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# CHEMICAL ENRICHMENT AT HIGH REDSHIFTS: UNDERSTANDING THE NATURE OF DAMPED Lyα SYSTEMS IN HIERARCHICAL MODELS

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## ABSTRACT

We use cosmological hydrodynamical simulations including star formation and metal enrichment to study the evolution of the chemical properties of galaxy-like objects at high redshift in the range $0.25 < z < 2.35$ in a hierarchical clustering scenario. We find that as the galactic objects are assembled, their gaseous components exhibit neutral hydrogen column densities with abundances and scatter comparable to those observed in damped Lyα systems (DLAs). The unweighted mean of abundance ratios and least-square linear regressions through the simulated DLAs yield intrinsic metallicity evolution for [Zn/H] and [Fe/H] consistent with results obtained from similar analyses of available observations. Our model statistically reproduces the mild evolution detected in the metallicity of the neutral hydrogen content of the universe, given by mass-weighted means, if observational constraints are considered (as suggested in 1998 by Boissée and co-workers). For the α-elements in the simulated DLAs, we find neither enhancement nor dependence on metallicity. Our results support the hypotheses that DLAs trace a variety of galactic objects with different formation histories and that both Type I and Type II supernovae are contributing to the chemical enrichment of the gas component, at least since $z \approx 2$. This study indicates that DLAs could be understood as the building blocks that merged to form current normal galaxies within a hierarchical clustering scenario.

*Subject headings:* cosmology: theory — dark matter — galaxies: abundances — galaxies: evolution — galaxies: formation — methods: numerical

## 1. INTRODUCTION

Studies of damped Lyα system (DLA) absorbers have provided hints as to the properties of structure at high redshift from both kinematical and chemical points of view (Lu et al. 1996; Pettini et al. 1997; Wolfe et al. 1995; Haehnelt, Steinmetz, & Rauch 1998; Pettini et al. 1999; Prochaska & Wolfe 1999). Analysis of the absorbers at low $z$ show that these systems have diverse morphologies (e.g., Rao & Briggs 1993; Le Brun et al. 1997), while at high $z$ their nature remains unclear. First kinematical studies suggested that high-redshift DLAs were large disks similar to those in present-day spiral galaxies (e.g., Wolfe et al. 1995; Prochaska & Wolfe 1997). However, Haehnelt et al. (1998) show that high-redshift DLAs could also be the building blocks of local typical galaxies, as predicted by hierarchical clustering scenarios (HCSs). The metallicity properties of DLAs support the idea that they are chemically young objects (e.g., Pettini et al. 1999; Prochaska et al. 2000). However, the dependence of their metallicities on $z$ is a controversial point, since, until recently, only very weak or no evolution has been reported from the analysis of the mean metallicity of the neutral hydrogen with the abundance ratios weighted by the H I column density ($N_{\rm H\,I}$) (Prochaska & Wolfe 2000; Pettini et al. 1999; Vladilo et al. 2000) in contrast to some theoretical models that predict substantial evolution of the neutral hydrogen abundances (e.g., Edmunds & Phillips 1997; Pei, Fall, & Hauser 1999; see Cen & Ostriker 1999 for a different result). However, the unweighted mean metallicities and linear regressions through the individual data show stronger signals of evolution, as reported in recent works (i.e., Prochaska & Wolfe 2000; Vladilo et al. 2000; Hou, Boissier, & Prantzos 2001). Detecting evolution in chemical abundances of H I gas mass may be difficult because of several biasing factors. Among them, dust depletion and obscuration have been proved to be a source of uncertainties for some element measurements (e.g., Vladilo 1998; Hou et al. 2001), while the limited redshift coverage with known DLAs may not be adequate for detecting the presence of evolution. As first pointed out by Boissé et al. (1998), DLAs with high $N_{\rm H\,I}$ and high metallicity might be missing from the data as a consequence of dust extinction, which would imply a biased determination of evolution. For the α-elements, dust-corrected data show mild enhancement or near-solar values for most observed elements, in contrast to the metallicity pattern of metal-poor Galactic stars (e.g., Vladilo 1998; Pettini et al. 2000). This might imply a different star formation (SF) history from that of the Milky Way, although Prochaska et al. (2000) found an agreement between the properties of the Galactic thick disk and the DLAs.

