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Chemical Evolution of the High Redshift Galaxies

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Abstract. We have tried to determine the rate of chemical evolution of high redshift galaxies from the observed redshift distribution of the heavy element absorption systems in the spectra of QSOs, taking into account the evolution in the intensity of the metagalactic UV ionizing radiation background, the radius and/or the co-moving number density of, and the fraction of mass in the form of gas in, the absorbers. The data for both the Lyman limit systems and the C IV systems have been fitted simultaneously. It seems that the abundance of carbon has possibly increased by about a factor of 5 to 20 from the cosmic time corresponding to the redshift $\simeq$ 4 to 2. The data also suggest that either the radius or the co-moving number density of the galaxies increased with redshift up to z = 2.0 and decreased slowly thereafter. The total mass of the halo gas was higher in the past, almost equal to the entire mass of the galaxy at z = 4. The hydrogen column density distribution for Lyman limit systems predicted by the model is in agreement with the observed distribution.

Key words: High redshift galaxies—chemical evolution—Lyman limit systems—C IV absorption systems—diffuse UV radiation background

1. Introduction

Quasar absorption lines provide an important means to probe the universe upto redshift around 4.0. Galaxies at such high redshifts are very difficult to observe in their own light and the only way to get information about them is by studying the absorption lines they produce in the spectra of the distant quasars. Important information can be obtained about the physical conditions existing in these galaxies by studying the ionization state of individual absorption systems. The nature of the ionizing radiation field at high redshift has been obtained through such studies (Steidel & Sargent 1989). Their result seems to rule out early type stars in young or nascent galaxies as being dominant contributors to the metagalactic UV flux up to $z\sim$ 4.0. The ionizing flux has been shown to have a shape similar to that of AGNs. The strength of the ionizing radiation field has been estimated from a study of Lyman alpha absorption lines (Bajtlik *et al.* 1988).

Another important contribution of the study of heavy element systems in QSOs has been towards an understanding of the number density and size evolution of the

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galaxies (Khare-Joshi & Perry 1982; Sargent *et al.* 1988; Steidel 1990a and references therein). Recently, Steidel *et al.* (1088) suggested that the number distribution with respect to redshift of the heavy element absorption systems at high redshift is an indication of the chemical evolution of galaxies, with heavy element abundance increasing linearly with time from t= 1.5 Gy to t = 4Gy, and remaining constant thereafter, the expansion of the universe dominating the behaviour of the number density distribution at low redshifts. However, the effect of the evolution of the diffuse UV background intensity as well as the size and/or co-moving number density of the absorbers has been neglected in the above work. More recently, Bergeron & Ikeuchi (1990); Miralda-Escudé & Ostriker (1990); and Peng & Weisheit (1991), have argued at length about the possible evolution of the ionizing metagalactic UV background radiation and its effect on the ionization state of the absorbers. This will naturally affect the evolution of both Lyman limit systems and the heavy element systems in a differential manner.

In this paper we have tried to construct a model for studying the chemical evolution of the galaxies including the effects of evolution of the abundance of the heavy elements and their ionization fractions in the absorbers, and the possible evolution of the radius and/or the co-moving number density of and the fraction of mass in the form of gas in these absorbers. A comparison is also made with the evolution of neutral hydrogen gas content of the absorbers through the observed redshift distribution of the Lyman limit systems.

2. Observational information

Heavy element absorption systems, which are likely to be formed in galactic halos, fall in two categories: the low ionization or the Lyman Limit Systems (LLS) and the high ionization systems which are characterized by the presence of lines of highly ionized species like the C IV and Si IV, unaccompanied by the lines of atoms in low stages of ionization like Mg II, C II etc. The Lyman limit systems are characterized by a large column density of neutral hydrogen $\sim 10^{17}$–10^{19} cm^{-2}, causing a discontinuity in the QSO continuum shortward of 912 Å in the rest frame of the absorbing cloud. In many cases, though not in all, these systems contain lines due to heavy elements and a preliminary analysis shows these systems to have a heavy element depletion of $\sim 10^{-1}$ to 10^{-3} at a redshift of three compared to the solar values (Steidel 1990b). It is believed that these systems are produced by diffuse clouds in the halos of the intervening galaxies. The number of such systems N(z), per unit redshift interval per line of sight, increases with redshift z as (Sargent *et al.* 1989)

$$N_{\mathrm{LLS}}(z) \propto (1+z)^{0.68 \pm 0.54} \quad \text{for} \quad 0.67 < z < 3.58 \tag{1}$$

