$ cm^{-2}.

C. Column density distribution of C IV lines

The column density distribution function of C IV clouds at $2.52 < z < 3.78$ has recently been obtained from high resolution Keck observations by Songaila (1998). The distribution is roughly a power law with a slope of -1.5 for column densities larger than 6×10^{12} for which her sample is complete. We have plotted model results for the column density distribution at z=3 for C IV, for δ = 3 and 4 in Figure 4. The model results bracket the observed values for column densities $> 10^{13}$ cm^{-2}. However, at lower column densities the model predicts many more lines than the observed number. The observed data, however, may be incomplete below 6×10^{12} cm^{-2} as noted by Songaila (1997) and it is possible that the number of small column density lines may actually be considerably larger. Note that large values of $\delta \simeq 4$, indicated by the dN/dz data, do not produce sufficient number of lines with column densities $> 10^{13.5}$ cm^{-2}. If the number of lines with column densities $< 6 \times 10^{12}$ cm^{-2} is indeed small, some basic assumptions have to be modified in our model. Increase in rate of abundance evolution does not serve the purpose as it reduces the number of higher column density lines more than that of the lower column density lines. This is discussed further in the next section.

D. Metal lines associated with low H I column density lines

As mentioned above, Lu et al (1998) have tried to detect C IV lines associated with H I lines having column density between $10^{13.5}$ cm^{-2} and 10^{14} cm^{-2}, (referred to below as 'associated C IV lines'), between redshifts 2.2 and 3.6, by obtaining a composite rest frame spectra of about 300 lines which did not have accompanying C IV lines. Note that in a spectra covering a total redshift path of $\Delta z = 4.15$ (leaving out the region of relative velocity ≤ 5000 km s^{-1} from the QSOs which may be contaminated by the lines associated with the QSOs) they detected 7 Ly α lines with column density between $10^{13.5}$ cm^{-2} and 10^{14} cm^{-2}, which were accompanied by C IV lines. They failed to detect any C IV line in the composite spectra and obtained an upper limit of $10^{10.5}$ cm^{-2} on the average column density of the 'associated C IV lines'. As noted before, this conclusion is likely to be erroneous (Cowie and Songaila, 1998). Here, however, we consider the consequences of this conclusion. The results quoted below can be easily scaled for the correct value of the upper limit on the C IV column density. We have also discussed the implications of the results of Cowie and Songaila (1998) below.

We have calculated the range of impact parameters as a function of circular velocity, which produce Ly α lines with H I column densities between $10^{13.5}$ cm^{-2} and 10^{14} cm^{-2}. These are plotted in Figure 5 for the redshift of 3. Note that the column density range is not obtained for galactic halos with $V_c < 90$ km s^{-1} (even though it is obtained in the mini-halos), in spite of the fact that we have taken the contribution from the hot (intercloud) medium into account. This is due to the higher value of core radius used for the galactic halos. The number of such Ly α lines per line of sight per unit redshift interval at $z \sim 2$, 3 and 4 bracketing the redshifts of the Ly α lines considered by Lu et al (1998) is given in Table 2. The number of 'associated C IV lines' per unit redshift interval, per line of sight, is same as the number of Ly α lines. The range of column densities of the 'associated C

IV lines' is plotted in Figure 6 as a function of the circular velocity for the redshift of 3. It can be seen that all the 'associated C IV lines', including those due to the mini-halos, have a column density $\geq 10^{11}$ cm^{-2} and hence would have been clearly observed by Lu et al (1998). The detection of only 7 lines by them in a path length of Δz =4.15 could then be used to obtain an upper limit on the chemical enrichment due to the Pop III stars. We find that the abundance has to be less than -3.7 w.r.t. the solar value for the column densities of 'associated C IV lines' produced by the mini-halos to be below $10^{10.5}$ cm^{-2}. The column density range for mini-halos for this value of abundance at z=3 is shown in Figure 6 (band 5). This conclusion is similar to that of Lu et al (1998).