In HCSs, where galaxies are formed by aggregation of smaller substructures, mergers and continuous gas infall play an important role, contributing to regulate the SF (Tissera 2000) and chemical histories (e.g., Cora et al. 2000) of the galactic objects. As suggested by Haehnelt et al. (1998) from a kinematical study of numerical simulations, DLAs could be the progenitor substructures of current galaxies that merged to form galactic objects in an HCS. The variety of morphological types, together with the fact that they tend to be chemically young, seems to support this hypothesis. With the aim of understanding the possible link between the structure in an HCS and the nature of DLAs, in this paper we assess the chemical properties of the building blocks of current normal galaxies as a function of redshift. For this purpose, we focus our study on the analysis of the

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unweighted mean metallicities of neutral hydrogen as a function of $z$, since they are more sensitive to the properties of the individual objects. We also comment on the mass-weighted mean metallicities that are related to the chemical content of the universe. We use hydrodynamical cosmological models that treat the nonlinear evolution of both baryons and dark matter in a self-consistent way, providing a well-described history of formation. Results of the simulations are compared with available observational data on chemical abundances of DLAs. We also discuss implications for galaxy formation.

## 2. CHEMICAL PROPERTIES OF GALACTIC OBJECTS

Our hydrodynamical chemical simulations follow the joint evolution of dark matter and baryons within a cosmological context (Tissera, Lambas, & Abadi 1997), including SF and chemical evolution. Stars are formed from cold and dense gas in a convergent flow according to the Schmidt law. Gaseous particles are gradually transformed into stars in different SF episodes. The contribution of Type I (SNe I) and Type II (SNe II) supernovae from each of these SF episodes to the chemical enrichment of the gas component are taken into account according to stellar evolution models and metallicity enrichment yields. Chemical elements generated in a given particle are distributed among gas particles in its neighboring area, with each contribution being weighted by a kernel function that depends on the distance (i.e., by using the smoothed particle hydrodynamics technique).

We adopt the yields given by Woosley & Weaver (1995) for SNe II and those given by Thielemann, Nomoto, & Hashimoto (1993) for SNe I. A time delay of $10^8$ yr is assumed for binary star systems to explode as SNe I. We adopt a fixed Salpeter initial mass function with lower and upper mass cutoffs of 0.1 and 120 $M_\odot$, respectively. In this work the effects of energy injection into the interstellar medium due to supernova explosions have not been included. For a detailed discussion of the chemical model see Mosconi et al. (2001).

We analyze cosmological simulations of a typical 10 Mpc cube volume represented by $64^3$ equal-mass particles ($\Omega_b = 0.1$). Initial conditions are consistent with a standard cold dark matter universe ($H = 50$ km s$^{-1}$ Mpc$^{-1}$) with cluster abundance normalization $\sigma_8 = 0.67$. We have run a set of three simulations with different realizations of the power spectrum, estimating averaged results over them. The SN parameters adopted in these simulations correspond to those giving the best agreement with observations of galaxies at $z = 0$ (Mosconi et al. 2001) and with the [O/Fe] abundance pattern in the Milky Way (Cora et al. 2000).

We identified galactic objects at their virial radius at different stages of evolution of the simulated volume. Galactic objects are formed by a dark matter halo and a baryonic component in the form of gas and stars. To diminish numerical resolution problems, we analyze galactic objects with more than 200 baryonic particles within their virial radius and in the range $0.25 < z < 2.35$. Consequently, the analyzed objects have virial velocities within $\approx$100–250 km s$^{-1}$. We study a total number of 380 galactic objects satisfying the above conditions; all are considered to be possible absorbers.

