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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. 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. 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. Recently reported absence of heavy element lines associated with most of the Ly-α lines with HI column density between $10^{13.5}$ cm^{-2} and 10^{14} cm^{-2} by Lu *et al* [13], 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. However, the mean value of 7×10^{-3} for the column density ratio of C IV and HI, determined by Cowie and Songaila (1998) for low Ly-α optical depths, implies an abundance of [C/H]$= -2.5$ in mini-halos as well as most of the region in galactic halos. The redshift and column density distribution of C IV has been shown to be in reasonable agreement with the observations.

Keywords. Quasar absorption lines; chemical abundance.

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1. Introduction

Recently there has been considerable interest in trying to determine and understand the chemical abundance and the process of enrichment in the early Universe. Observationally, QSO absorption lines have proved to be the best tools to determine the abundances at high redshifts. The ubiquitous Ly-α absorbers, which are responsible for the formation of the Ly-α forest in the QSO spectra, have earlier been thought of as made up of pristine, intergalactic material [1]. Meyer and York [2] showed, with the help of high signal to noise ratio of 100, that the Ly-α lines do show associated lines of heavy elements. Lu *et al* [3] reached the same conclusion by stacking a large number of Ly-α lines, to effectively increase the signal to noise ratio. Recently (1995 onwards), high resolution (FWHM=6 km/s), high S/N observations have been possible with the help of the KECK telescope and have resulted in direct detection of heavy element lines associated with Ly-α lines [4,5]. It was found that 50 to 75 % of Ly-α lines with column density $\geq 10^{14.5}$ cm^{-2} do show associated metal lines, the metallicity being around -2.5. On the theoretical front, Gnedin and Ostriker [6] and Gnedin [7], with the help of high resolution simulations, showed that the first generation of stars could have formed at redshifts of about 15 (due to molecular hydrogen cooling) as a result of which the Universe could have been reionized, temporarily halting the star formation, which would resume at a lower redshift. The Pop III stars are however too few and could only enrich the Universe to a metallicity of 10^{-5} solar. Individual objects e.g. protogalaxies or QSOs, could have reached solar or higher metallicities at $z \simeq 6$ through Pop II stars. Metals from protogalaxies could have spread in the neighbouring IGM through SN explosions and more efficiently through galaxy mergers. Pop II stars could have enriched the Universe to a mean metallicity ($Z/Z_\odot$) of 1/200 at a redshift of 4. Large variation in the IGM metallicity is predicted with high density regions having ($Z/Z_\odot$) of 1/30 and the low density regions having essentially no metals. According to these simulations, the Ly-α lines with column density $\geq 10^{14}$ cm^{-2} form in filaments surrounding and connecting collapsed objects while smaller column density clouds occupy voids, so that Ly-α lines with lower column density are not expected to show associated heavy element lines. Attempts to detect such lines have recently been made by two groups which obtained conflicting results. Lu *et al* [8] used the method of stacking of high resolution data for weak lines, thereby obtaining an effective S/N of 1860. They failed to detect C IV lines and obtained an upper limit of -3.5 for the abundance of C in such clouds. Similar conclusion was drawn by Dave *et al* [9] who tried and failed to detect O VI lines associated with weak Ly-α lines. Cowie and Songaila (1998), on the other hand, used a new method based on optical depths to determine the C IV/HI ratio and obtained a mean value of N_{CIV}/N_{HI} of 7×10^{-3} for weak Ly-α lines. We have tried to understand these observations in the two component model of Ly-α absorbers.

This model has recently been considered in somewhat detail by Chiba and Nath [10]. The model, based on CDM models of structure formation, assumes that the Ly-α absorption lines are produced by virialized gas clouds. The gas confined to the smaller halos, called the mini-halos (with circular velocities between 15 and 55 km s^{-1}), do not undergo enrichment 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 HI column density Ly-α lines which may not be accompanied by lines of heavy elements. Gas in bigger halos called the galactic halos ($55 \leq V_c \leq 250$ km s^{-1}), on the other hand, would cool and form clouds and stars and would contribute more to the higher HI column density Ly-α lines which will be accompanied by lines of heavy elements. The limits on V_c pertaining to the two types of halos are based on various physical reasons. The lower limit on V_c ($\sim$ 15 km s^{-1}) is roughly the value below which the perturbations in baryonic mass are suppressed. The upper limit on V_c ($\sim$ 55 km s^{-1}) for mini-halos is roughly the value below which photoionization suppresses cooling and formation of clouds.