The column densities of the 'associated C IV lines' produced by galactic halos will reduce if the chemical enrichment due to star formation is confined only to the inner parts of the galactic halos, the outer parts having an abundance (of -3.7) same as the mini-halos. This is expected if further enrichment in these halos is produced due to in situ star formation, which will occur more efficiently towards the centres of the galaxies due to the higher densities occurring there. We therefore, considered two possibilities (i) an abundance gradient $\mathrm{Z(r,z)=Z(0,z)e^{-2\,r/V_c}}$ for the heavy elements produced in situ in the galaxies and (ii) an upper limit on the radial distance up to which heavy elements enrichment has occurred in the galaxies, given by $\mathrm{r_{max}\ (V_c,z)=\frac{4V_c}{(1+z)}}$. Here r and $\mathrm{V_c}$ are in units of kpc and km s^{-1} respectively. The column densities of the 'associated C IV lines' for these two assumptions are also shown in Figure 6 for z=3. The column densities of C IV lines are below the detection limit of Lu et al (1998) for most of the range of circular velocities for both the possibilities. The number of all these 'associated C IV lines' per unit redshift interval per line of sight for the assumption (ii) above, is ≥ 6.2 so that for the sample of Lu et al (1998) about 26 lines are expected, some of which may have column densities below the observable limit. Note that they have observed 7 lines. The dN/dz for the assumption of abundance gradient, on the other hand, is same as that in Table 2. However, as seen from the Figure, most of these would be below the sensitivity of detection, consistent with observations of Lu et al (1998).

We have calculated the column density distribution of C IV lines for these two possibilities which is shown in Figure 4 for $\delta = 3.0$ at z=3. It can be seen that the assumption of abundance gradient reduces the number of high column density lines much below the observed number. The assumption of maximum radial distance for in situ chemical enrichment, however, gives a distribution closer to the observed distribution. We have also calculated the redshift distributions for the two possibilities. These are plotted in Figure 3 for $\delta = 3$ and $N_{CIV} > 10^{13}$ cm^{-2}. The distribution for the assumption (ii) above is closer to the observed values. γ is again negative for higher redshifts, its value ($\simeq$ -1.6, for z>2) is somewhat smaller than the values obtained for higher column density cutoffs in Table 1 and than the value of -1.2 obtained for low resolution observations by Steidel (1990).

We now discuss the implications of the results of Cowie and Songaila (1998) for our results. Taking their mean value of 7×10^{-3} for $N_{C\,IV}/N_{H\,I}$, the range of column density of the ' associated C IV lines' is $2.2\times10^{11} - 7\times10^{11}$ cm^{-2}. The lines produced by mini-halos for the assumed carbon abundance of [C/H]= -2.5 (band 5 in Figure 6) are roughly consistent with this range. The C IV lines produced by the galactic halos for $\delta = 3$ (band 1 in Figure 6), have higher column densities, indicating lower or absence of chemical enrichment in the outer parts of the galactic halos due to in situ star formation (assumptions (i) and (ii) above). We have plotted in Figure 6 (band 6) the range of C IV column density for the galactic halos assuming a uniform abundance of [C/H]=-2.5. These are consistent with the expected range of $2.2\times10^{11} - 7\times10^{11}$ cm^{-2}. Thus an abundance of -2.5 in the mini-halos as well as in the outer parts of the galactic halos due to an earlier generation of stars seems to be consistent with the results of Cowie and Songaila (1998). The chemical enrichment due to in situ star formation has to be restricted to the central regions of the galactic halos at the redshift of about 3. We have calculated C IV column density distribution at z=3, δ=3, for the assumption (ii) above, taking the abundance in the mini-halos and outer parts of galactic halos to be -2.5. This is shown in Figure 4. The distribution is close to that for δ=4, for low column densities $\leq 10^{13}$ cm^{-2} as the abundance for δ=4 for z=3 is close to -2.5. The number of these lines is thus considerably higher than the observed values. For this possibility the number of C IV lines with column density $\geq 10^{13}$ cm^{-2} at z = 2 is 15.8, somewhat larger than the observed values.