It is likely that DLA observations map the chemical properties of the gaseous disks that are not expected to be good tracers of the metal content at the central regions (e.g., Jimenez, Bowen, & Matteucci 1999; Somerville, Primack, & Faber 2001; Savaglio 2000). Hence, in order to carry out a suitable comparison between the simulated galactic objects and DLA observations, we use a Monte Carlo technique to simulate lines of sight (LOSs) and estimate the chemical properties of the neutral hydrogen component with $N_{\rm H\,I} > 2 \times 10^{20}$ atoms cm$^{-2}$ (Wolfe et al. 1986) along the LOSs. We assume that the hydrogen mass in a gas particle remains neutral if no SF activity has ever occurred within that particle.

As a combined result of dynamical evolution, mergers, and interactions, the SF rate history of each galactic object can be described as a combination of an ambient SF rate and a series of starbursts (e.g., Tissera 2000). The timings between starbursts are not ad hoc, but are given naturally by the evolution of the objects in the HCS adopted. Thus, we have a consistent description of the chemical enrichment of the stellar populations and gaseous components because of the fact that the different ejecta times of SNe I and SNe II can be properly taken into account. Note that the simulated sample is not affected by dust depletion or obscuration. These facts make our simulations powerful tools for exploring the nature of DLAs.

For each galactic object selected at a given redshift, we define the H I mass-weighted mean of abundance ratio of elements $K$ and $J$, $[K/J]$ in the column of H I along a LOS, as

$$[K/J] = \log \frac{\sum_{i=1}^{n_p} K_i M_i^{\rm gas}}{\sum_{i=1}^{n_p} J_i M_i^{\rm gas}} - \log (K/J)_\odot \,, \qquad (1)$$

where $n_p$ is the total number of gas particles belonging to a galactic object along a certain LOS, $M_i^{\rm gas}$ is the neutral hydrogen mass of the $i$th particle, $K_i$ and $J_i$ are their chemical abundances, and $(K/J)_\odot$ is the corresponding solar abundance ratio. We can similarly define the mean abundance ratios for the stellar populations. This point will be discussed in a separate paper.

In order to study the metallicity evolution of DLAs, we consider the abundance ratios of [Zn/H] and [Fe/H]. In our sample, both elements can be measured without introducing biases such as those produced by dust extinction and depletion, or, in the case of zinc, by the fact that this element is difficult to detect at low metallicities. Note that zinc is usually considered a reliable tracer of metallicity because it is weakly depleted onto dust grains; however, its nucleosynthesis remains to be fully understood (Prochaska & Wolfe 2000; Prantzos & Bossier 2000). Current models of the production of this element (Woosley & Weaver 1995) have problems in reproducing the observational fact that, regardless of metallicity, stars in the halo and thin disk of the Galaxy have nearly solar [Zn/Fe] values (see also Hou et al. 2001). Nevertheless, recent results suggest that Zn is enhanced relative to Fe in the stars of the Galactic thick disk (Prochaska et al. 2000). This makes results from Zn analysis more difficult to interpret. For the purpose of carrying out a reliable comparison between observations and simulations, we gathered the available observations from the literature (see Fig. 1) and estimated the same parameters calculated for the simulations within the same redshift range.