2. Calculations

Here we describe the calculations very briefly, details can be seen in [11]. We assume the Press–Schecter type of mass distribution of the virialised halos and assume the baryonic matter density to be 0.05 times the total matter density. We assume the galactic halos to have 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. The clouds are assumed to be in pressure equilibrium with the hot intercloud medium. We have used photoionization code 'CLOUDY' to calculate the fraction of ions. With all these assumptions, we can calculate the column density of any ion along a line of sight through a given halo at a given impact parameter. The number of clouds per unit volume at the centre of the galaxy is the only unknown factor. Its value is obtained by making the predicted redshift distribution for Ly-α lines match with the observed values.

3. Comparison with observations

3.1 *Column density distribution of neutral hydrogen*

The column density distribution function, $f(N_{\rm HI})$, is defined as the number of absorption lines per unit column density per unit redshift path which is defined by $X(z) = 2/3[(1+z)^{3/2} - 1]$ for $q_0 = 0.5$.

A comparison of the observations with the predictions of our model is presented in figure 1a.

3.2 *Redshift distribution of C IV lines*

We 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]$\simeq -2.5$,

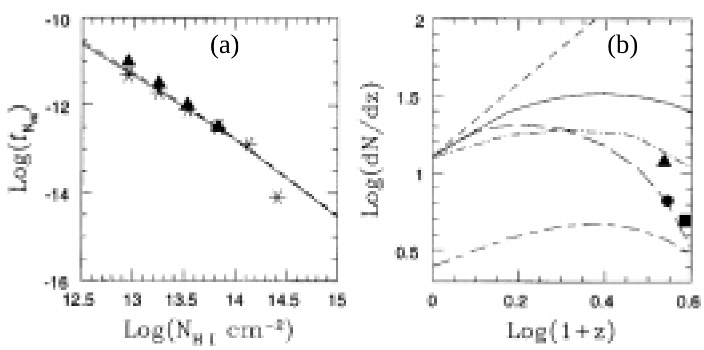

Figure 1. (**a**) Column density distribution of Ly-α lines. Solid and dashed lines are at $z = 2.31$ and $z = 3.35$ respectively. Stars and solid triangles are observed values at $z = 2.31$ $z = 3.35$ respectively. (**b**) Redshift distribution for C IV lines with $N_{\rm CIV} > 10^{13}$ cm^{-2}. Small-dashed, 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 [14].

assumed to be produced by the Pop III stars. In figure 1b 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}. The observed values of dN/dz, have been obtained by a maximum likelihood analysis of the data collected from the literature. One important result that emerges from this is that the contribution of mini-halos, assuming the abundance in these halos to be [C/H]$= -2.5$, to the C IV lines with column density $> 10^{12}$ cm^{-2} is only about 10% of the total number of such C IV lines at $z = 3$.

3.3 *Column density distribution of C IV lines*

The observed column density distribution function of C IV clouds at $2.52 < z < 3.78$ has been plotted along with the model results for $z = 3$ for C IV, for $\delta = 3$ and 4 in figure 2a. 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 [12] and it is possible that the number of small column density lines may actually be considerably larger.

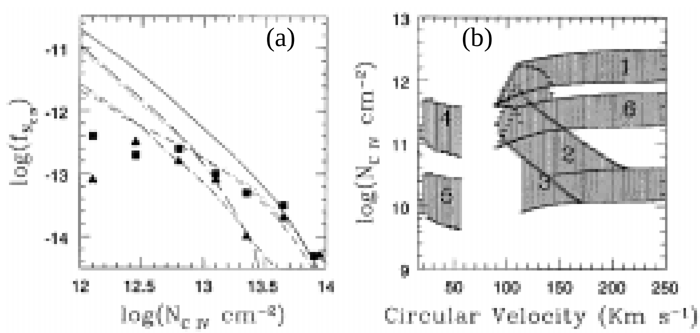

Figure 2. (**a**) Column density distribution for C IV lines at $z = 3.0$. Solid and long-dashed lines are for $\delta = 3$ and 4 respectively. Small-dashed and dash-dotted lines are for the assumptions of upper limit on radial distance for galactic chemical enrichment and abundance gradient respectively, 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 [14] for $z < 3$ and $z \geq 3$ respectively. (**b**) 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 $\delta = 3$ at redshift of 3. Band 6 is for galactic halos assuming a uniform abundance of -2.5, at $z = 3$.