IV. DISCUSSION AND CONCLUSIONS

We have tried to understand the recent observations of Ly α forest lines and accompanying C IV lines, in the framework of hierarchical structure formation model. The observed redshift distribution of the Ly α lines has been used to fix the number of clouds in galactic halos. The predicted column density distribution of Ly α clouds is found to be similar to the observed distribution. We find that at redshifts ≤ 2, the number of Ly α lines with column density $> 6 \times 10^{13}$ cm^{-2} contributed by the mini-halos is $\simeq 25$ % of the total lines. Recently Fernandez-Soto et al (1997) have determined the expected density of crossings for an arbitrary line of sight (for $z \leq 2$) by the halos of galaxies, the luminosity function for which was obtained by them from the observations of the Hubble deep field galaxies. They concluded that this number is consistent with the observed number of Ly α lines. They, therefore, suggest that all the observed Ly α lines with $N_{\rm H\,I} > 6 \times 10^{13}$ cm^{-2} are produced by lines of sight crossing galactic halos alone and that no other population (e.g. the intergalactic clouds) is needed to explain the occurrence of these lines. Our values of fraction of Ly α lines with $N_{\rm H\,I} > 6 \times 10^{13}$ cm^{-2} contributed by mini-halos are, however, not consistent with these findings.

In this scenario, the Ly α forest lines should show clustering over velocity scales of a few hundred km s^{-1}, over which the galaxies are known to cluster strongly. Clustering on smaller scales will also be present due to the multiple clouds crossing the line of sight in a single halo. Clustering among the forest lines has been observed (Srianand and Khare, 1994). Recently Fernandez-Soto et al (1996) studied the clustering by studying the two point correlation function of C IV lines associated with Ly α lines. They concluded that Ly α lines with H I column density $> 3 \times 10^{14}$ cm^{-2} are strongly correlated in redshift on velocity scales ≤ 250 km s^{-1}. The clustering seems to persist to lower column densities, though it seems to be weaker compared to that at higher column densities.

Chen et al (1997) have tried to investigate the relation between properties of Ly α absorptions systems and the associated galaxies. They find that out of a sample of 33 galaxies, 7 do not produce Ly α absorption. The covering factor of absorbing clouds in galaxies producing Ly α lines with equivalent width $> 0.3\mathring{A}$ ($N_{\rm H\,I} \geq 6 \times 10^{13}$ cm^{-2}) was earlier found by Lanzetta et al (1995) to be 1 for impact parameters $<$ 160 kpc while it was significantly smaller for higher impact parameters. The covering factor for such clouds in galactic halos in our model for impact parameter $<$ 160 kpc, is 0.03 for z=1 and 0.02 for z=2. However, we have assumed the galactic halos to have circular velocities from 55 to 250 km s^{-1}. It is very likely that the galaxies observed by Lanzetta et al (1995), on which their estimates of covering factor are based, may only correspond to circular velocity towards the higher end of the range considered by us. We have calculated the covering factor by restricting the circular velocities to above 100, 150 and 200 km s^{-1}, the values are 0.14, 0.34 and 0.43 respectively. These are still considerably smaller than the values found by Lanzetta et al (1995).

We have shown that the mini-halos would not contribute significantly to the number of C IV lines with column density $> 10^{12}$ cm^{-2} even if the heavy element abundance in these halos was [C/H]$\simeq$-2.5. Thus no definite conclusions about the level of enrichment by Pop III stars can be drawn from observations of such lines. The reported presence of very few lines of C IV associated with the Ly α lines with column density between $10^{13.5}$ cm^{-2} and 10^{14} cm^{-2}, if correct, indicates an upper limit of [C/H]$\leq$-3.7, not only for the mini-halos, but also for the outer parts of the galactic halos. We have shown that heavy element enrichment beyond [C/H]=-3.7, in the galactic halos, should be confined only to the inner regions of the galaxies in order to be consistent with the results of Lu et al (1998). This is shown to be consistent with the observed distribution of C IV lines. The values of $r_{\rm max}$, suggested here are larger than the impact parameters obtained for heavy element line producing galaxies (Bergeron & Boisse, 1988; Steidel, 1995). The values are also consistent with the expected distances traveled by the material ejected by supernovae in about 10^9 years assuming the velocity of the ejecta to be a few hundred km s^{-1}. These results are consistent with the suggestions of numerical simulations studies that the heavy elements observed in the Ly α absorbers are indeed produced in the absorbing clouds themselves. The values obtained by Cowie and Songaila (1998) for the column density ratio of C IV and H I, however, indicate an enrichment of mini-halos as well as galactic halos to [C/H] =-2.5 by an earlier generation of stars.