In Figure 1$a$, we show the unweighted mean ratios $\langle [{\rm Zn/H}] \rangle = (1/n) \sum_n [{\rm Zn/H}]$ (where $n$ is the number of

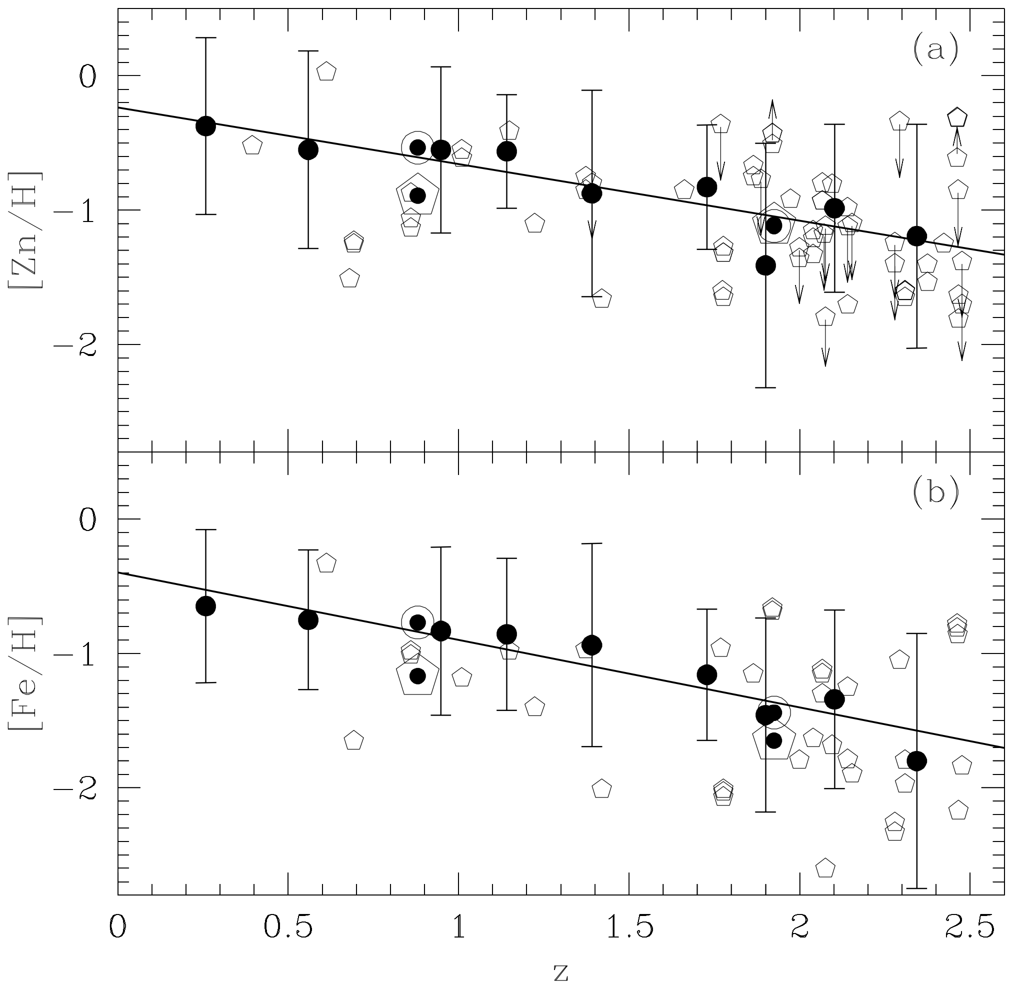

FIG. 1.— (*a*)[Zn/H] and (*b*)[Fe/H] unweighted mean abundances for the neutral hydrogen along LOSs in the galactic objects in the three simulations as a function of redshift (*filled circles*). Error bars correspond to a 1 $\sigma$ standard deviation. We include observational data (*open pentagons*) for DLAs taken from Lu et al. (1996), Pettini et al. (1997, 1999, 2000), Vladilo (1998), and Prochaska & Wolfe (1999, 2000). The downward- (upward-) pointing arrows indicate upper (lower) limits of [Zn/H]. Unweighted mean values for the simulated DLAs (*filled circles in open circles*) and the observations (*filled circles in open pentagons*) in the low- and intermediate-redshift intervals are also plotted. These symbols are superimposed in the intermediate-redshift interval in (*a*). Solid lines show the least square linear regression for the whole sample of simulated DLAs.