A large sample for the heavy element systems characterized by Mg II lines has been compiled by Steidel & Sargent (1992). This sample covers the redshift range of 0.2 to 2.2. The number density for this sample was found to vary as

$$N_{\mathrm{Mg\,II}}(z) \propto (1+z)^{0.78 \pm 0.42} \tag{2}$$

Both Lyman limit systems and the Mg II systems show an increasing $N(z)$ with z. Compared to these, the C IV systems show a very different behaviour. Before the survey of Sargent *et al.* (1988) was available, the existing data gave

$$N_{\mathrm{C\,IV}}(z) \propto (1+z)^{1.80 \pm 2.00} \tag{3}$$

for $z = 1.4$ — 2.0 (Bergeron 1988). The new survey, however, gives

$$N_{\mathrm{C\,IV}}(z) \propto (1+z)^{-1.20 \pm 0.56}, \quad \text{for} \quad 1.3 \leqslant z \leqslant 4.0 \tag{4}$$

The data of Khare *et al.* (1989) suggest an increase in $N_{\mathrm{CIV}}(z)$ up to $z \sim 2.4$ and a decrease thereafter. A similar trend of an increase in $N_{\mathrm{CIV}}(z)$ up to $z \sim 2$ is also apparent in the data of Sargent *et al.* (1988) (see their figure 6).

Therefore, given the observational uncertainties and the dispersion in the data for a power law fit to the number per unit redshift interval per line of sight versus redshift, the observational results as noted above may be expressed in the form of a single power law

$$N(z) \propto (1+z)^{\gamma},$$

with possibly a unique value of $\gamma \simeq 0.7$ over the low redshifts, say, $z < 2$, for the LLS and the high ionization systems alike. It is also noted that there is a marked deviation in the value of the above exponent for the C IV absorbing systems at high redshifts.

The theoretical number distribution of the absorbing systems per unit redshift interval in a Friedmannian universe is given by (Peterson 1978)

$$N(z) = \frac{c}{H_0} \phi \sigma_e (1+z)(1+2q_0 z)^{-1/2}, \tag{5}$$

where ϕ is the co-moving number density of absorbers per unit volume, σ_e is their effective cross-section for observation (with reference to some particular chemical species), H_0 is the present day Hubble constant and q_0 is the present day cosmological deceleration parameter. In the absence of evolution, the quantities ϕ and σ_e remain constant. However in general, one can assume ϕ and σ_e to be functions of redshift. Thus, we can write

$$N(z) = \frac{c}{H_0} \phi(z) \sigma_e(z)(1+z)(1+2q_0 z)^{-1/2}, \tag{6}$$

where

$$\sigma_e(z) = \pi r_e^2(z), \tag{7}$$

$r_e(z)$ being the effective radius of the absorbers (with reference to a particular chemical species, of course) defined to be the radial distance from the centre of the galaxy to the intercepting line of sight producing a total column density of the species equal to the minimum column density used to define the sample of the absorption lines, at the redshift z.

If, for simplicity, we now assume that $q_0 = 0.5$ and ϕ and r_e are independent of z, Equations (6) and (7) reduce to $N(z) \propto (1+z)^{\gamma}$ with $\gamma = 0.5$. Thus, in the first appearance, the observed redshift dependences of $N_{\mathrm{LLS}}(z)$ and possibly also that of $N_{\mathrm{CIV}}(z)$ at low redshift seem to be consistent with no evolution of ϕ and σ_e for the absorbers, but then the behaviour of $N_{\mathrm{C\,IV}}(z)$ for $z \geqslant 2.0$ is a manifestation of the chemical evolution of the galaxies through the evolution of $r_e(z)$.

However in view of the recent detailed investigations (Bergeron & Ikeuchi 1990; Miralda-Escudé & Ostriker 1990; and Peng & Weisheit 1991), a possible evolution of the intensity of the ionizing diffuse UV background radiation of metagalactic origin cannot be ruled out. In fact, from figure 5 and 6 of Miralda-Escudé & Ostriker (1990), it is apparent that the intensity of the UV radiation at the Lyman limit varies with redshift approximately in proportion with $(1 + z)^2$, up to a redshift of of 2.0, beyond which different models seem to give very different behaviour. Some models predict a drastic drop in the ionizing field, several others predict a slower increase while some predict more or less uniform ionizing radiation field. In what follows, we assume that the ionizing radiation field for hydrogen increases as $(1 + z)^2$ with redshift up to a redshift of 2 and as $(z-1)^{0.37}$ beyond that (see figure 7 of Miralda-Escudé & Ostriker 1990). Consequences of any deviation from this redshift dependence are discussed in the last section. The increase in the ionizing field for hydrogen decreases the effective radius for detection of a Lyman limit system for fixed physical radius of a galaxy, as shown in the next section. The observed value of γ for LLS thus suggests an increase in the physical radius and/or the co-moving number density of galaxies so as to compensate the effect of increasing ionization field. The fraction of mass of a galaxy in the form of gas is also expected to be higher in the past. In what follows, we assume the co-moving number density of galaxies to be constant. The physical radius of the galaxies as well as f_g , the ratio of the mass of gas in the galaxy compared to the luminous mass at z = 0, is allowed to vary with redshift so as to have a constant effective radius for LLS. We have assumed $f_g(z) = f_g(0)\,(1+z)^{\alpha}$, α being > 0. The value of α was varied and its minimum value necessary to get constant σ_e for varying $R(z)$ was adapted for calculations.