3.4 *Metal lines associated with low HI column density lines*

As mentioned above, Lu *et al* [8] have failed to detect C IV lines associated with HI lines having column density between $10^{13.5}$ cm^{-2} and 10^{14} cm^{-2}, (referred to below as 'associated C IV lines' or ACLs), between redshifts 2.2 and 3.6, and obtained an upper limit of $10^{10.5}$ cm^{-2} on the average column density of these lines. We have calculated the numbers of such Ly-α lines per line of sight per unit redshift interval for z between 2 and 4. These are between 30 and 130. The number of ACLs per unit redshift interval, per line of sight, is same as the number of Ly-α lines. The range of column densities of the ACLs is plotted in figure 2b as a function of the circular velocity for the redshift of 3.

All the ACLs have a column density $\geq 10^{11}$ cm^{-2} and hence would have been observed by Lu *et al* [8]. We find that the abundance has to be less than -3.7 with respect to the solar value for the column densities of ACLs 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 2b (band 5). The column densities of the ACLs 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. We therefore, considered two possibilities (i) an abundance gradient $Z(r,z) = Z(0,z)\mathrm{e}^{-2r/V_c}$ for the heavy elements produced in situ in the galaxies and (ii) an upper limit on the radial distance up to which in situ heavy element enrichment has occurred in the galaxies, given by $r_{\max}\ (V_c, z) = 4\mathrm{V_c}/(1+\mathrm{z})$. The column densities of the ACLs for these two assumptions are also shown in figure 2b for $z = 3$. Most of these would be below the sensitivity of detection, consistent with observations of Lu *et al* [8].

We have shown in figure 1b and 2a the redshift and the column density distribution of C IV lines for these two possibilities for $\delta = 3.0$ at $z = 3$. We now discuss the implications of the results of Cowie and Songaila [13] for our results. For their mean value of 7×10^{-3} for $N_{\mathrm{C\ IV}}/N_{\mathrm{HI}}$, the range of column density of the ACLs is $2.2 \times 10^{11} - 7 \times 10^{11}$ cm^{-2}. The lines produced by mini-halos for the assumed carbon abundance of [C/H]$= -2.5$ (band 5 in figure 2b) are roughly consistent with this range. The C IV lines produced by the galactic halos for $\delta = 3$ (band 1 in figure 2b), have higher column densities, again indicating lower or absence of chemical enrichment in the outer parts of the galactic halos due to in situ star formation. We have plotted in figure 2b (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 $2.2 \times 10^{11} - 7 \times 10^{11}$ 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 [13]. The C IV column density distribution at $z = 3$, δ=3, for the assumption (ii) above, for this case is shown in figure 2a.

4. 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 predicted column density distribution of Ly-α clouds is found to be similar to the observed distribution. 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]≤ -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* [8]. 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 observed for heavy element line producing galaxies. 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}. The values obtained by Cowie and Songaila [13] for the column density ratio of C IV and HI, however, indicate an enrichment of mini-halos as well as galactic halos to [C/H] $= -2.5$ by an earlier generation of stars.

References

[1] 1 W L W Sargent, P J Young, A Boksenberg and D Tytler, *Astrophys. J. Suppl.* **42**, 41 (1980)
[2] D M Meyer D G York, *Astrophys. J.* 315, L5 (1987)
[3] L Lu, A M Wolfe and D A Turnshek, *Astrophys. J.* **367**, 19 (1991)
[4] D Tytler, X Fan, S Burles, L Cottrell, C Davis, D Kirkman and L Zuo, *QSO absorption lines*, edited by G Meylan (Springer, 1995) p. 289
[5] L L Cowie, A Songaila, T S Kim and E M Hu, *Astron. J.* **109**, 1522 (1995)
[6] N Y Gnedin and J P Ostriker, *Astrophys. J.* **486**, 581 (1997)
[7] N Y Gnedin, astro-ph/9709224 (1997)
[8] L Lu, W L W Sargent, T A Barlow and M Rauch, astro-ph/9802189 (1998)
[9] R Dave, U Hellsten, L Hernquist, N Katz and D H Weinberg, *Astrophys. J.* astro-ph/9803257 (1998)
[10] M Chiba and B B Nath, *Astrophys. J.* **483**, 638 (1997)
[11] S Das and P Khare, *Astrophys. J.* **510**, 597 (1999)
[12] A Songaila, *Astrophys. J. Lett.* **490**, L1 (1997)
[13] L L Cowie and A Songaila, *Nature* **394**, 44 (1998)
[14] A Songaila, astro-ph/9803010 (1998)