galactic objects in the total simulated sample that are located at a certain *z*) for the H I component along the LOSs of galactic objects in the three simulations as a function of redshift. Error bars correspond to the dispersion of the ratios of the galactic objects at each analyzed *z*. As can be seen, the simulated neutral gas abundance ratios are within the observed range for DLAs. In order to quantify their evolution with *z*, we compute the unweighted mean $\langle[\mathrm{Zn/H}]\rangle$ in two redshift intervals, $z_{\mathrm{low}} = [0.26, 1.5]$ and $z_{\mathrm{inter}} = [1.5, 2.35]$. We obtain $\langle[\mathrm{Zn/H}]_{\mathrm{low}}\rangle = -0.53 \pm 0.06$ and $\langle[\mathrm{Zn/H}]_{\mathrm{inter}}\rangle = -1.12 \pm 0.17$.[5] These results imply an evolution of $0.58 \pm 0.13$ dex between the low- and intermediate-redshift bins in the models, while DLA observations show a variation of $0.22 \pm 0.09$ for the same redshift bins. The observed mean values are $\langle[\mathrm{Zn/H}]_{\mathrm{low}}\rangle = -0.89 \pm 0.10$ and $\langle[\mathrm{Zn/H}]_{\mathrm{inter}}\rangle = -1.11 \pm 0.07$. Hence, at high *z* the simulated and observational values agree very well. However, the low *z* values differ by ≈0.40 dex. This difference in the lower *z* interval could be attributed to the observational bias first discussed by Boissé et al. (1998) that would prevent high $N_{\mathrm{H\,I}}$ systems with high metallicities from being detected (see also Prantzos & Bossier 2000; Savaglio 2000). By analyzing the chemical properties of the individual DLAs, Vladilo et al. (2000) found an anticorrelation signal for the [Zn/H] data which yields a linear regression with a slope of $d\log\mathrm{Zn}/dz = -0.32 \pm 0.13$, detecting intrinsic evolution for $z < 3.5$. A similar analysis applied to our set of observational data within our *z* range yields $d\log\mathrm{Zn}/dz = -0.24 \pm 0.11$. For the simulated DLAs, we obtain a slope of $d\log\mathrm{Zn}/dz = -0.42 \pm 0.08$ which, albeit larger, is statistically consistent with observations.

Figure 1*b* shows the unweighted $\langle[\mathrm{Fe/H}]\rangle$ versus *z* for the same galactic objects plotted in Figure 1*a*. This element suffers strong gas depletion, but can be observed over a larger *z* interval; its nucleosynthesis is better understood and can be easily detected at low metallicities. From Figure 1*b* we see that the estimated ratios for H I along the LOSs in the simulations match the observational range of the DLAs. Estimates of their unweighted $\langle[\mathrm{Fe/H}]\rangle$ at $z_{\mathrm{low}}$ and $z_{\mathrm{inter}}$ give a $0.67 \pm 0.13$ dex evolution in the simulations. Calculations for the available DLA observations in the range $0.25 < z < 2.35$ show, in this case, a signal for evolution of $0.48 \pm 0.13$ dex. A linear regression through the observed

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[5] Standard deviations have been calculated by using the resampling bootstrap technique with 500 random samples.