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Figure Captions Fig 1: Redshift distribution of Ly α lines with column density greater than $10^{13.77}$ cm^{-2}. Upper and lower solid lines are for f = 0.0035, for $\alpha = 2$ and 0 for z < 2.5 respectively. Long dashed line is the best fit line for observed values taken from Kim et al (1997). Upper and lower short dashed lines are for $\alpha = 0$, for f = 0.01 and 0.001 respectively.

Fig 2: Column density distribution of Ly α lines for $\alpha = 2.0$. Solid and dashed lines are at z=2.31 and z=3.35 respectively. Stars and solid triangles are observed values at z=2.31 z=3.35 respectively.

Fig 3: Redshift distribution for C IV lines with $N_{CIV} > 10^{13}$ cm^{-2}. Small-dashed, solid and long-dashed lines are for $\delta = 0$, 3 and 4 respectively. Dash-dotted line is the distribution obtained with the assumption of an upper limit on radial distances for which chemical enrichment has occurred while long and short dashed line is for the case of an abundance gradient being present in the galactic halos ($\delta = 3$, for both cases), assuming an abundance of -3.7 due to an earlier generation of stars. Triangle shows the observed value for the data set collected from the literature (Table 1), circle shows the observed value for the poissonian sample (obtained by counting lines within 200 km s^{-1} of each other as one line), while square represents the value for the data from Songaila (1998).

Fig 4: Column density distribution for C IV lines at z = 3.0. Solid and long-dashed lines are for $\delta = 3$ and 4 respectively. Small-dashed and dash-dotted lines are for the assumptions of upper limit on radial distance for galactic chemical enrichment and abundance gradient respectively, assuming an abundance of -3.7 in the mini-halos and outer parts of galactic halos. Dotted line is for the assumption of upper limit on the radial distance for galactic chemical enrichment for an abundance of -2.5 in the mini- halos and in the outer parts of galactic halos. $\delta = 3$ for all the three cases. Triangles and squares are the observed values from Songaila (1998) for z< 3 and z $\geq$ 3 respectively.

Fig 5: Range of values of impact parameter for which the column density of H I is between $10^{13.5}$ cm^{-2} and 10^{14} cm^{-2} as a function of circular velocity.

Fig 6: Range of column density of C IV for lines of sight giving rise to Ly α lines with column densities between $10^{13.5}$ cm^{-2} and 10^{14} cm^{-2} as a function of circular velocity. Bands labeled 1, 2 and 3 are results for assumptions of uniform chemical abundance in a given galactic halo ($\delta = 3$), radial abundance gradient in the galactic halos and an upper limit on radial distances inside galactic halos for heavy element enrichment respectively. Bands 4 and 5 are for mini-halos with [C/H]=-2.5 and [C/H]=-3.7 respectively,for δ =3 at redshift of 3. Band 6 is for galactic halos assuming a uniform abundance of -2.5, at z=3.