The $N(z)$ v/s z relation for the C IV systems will be affected, in addition to the redshift dependence of ionizing radiation field for C III and variation in gas fraction, physical radius and/or co-moving number density of galaxies, by the variation of carbon abundance with respect to redshift due to the chemical evolution of galaxies. In the following section we model the LLS and the C IV systems and obtain the rate of chemical evolution of the galaxies by trying to consistently explain the observed $N(z)$ v/s z distributions for these systems.

3. The model

First we consider the Lyman limit systems. For the observation of the Lyman limit system at a particular absorption redshift, the required minimum column density of H I gas through the intervening galaxy is approximately $N_{HI}^{min} \simeq 2.4 \times 10^{17} cm^{-2}$ (Tytler 1987). We assume a typical intervening galaxy to be of gas-rich type with a spherically symmetric gaseous halo extended upto a typical galactic radius of R = 50 kpc at z = 0, having its gas distribution quite similar to the total matter distribution indicated by the rotation curve and given, for example (Binney & Tremaine 1987) by

$$\rho(r) = \frac{\rho_0}{\left[1 + \left(\frac{r}{r_c}\right)^2\right]^n} \quad 0 \leqslant r \leqslant R. \tag{8}$$

Here ρ_0 is the central density, r_c the core radius, and R the total radius of the galaxy, n being ~ 1.0. For chosen values of R and r_c, the normalizing value of ρ_0 can be obtained from a knowledge of the total baryonic mass of the galaxy. Note that the smaller values of ρ_0 will correspond to larger values of R for a given *rc.* As the presence of a dark matter halo, if any, is irrelevant to our calculations, we choose the luminous mass of the galaxies, M_L , to be ~$2 \times 10^{11} M_\odot$ and further assume the mass of the gas in the spherical halo to be 10% of this luminous mass at z=0. We assume r_c = 6.0 kpc at z = 0 and R/r_c is taken to be independent of redshift. The deceleration parameter, q_0 , is taken to be 0.5.

The neutral hydrogen column density distribution for LLS at $z \sim 3.0$ has been observed to be a power law with power law index, β, to be = – 1.25 ± 0.03 (Tytler 1987; Lanzetta 1991), over the column density range $17.2 \quad \log N_{\rm H\,I} \leqslant 21.8$. Using photoionization calculations for optically thick clouds, Lanzetta (1991) has shown that this corresponds approximately to a power law distribution of total hydrogen column density, $N_{\rm H}$, with power law index, $\beta_T \sim -2.0$, over the column density range $19.5 \leqslant \log N_H \leqslant 21.7$. With our assumed radial dependence of the total gas density we can derive the total hydrogen column density distribution. We can compare this with the total hydrogen column density distribution inferred by Lanzetta. However, not too much emphasis can be put on this comparison as Lanzetta has assumed a constant ionization parameter for all the LLSs. This is not true in our model, because even though the flux of ionizing radiation, believed to be metagalactic, will be uniform, the density is changing with radius. Also we have assumed continuous distribution of matter in the halo of galaxies. This may not be correct in view of the multiple component nature of the heavy element lines. The comparison may therefore, only be used as a guideline to check, roughly, the consistency of the density distribution assumed in our model with the observed neutral hydrogen column density distribution.

The number of absorption systems, $f(N_{\rm H})$, with a column density of total hydrogen, $N_{\rm H}$, at a fixed redshift is given by

$$f(N_{\rm H})\,{\rm d}N_{\rm H} \propto 2\pi P \left|\frac{{\rm d}P}{{\rm d}N_{\rm H}}\right| {\rm d}N_{\rm H}, \tag{9}$$

where P, the impact parameter for a given $N_{\rm H}$ is given by

$$N_{\rm H} = 2\rho_0(z) \int_0^{\sqrt{R^2(z)-P^2}} \frac{{\rm d}x}{\left(1+\left(\frac{P^2+x^2}{r_c^2(z)}\right)\right)^n}. \tag{10}$$

We have obtained the column density distributions for n= 0.5, 1.0 and 1.5. These distributions were then fitted with a power law. In doing so we only considered the region of the galaxy within a radius of 45 kpc as the column density for P > 45 kpc is likely to be too low to be detected as LLS. Also the function $f(N_{\rm H})$ actually decreases for larger values of P. The results of the fit are given in the first three columns of Table 1. It is to be noted that these distributions have been calculated taking values of R and r_c to be those at z= 0. These are likely to be different at z= 3.0. This is discussed later in this section. It is clear from Table 1 that the column density distribution is adequately described by a power law, the power law index is however somewhat higher than the expected value of – 2.0. The power law index approaches the expected value if we restrict ourselves to regions of the galaxy within a radius of 40 kpc as is seen from the last two columns in Table 1. These results do not offer any clear choice for n. We have chosen, in what follows, n = 1 as it is the value used