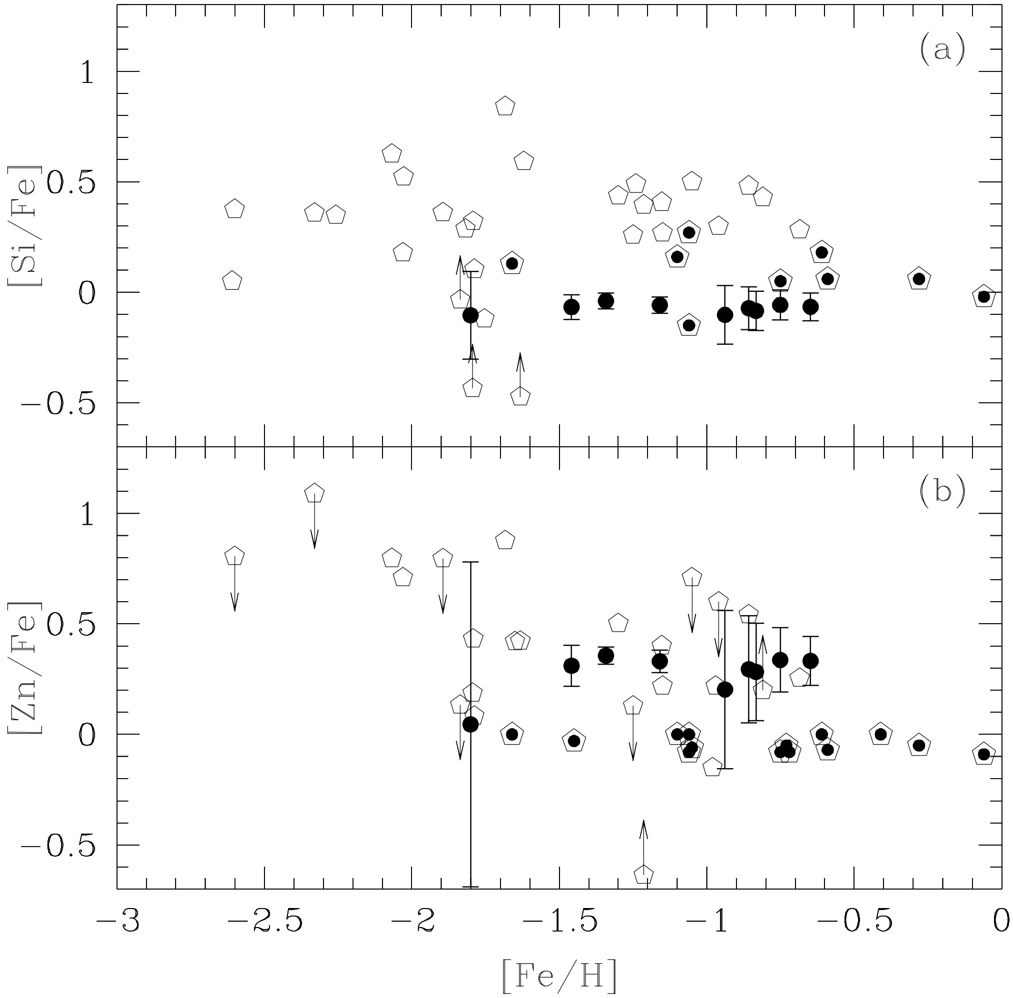

FIG. 2.—(*a*) [Si/Fe] and (*b*) [Zn/Fe] unweighted mean abundances for neutral hydrogen along LOSs in the simulated DLAs in the three simulations for each redshift analyzed as a function of the metallicity [Fe/H] (*filled circles*). Error bars correspond to a 1 $\sigma$ standard deviation. We include observational data for DLAs without dust corrections (*open pentagons*) taken from Lu et al. (1996) and Prochaska & Wolfe (1999); dust corrected values (*filled circles in open pentagons*) are obtained from Vladilo (1998) and Pettini et al. (2000). The downward- (upward-) pointing arrows indicate upper (lower) limits of [Si/Fe] and [Zn/Fe].

[Fe/H] data within the same $z$ range shows a slope of $-0.50 \pm 0.17$ (see also Savaglio 2000; Hou et al. 2001). The linear correlation of the simulated [Fe/H] ratios gives $d\log\mathrm{Fe}/dz = -0.50 \pm 0.09$. All these values are in suitable agreement within statistical uncertainties.