TABLES

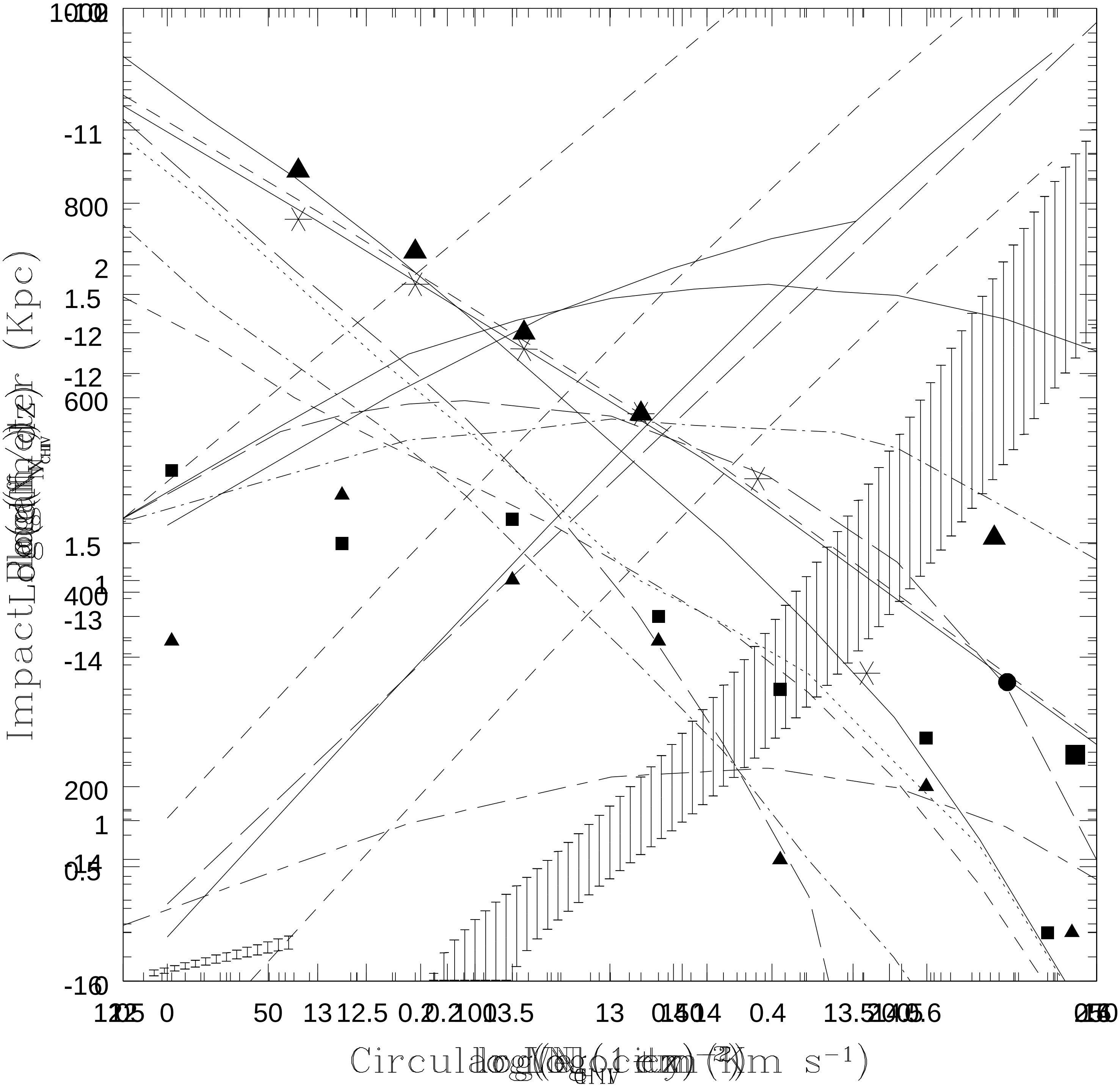
TABLE I. Results of maximum likelihood analysis for C IV lines