Table 1. Results of power law fit to the total hydrogen column density distribution.

n	$\beta_T(P \leqslant 45\,\text{kpc})$	Percentage of residuals explained	$\beta_T(P \leqslant 40\,\text{kpc})$	Percentage of residuals explained
0.5	− 1.68	84	− 1.76	99
1.0	− 1.75	95	− 2.05	98
1.5	− 1.61	99	− 2.29	91

often in the literature (Binney & Tremaine 1987) and, in fact, it is marginally better than the other values in Table 1. For n= 1, $\rho_0(z)$ is given by

$$M_L f_g(z) = 4\pi\rho_0(z) r_c^3(z)\left[\frac{R(z)}{r_c(z)} - \tan^{-1}\frac{R(z)}{r_c(z)}\right] \tag{11}$$

The effective radius of a galaxy, P_e, defined to be the radial distance from the center of the galaxy upto the farthest intercepting line of sight producing a total column density of H I equal to $N_{\rm HI}^{\rm min}$ in the galaxy, is given by

$$N_{\rm H\,I}^{\rm min} = 2\rho_0(z)K(z)I(R(z), P_e), \tag{12}$$

where $K(z)$ is the fraction of H I column density compared to the total column density of hydrogen, for a cloud at redshift z, having a neutral hydrogen column density of $N_{\rm HI}^{\rm min}$.

$$K(z) = \frac{N_{\rm H\,I}}{N_{\rm H}}(z). \tag{13}$$

This fraction will depend on the redshift because of its dependence on the radiation field. This dependence can be estimated by constructing photoionization models for clouds for different values of ionization parameter and demanding the neutral hydrogen column density to be $N_{\rm HI}^{\rm min}$. We constructed photoionization models using the code 'cloudy C76.03', kindly given to us by Prof. G. Ferland, taking clouds with radiation incident from one side. The results for the fraction of neutral hydrogen as a function of ionization parameter are given in Fig. 1 for the number density of hydrogen =0.1 cm^{-3} and metal abundance =0.1 and 0.01 of its cosmic value. The results are insensitive to the value of the hydrogen number density in the range 0.01–0.1 cm^{-3}, expected in the absorbers. It is clear that $K(z)$ is inversely proportional to the ionization parameter. This is also seen from the photoionization calculations of Lanzetta (1991). The z dependence of the ionization parameter, which is the ratio of the photon number density to the particle density in the absorbing column can be expressed in terms of the assumed z dependence of the radiation field and that of ρ_0(z) (which in turn can be expressed in terms of $R(z)$) using Equations (8) and (11). Finally I($R(z)$, P_e) in equation (12) is given by the definite integral

$$I(R(z), P_e) = \int_0^{\sqrt{R^2(z) - P_e^2}} \frac{\mathrm{d}x}{\left(1 + \frac{P_e^2 + x^2}{r_c^2(z)}\right)^n}, \tag{14}$$

which foe n=1 is

$$I(R(z), P_e) = \frac{r_c^2(z)}{(r_c^2(z) + P_e^2)^{1/2}} \tan^{-1}\sqrt{\frac{R^2(z) - P_e^2}{r_c^2(z) + P_e^2}} \tag{15}$$

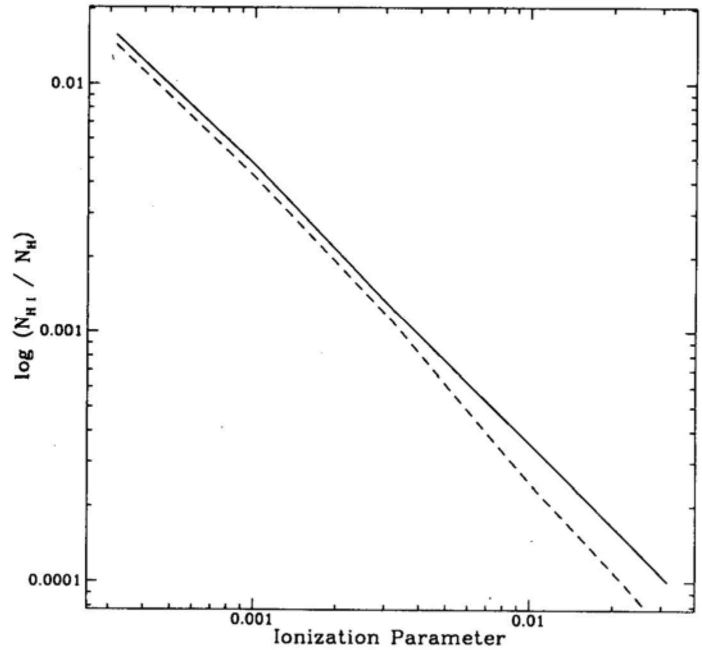

Figure 1. Plot showing the fraction of neutral hydrogen as a function of ionization parameter for a cloud radiated from one side and having a column density of neutral hydrogen $\simeq 2.0 \times 10^{17} \mathrm{cm}^{-2}$, necessary for its observation as an LLS. The solid and dashed curves are for the metal abundance =0.1 and 0.01 of its cosmic value respectively. The number density in the clouds is taken to be 0.1 cm^{-3}.