The mass-weighted mean metallicities of H I assess the evolution of the chemical properties of the population as a whole, and, consequently, of the chemical history of the universe. As previously reported, both the observed $N_{\mathrm{H\,I}}$-weighted mean [Zn/H] and [Fe/H] ratios show mild or no evolution for $z \leq 3.5$ (Pettini et al. 1999; Prochaska & Wolfe 2000), while most theoretical models predict substantial change of the metallicity of neutral gas with redshift. Estimates of the corresponding ratios in our model at low- and intermediate-$z$ intervals also yield a signal of evolution: $0.33 \pm 0.08$ and $0.47 \pm 0.09$ for [Zn/H] and [Fe/H], respectively.

We would like to stress that the conclusions regarding the evolution of the observed [Zn/H] and [Fe/H] found by using mean values at low and intermediate $z$ should be taken with caution because of the small number statistics in the low-$z$ bin. More observations of DLAs at low $z$ are needed to draw final conclusions on this point. Mainly, more observations of DLAs with high $N_{\mathrm{H\,I}}$ and high metallicity are required to properly assess the presence of evolution. In fact, if DLAs with these characteristics were missing from the data then the presence of evolution could be difficult to detect. In order to mimic this effect, Prantzos & Boissier (2000) applied a filter to their model by selecting DLAs according to the observationally determined constraint $18.8 < [\mathrm{Zn/H}] + \log N_{\mathrm{H\,I}} < 21$. Following their work, we estimate the evolution of filtered, simulated DLAs, using [Zn/H] ratios. For the unweighted means we obtain an evolution signal of $0.46 \pm 0.10$, while the weighted ratios show a weaker change consistent with mild evolution: $0.24 \pm 0.12$. Clearly, selection biases could have strong implications when estimating changes with redshift.

The standard dispersions shown in Figure 1 for both elements in the simulated sample reproduce fairly well the observed dispersions of DLAs; for [Zn/H] the building blocks show a dispersion of $\sigma_{z_{\mathrm{low}}} = 0.68$ and $\sigma_{z_{\mathrm{inter}}} = 0.78$, while observations show $\sigma_{z_{\mathrm{low}}} = 0.42$ and $\sigma_{z_{\mathrm{inter}}} = 0.86$. The simulated [Fe/H] ratios show $\sigma_{z_{\mathrm{low}}} = 0.60$ and $\sigma_{z_{\mathrm{inter}}} = 0.77$, compared with the observed ones of $\sigma_{z_{\mathrm{low}}} = 0.45$ and $\sigma_{z_{\mathrm{inter}}} = 1.24$. In our models this dispersion arises as the result of the variety of galactic objects with diverse evolutionary histories: merger tree, star formation, chemical enrichment, etc., at different $z$, supporting a similar origin for the large dispersion observed in DLAs.

We estimate the unweighted mean [Si/Fe] and [S/Fe] ratios in order to analyze the behavior of the $\alpha$-elements in the H I gas mass of the simulated galactic objects. From Figure 2*a* we can appreciate that the mean [Si/Fe] ratios have nearly solar values and show no dependence on metallicity, consistent with the dust-corrected observations reported by Vladilo (1998) and Pettini et al. (2000), who assumed that Zn is undepleted and traces Fe. A similar behavior was found for mean [S/Fe] ratios.

In Figure 2*b* we show the unweighted $\langle[\mathrm{Zn/Fe}]\rangle$ abundances versus $\langle[\mathrm{Fe/H}]\rangle$. We find that the H I component of the simulated DLAs tends to exhibit [Zn/Fe] values around a mean of $0.27 \pm 0.28$ ($1\ \sigma$ deviation). It should be noted that these values are consistent with the observed range for DLAs with no dust corrections (with a mean of $0.47 \pm 0.31$), while dust-corrected ratios show nearly solar values. As more extensively discussed by Prantzos & Boissier (2000; see also Lu et al. 1996 and Prochaska & Wolfe 2000), current nucleosynthesis models of Zn have problems in reproducing the observed abundance pattern of the Milky Way. If we had assumed that Zn traces Fe for all metallicites (e.g., Pettini et al. 2000), our models would have produced mean ratios in agreement with those of Vladilo (1998) corrected by dust depletion.