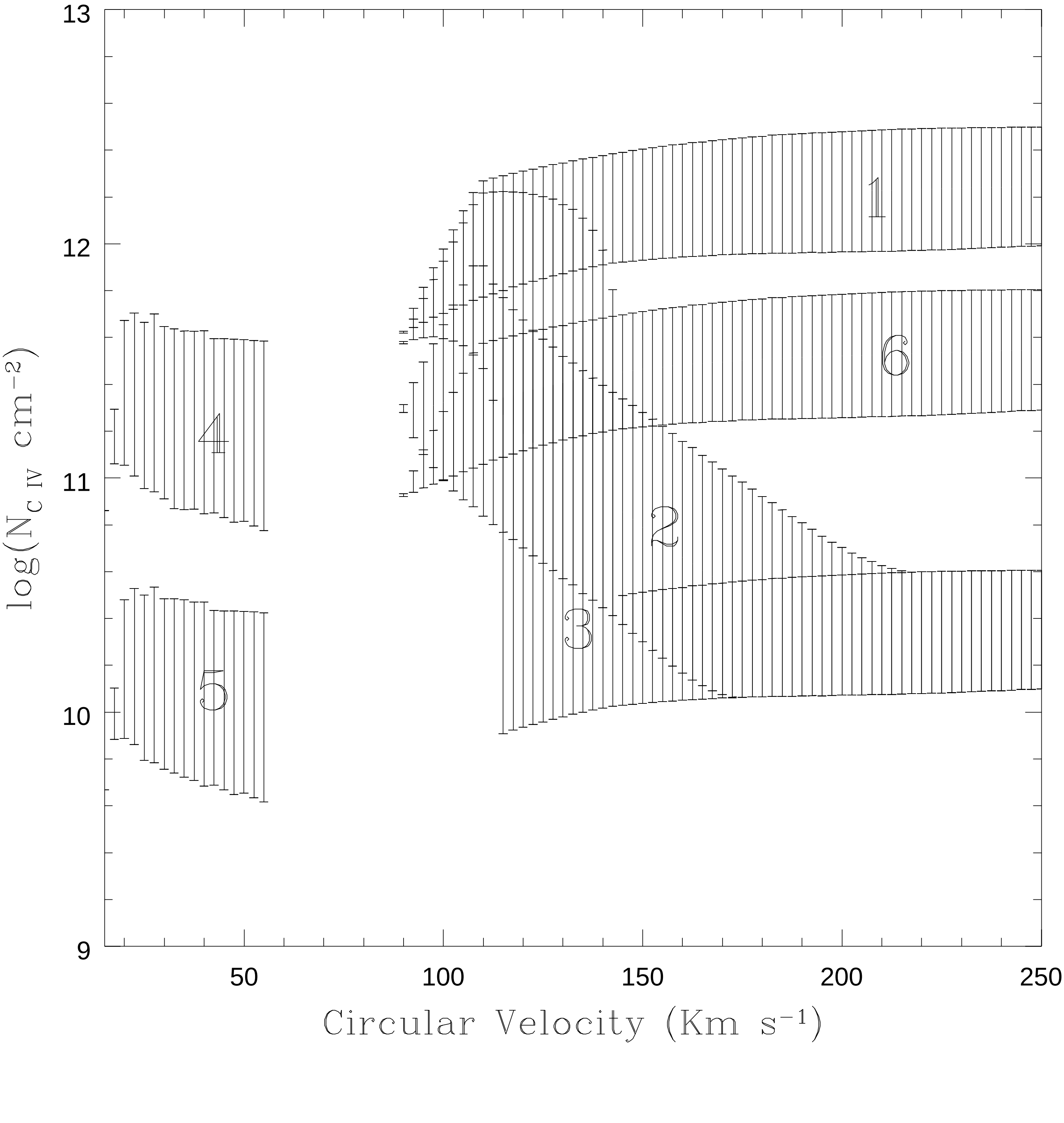
$N_{\rm C\,IV}^{\rm min}$	No of lines	γ	$\frac{\rm dN}{\rm dz}$	$z_{\rm av}$
12.0	186.0	0.52±0.42	15.5	2.47
12.5	175.0	0.41±0.43	14.6	2.46
13.0	143.0	0.24±0.48	11.9	2.45
13.5	87.0	-1.02±0.59	7.2	2.32
13.77	58.0	-1.22±0.47	4.8	2.29
13.0	80.0	0.78±0.65	6.7	2.51
13.5	56.0	-0.25±0.76	4.7	2.39

Ref: Cowie et al 1995, Khare et al 1997, Tripp et al 1996, Savaglio et al 1996, Petitjean & Bergeron 1994, Petitjean, Rauch, Carswell 1994, Tripp, Lu, Savage 1996, Giallongo et al 1993, Cristiani et al 1995, Williger et al 1994, Kulkarni et al 1996, Carswell et al 1984, Carswell et al 1991, Wampler et al 1993, Wampler et al 1991, Petitjean & Bergeron 1994, Pettini et al 1983

TABLE II. Number of Ly α lines with column density between $10^{13.5}$ and 10^{14} cm^{-2}

z	mini-halos	galactic halos	Total
2	14.4	65.4	79.9
3	40.5	91.9	132.4
4	73.3	133.0	206.3





13
12
11
10
9
50
100
150
200
250
log(N_C IV cm^-2)
Circular Velocity (Km s^-1)
1
2
3
4
5
6