Equation (12) for assumed value of $R(0)$ and $rc(0)$ gives P_e = 48.5 kpc for $K(0) = 5 \times 10^{-3}$. The equation can then be solved for higher values of z, keeping P_e fixed (as indicated by the value of γLLS) and taking the z dependence of K as discussed above to obtain $R(z)$. The value of a, the power law index for redshift dependence of gas mass, was varied, and its minimum value to give a solution of equation (12) upto z= 4.0 was found to be 1.5. This value is adopted in the rest of this paper. This gives the mass of the gas at z = 4.0 to be $\sim 1.1 M_L$ compared to 0.1 M_L at z = 0 indicating that the entire mass of the galaxy was in the form of halo gas at z= 4.0. The values of the physical radius $R(z)$ in kpc and the central gas density $\rho_0(z)$ in particles cm^{-3} as the function of redshift are plotted in Fig. 2. The variation of these quantities with z reflects the variation in the radiation field and gas content with z.

We have again calculated the column density distribution of total hydrogen, $f(N_H)$ at z= 3.0 taking the value of $R(3)$ = 52.5 kpc from Fig. 2, and P_e = 48.5 kpc. The power law fit is shown in Fig. 3. The power law index, β_T, is found to be — 2.043 (with 98% of the residuals explained), in close agreement with the value inferred from observations. This exact agreement, however, may be somewhat fortuitous in view of the fact that the assumption of constant ionization parameter made in deriving the total hydrogen column density distribution from observed neutral hydrogen column density distribution is not valid in our model and that the possible clumpiness of matter in the halo has not been incorporated in our model.

Now we move on to the C IV absorption systems. The z dependence of the effective radius of the galaxy for detection of C IV absorption features, $r_e(z)$, is obtained

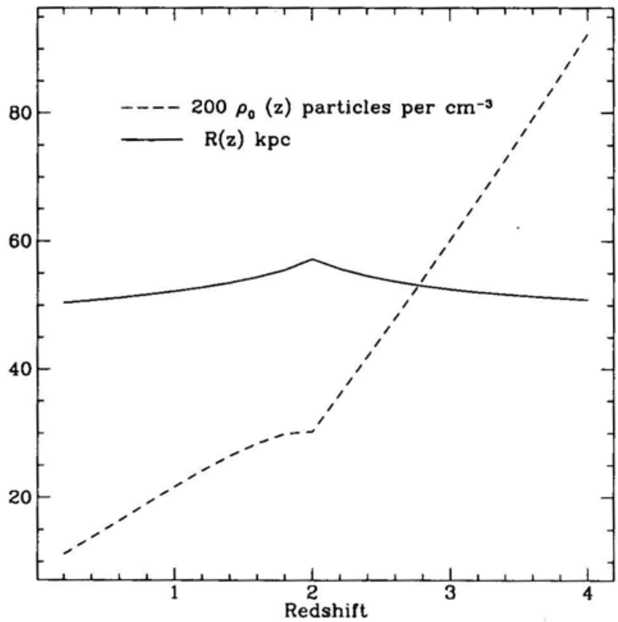

Figure 2. Plot showing the variation of the radius $R(z)$ (solid line) in kpc and central density $\rho_0(z)$ (dashed line) in particles cm^{-3} of a galaxy as a function of redshift. The particle density has been multiplied by a factor of 200 for convenience in presentation.

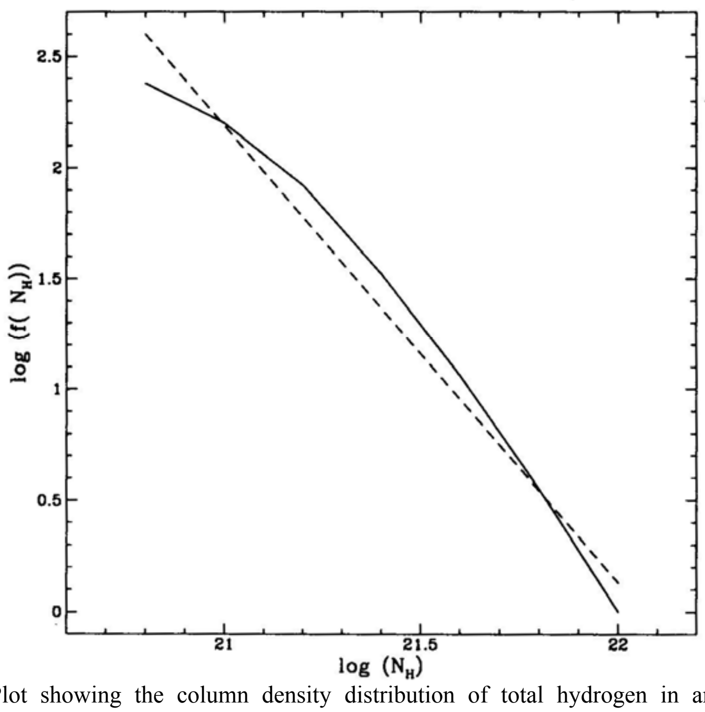

Figure 3. Plot showing the column density distribution of total hydrogen in arbitrary units for Lyman limit systems. The best fit power law is shown by dashed lines.