## 3. DISCUSSION AND CONCLUSIONS

Observational studies of the chemical properties of DLAs have provided invaluable information on galaxy evolution up to $z \approx 4$. This paper aims to provide a theoretical frame for understanding these observations within HCSs. The chemical hydrodynamical cosmological models analyzed take into account the different physical mechanisms that control the formation and evolution of galaxies: gravitational collapse, tidal torques, mergers, interactions, gas infall, gradient pressure, radiative cooling, SF, and chemical enrichment by SNe I and SNe II explosions. In this scenario we follow the formation and evolution of galaxy-like objects, analyzing the chemical properties of the different substructures that merge hierarchically.

In order to properly compare the galactic objects in the simulations with the observed DLAs, we estimate the abundances of H I along randomly distributed LOSs. We find that the simulated galactic objects have gaseous components that, when randomly sampled, have [Zn/H] and [Fe/H] abundances within the observed range for DLAs. In the simulations, the unweighted [Zn/H] and [Fe/H] ratios show evolution with $z$ in statistical agreement with results obtained from similar analyses of the available observations (see also Vladilo et al. 2000; Prochaska & Wolfe 2000; Hou et al. 2001). However, the mass-weighted metallicities of the simulated and observed $N_{\mathrm{H\,I}}$ show opposite trends: while the former show evolution, the latter do not. Part of this discrepancy can be attributed to observational biases that might prevent low-density, metal-poor and very metal-rich and dense zones from being detected by current observations. In fact, taking into account these effects by applying a filter to the simulated [Zn/H], we find, on the one hand, that the unweighted means still show a clear evolution, and on the other hand, that the filtered weighted abundances yield a weaker dependence with $z$, in agreement with corresponding observations (e.g., Pettini et al. 1999). According to our results, this observational bias seems to more strongly affect the weighted means, suggesting that the interpretation of the evolution of the chemical content of the universe using DLAs should be taken with extra caution. More observations, principally of high-density and high-metallicity H I column densities, are needed to draw a final conclusion.

The lack of $\alpha$-enhancements in the *mean* abundances of simulated galactic objects shows that, in the redshift range analyzed, there are already significant contributions from both types of supernovae, so that the mean unweighted metallicities of the $N_{\mathrm{H\,I}}$ are nearly solar, in agreement with DLA observations after dust corrections. We detect no evolution of [$\alpha$/Fe] with metallicity, implying that, for our galactic objects, their SF histories are the result of the superposition of different starbursts occurring at different epochs. Moreover, the starbursts could have been triggered in different substructures that merged to form the galactic objects analyzed at a given $z$. In the case of Zn we found enhancement with respect to the Fe, but no dependence on metallicity. A lower Zn nucleosynthesis production in the models (or assuming that Zn traces Fe) would have produced [Zn/Fe] values in agreement with the dust-corrected observed DLAs (Vladilo 1998). This lower Zn production does not affect the agreement shown in Figure 1*a* between the observed and simulated [Zn/H] at low $z$. At high $z$, models and observations can be reconciled if one takes into account that several high-$z$ estimations of [Zn/H] in observed DLAs are upper limits instead of accurate values. Zinc remains a controversial element, the production and evolution of which are not fully understood, as pointed out by several authors (Lu et al. 1996; Pettini et al. 1999, 2000; Prantzos & Bossier 2000; Savaglio 2000).

To sum up, the chemical properties of galactic objects in our models at a given $z$ are the result of their past evolution: collapse, mergers, interactions, SF history, etc. Since we do not impose any particular constraint to select the galactic objects in the models, the results of our chemical analysis seem to support that DLAs could be the building blocks of current normal galaxies within a hierarchical context.

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