from the observed z dependence of $N_{\rm CIV}(z)$ at high redshifts ($z > 2$). From equations (4), (6) and (7), we have, for $z > 2$,

$$r_e^2(z)(1+z)(1+2q_0z)^{-1/2} \propto (1+z)^{\gamma}, \tag{16}$$

giving

$$r_e(z) \propto (1+z)^{\frac{\gamma-1}{2}}(1+2q_0z)^{1/4}, \quad \text{with} \quad \gamma = -1.2 \pm 0.56. \tag{17}$$

Equation (17), along with the redshift dependence of the radiation field responsible for ionization of C III (see figure 7 of Miralda-Escudé & Ostriker 1990) and the variation of the physical radius and the gas content of the galaxies with redshift, as obtained from the fit to the $N_{\rm LLS}$ (z), can be used to derive the rate of chemical evolution of galaxies, as described below.

The radial dependence of the heavy element abundance in the galaxies is assumed to have a form

$$X(r,z) = A(z)\exp\left(\frac{-br}{1+z}\right), \tag{18}$$

where $b \simeq 0.092$ kpc^{-1} is a constant, related to the radial gradient of metallicity in the galaxies at the present epoch (Pagel & Edmunds 1981), *A(z)* being the carbon abundance at the center of the galaxy with respect to hydrogen. We have included a factor $(1 + z)$ in the denominator of the exponent for radial dependence, to symbolically account for the gradual evolution of the radial variation of metallicity from a uniform distribution in the beginning, that is for $z \to \infty$.

The sample of C IV lines considered by Sargent *et al.* (1988) is limited by a lower cut-off on the rest equivalent width of 0.15 Å, for each of the lines of the doublet. This, for velocity dispersion of $\simeq$ 10-15 kms s^{-1} in the absorbing clouds, corresponds to a column density of $N^{\rm min}_{\rm CIV} \sim 6.0 \times 10^{13}$ cm^{-2} in a galaxy, and is given by

$$N^{\rm min}_{\rm C\,IV} = 2\rho_0(z)A(z)K(z)I(R(z), r_e(z)), \tag{19}$$

where the ionization fraction

$$K(z) = \frac{N_{\rm C\,IV}(z)}{N_{\rm C}(z)}, \tag{20}$$

and the integral

$$I(R(z), r_e(z)) = \int_{r_e^{(z)}}^{R(z)} \frac{r\exp\left(\frac{-br}{1+z}\right)\mathrm{d}r}{(r^2 - r_e^2(z))^{1/2}\left(1 + \frac{r^2}{r_c^2(z)}\right)}. \tag{21}$$

To estimate $K(z)$ we again constructed photoionization models for clouds with the column density of C IV $\simeq 6.0 \times 10^{13}$ cm^{-2}. The results are plotted in Fig.4. The dependence of the fraction of CIV on ionization parameter is not uniform, the fraction being independent of the ionization parameter for its values around 10^{-2}. We therefore assume the fraction of C IV to be proportional to a power δ of the ionization parameter and consider three values of δ = 0.0,0.5,1.0, to take into account the possible dependence of the fraction of C IV on the ionization parameter. The z dependence of the ionization parameter can, as before, be expressed in terms of the

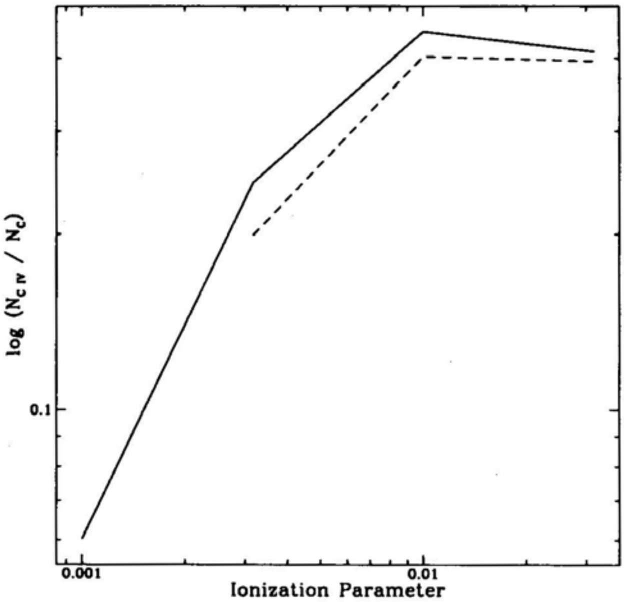

Figure 4. Plot showing the fraction of C IV as a function of the ionization parameter for a cloud radiated from one side and having a column density of CIV = $6.0 \times 10^{13} cm^{-2}$, necessary for its inclusion in the C IV sample. The solid and dashed curves are for the metal abundance =0.1 and 0.01 of its cosmic value respectively. The number density in the clouds is taken to be $0.1 cm^{-3}$.

z dependence of the radiation field and that of the central density in the halo and thereby the mean density in the absorbing column.

The abundance of carbon for $z \geqslant 2$ relative to its abundance at z=2 can be obtained from equation (19) and is given by

$$\frac{X_c(z)}{X_c(2)} = \frac{A(z)}{A(2)} = \frac{\rho_0(2) I(R(2), r_e(2)) K(2)}{\rho_0(z) I(R(z), r_e(z)) K(z)}. \quad (22)$$

$r_e(2)$ can be calculated from equation (19), for known values of $A(z)$ at z = 2.0, alternatively, it can be obtained from the knowledge of N_{CIV} (2) and $N_{LLS}(2)$. Considering the uncertainity in all these quantities we have assumed $r_e(2)$ = 50kpc. The effect of changing $r_e(2)$ is also discussed in the next section.

4. Results and discussion

The results of our calculations are plotted in Figs. 5–7. These figures show the variation of carbon abundance, relative to its value at z = 2.0, for various values of the parameters used in the model. Fig. 5 shows the effect of variation in the assumed value of the effective radius, r_e (2), at z = 2.0 of the galaxy for its detection as a C IV system; Fig. 6 shows the effect of variation in the dependence of the fraction of C IV on the ionization parameter and Fig. 7 shows the effect of variation in the value of γ_{CIV}. The abundance variation was found to be rather insensitive to the chosen value of q_0 , the deceleration parameter, b, the metallicity gradient and r_c , the core radius.

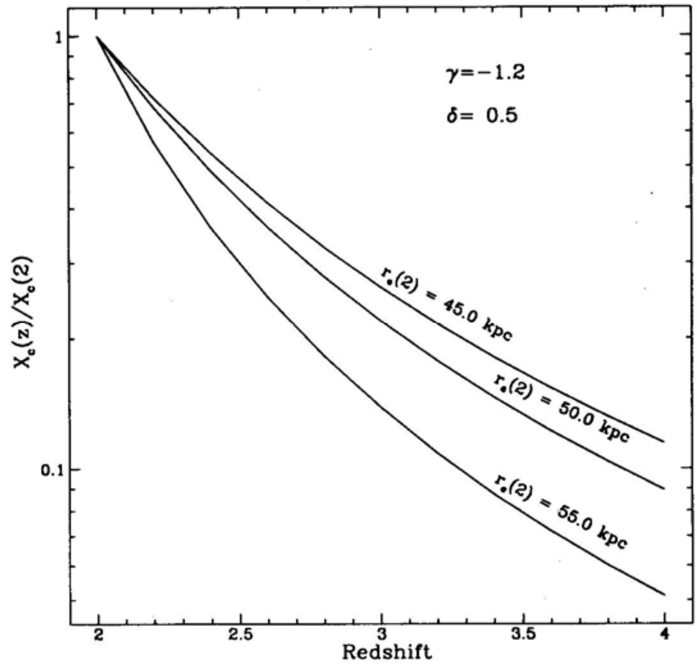

Figure 5. Plot showing the abundance of carbon relative to its value at z = 2.0 as a function of redshift for various values of the effective radius r_e of the galaxy for its detection as a C IV system at z = 2.0.

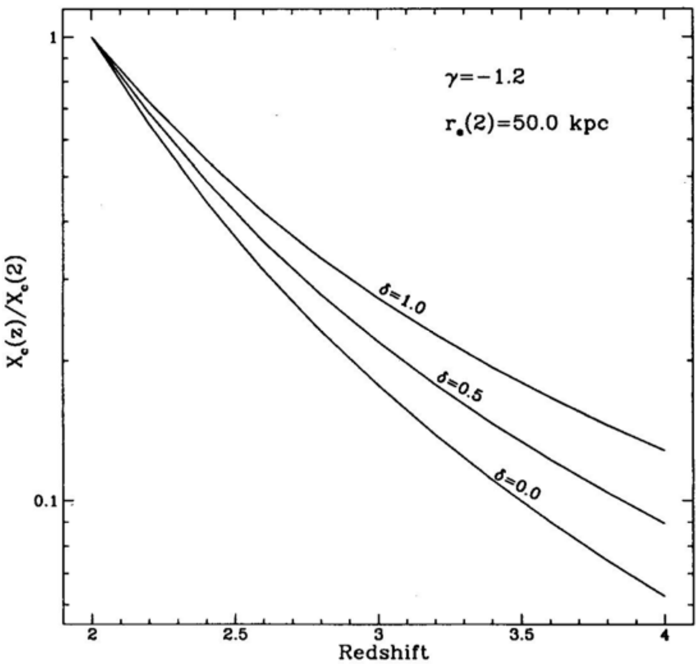

Figure 6. Plot showing the variation of carbon abundance relative to its value at z = 2.0 as a function of redshift for different possible dependence of the fraction of C IV on the ionization parameter.

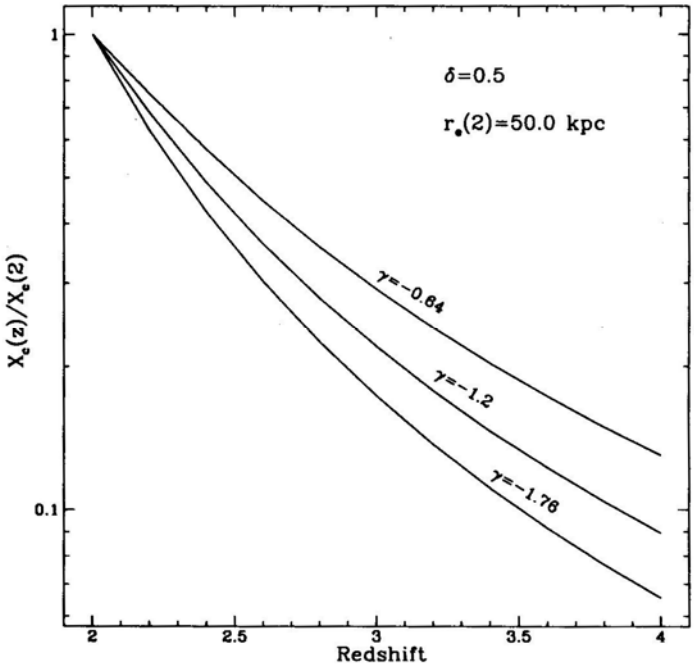

Figure 7. Plot showing the variation of carbon abundance relative to its value at z = 2.0 as a function of redshift for various values of $\gamma_{\text{C IV}}$.

The abundance variation is more sensitive to the value of γ_{CIV} and $r_e(2)$ and most sensitive to the ionization parameter dependence of the fraction of C IV, a variation in these three quantities over the ranges considered can change the abundance at $z = 4.0$ by a factor of 2 to 3.

The rate of chemical evolution in the galactic halo obtained in this model is rather high, compared to that estimated by Steidel *et al* (1988), the abundance of carbon changing by a factor of 5–20 from z = 4.0 to 2.0. For $q_0 = 0.5$ and $H_0 = 50 \text{kms}^{-1}$ Mpc^{-1}, this corresponds to the time period from 1.2 Gy. to 2.5 Gy.

The rate of chemical evolution obtained here crucially depends on the assumptions regarding the z dependence of the UV field. For example if we assume the radiation field to depend on the redshift as $(z–1)^{1.0}$ instead of$(z—1)^{0.37}$ for $z > 2$ as assumed above the chemical abundance at $z = 4$ is lower by a factor of 3. A comparison with observed abundances, at high redshifts may provide important constraints on the radiation field at these redshifts.

The total hydrogen column density distribution at $z \simeq 3.0$ is found to be consistent with that inferred from the observed neutral hydrogen column density distribution.

Our model assumes a continuous distribution of matter in the halo. The presence of clumpiness in the matter distribution will affect the column density distribution but is not likely to change the conclusions regarding the chemical evolution. This calculation only needs the effective radius of the galaxy for detection as a CIV system and as an LLS. Thus we calculate the maximum impact parameter for the line of sight having a column density of around 10^{13} – 10^{14} cm^{-2} in C IV and the line of sight having a column density of $2.0 \times 10^{17} \text{cm}^{-2}$ in H I. With this column density the C IV lines will be close to the linear portion of the curve of growth and the presence of the column density in multiple clouds instead of a single cloud will not alter our results. For the LLS the line of sight with this column density can only have one optically thick cloud (Srianand & Khare 1993) which is equivalent to our assumption of smooth matter distribution.

The other result of our model is regarding the evolution of the physical radius and/or co-moving number density of the galaxies and the mass of gas in the halo of the galaxy with redshift. The radius of the absorbing galaxies is found to increase with redshift upto a redshift of 2.0 and decreases thereafter. The mass of gas in the galactic halo is found to be higher in the past, being equal to the entire mass of the galaxy at the redshift of 4. This conclusion is a direct consequence of the variation of ionizing radiation field with redshift and thus depends on the viability of the models proposed by Miralda-Escudé & Ostriker (1990). An independent estimate of the ionizing radiation field from Ly α cloud studies or profile fitting of high resolution observations of heavy element systems followed by ionization calculations will be useful in examining our conclusions further.

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