Star Formation Histories versus Redshift: Consequences for Overall Metallicity and Deuterium Destruction\(^1\)

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Abstract

The flood of new data on deep surveys, and above all the CFRS (Canada-France - Redshift-Survey), has had a great impact on studies of galactic evolution. On the basis of cosmological models consistent with the improved values of the Hubble parameter, different star formation histories are tested against the observed UV, B and IR broad band comoving luminosity densities. Using these spectrophotometric results, we analyze the global metal enrichment with the help of chemical evolutionary models and we discuss the pertinence of different metallicity tracers (quasar absorption systems and clusters of galaxies) as representative of the bulk chemical evolution of the Universe. Moreover, as deuterium is very fragile, this isotope is destroyed in all stars and its evolution is particularly sensitive to the history of star formation. Relying on models constrained to fit the solar vicinity, it is shown that models with high D destruction corresponding to a large decrease of the star formation rate (SFR) from \(z = 1.5\) to 0 are in good agreement with spectrophotometric data. In contrast, low D destruction models which require only a moderate variation of the SFR in the same redshift range seem to encounter difficulties in matching the evolution of the luminosity densities (UV, B and IR) versus redshift. The sensitivity of the results with the cosmological models of the universe is discussed.

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1 Introduction

UV, optical, and IR observations of high redshift objects have recently achieved a spectacular breakthrough (Lilly et al. 1996, Steidel et al. 1996, Sawicki, Lin, & Yee 1997, Madau et al. 1996, Treyer et al. 1997), revealing a relatively intense period of star formation at $1 < z < 2$ (Madau et al. 1996, 1997) with a decrease by a factor of about ten since then. The Canada-France Redshift Survey (CFRS) has produced data on the comoving luminosity densities $L(\lambda, z)$ in three wavelength bands ($0.28$, $0.44$, and $1 \mu$m) over the redshift range $0 < z < 1$ (Lilly et al. 1996). These data are complemented by the Hubble Deep Field (HDF) data in the redshift range $0.5 < z < 2$ at $0.28 \mu$m (Connolly et al. 1997) and in the range $0.2 < z < 4$ at $0.3 \mu$m and $0.45 \mu$m (Sawicki, Lin, & Yee 1997). Because it is expected that the UV luminosity density of star forming galaxies is related to their star-formation rate, these data have allowed one to map out the cosmic star formation history as well as the metal enrichment history as a function of redshift out to $z \approx 2$. Note however, that above $z = 2$ the luminosity data are still uncertain. Specifically, the luminosity function of Lilly et al. (1996) are the most reliable being derived from spectroscopic redshifts plus photometric data. The luminosity functions of Connolly et al. (1997) and Sawicki et al. (1997) are based on photometric redshifts, and are subject to uncertainties. This is in addition to the uncertainties due to dust at high redshift. We stress that the lower redshift data provide significant constraints on the models considered, thus our essential conclusions are not strongly dependent on the high redshift data.

Indeed, because of these observations, it has become possible to extend the earlier notions of so-called cosmic chemical evolution (see e.g. Pei & Fall 1995) based on damped Ly$\alpha$ systems (DLAs). Such systems show a large variation of comoving H I with respect to redshift (Lanzetta et al. 1995) and a metallicity of about $Z \approx 0.1Z_\odot$ at $z \sim 2$, however with a large dispersion (Pettini et al. 1997c). Although, as we will argue below, these systems may not be representative of the globally averaged star formation history, since they map out the outer part of spiral galaxies (Phillips & Edmunds 1996) and/or protogalactic clumps not totally constituted in galaxies. In addition, it was shown (Fall & Pei 1993; Pei & Fall 1995) that obscuration plays a crucial role in understanding the evolution of such systems particularly at high redshift. Because of the problems associated with obscuration, observations at somewhat lower redshift $z \lesssim 2$ are interesting from the point of view of cosmic
chemical evolution and allow one to model the bulk of the history for galaxy evolution.

It is worth noting however, that the conversion of the luminosity densities into a star formation rate (SFR) is model dependent through the adopted initial mass function (IMF). In addition, the corrections needed to account for dust obscuration are rather uncertain and most probably lead to an upward revision of the star formation rate at high redshift by a factor of a few deduced from UV observations (Pettini et al. 1997b). This seriously affects the high redshift observation at 0.15 \( \mu \)m by the HDF (Madau et al. 1996) and we treat this data as a lower limit on the luminosity density at that wavelength. With the same caveat, we also consider the HDF data of Sawicki, Lin, & Yee 1997, which give higher values. As we said, obscuration is expected to be small at low \( z \), since we know that only a third of the luminosity of galaxies at \( z = 0 \) is radiated in the IR (Soifer & Neugebauer 1991). Thus, the CFRS data (Lilly et al. 1996) are of special interest.

Independently, the evolution of the overall metallicity \( Z \), can be derived from observations of heavy abundances seen in i) absorbing systems along the line of sight to distant quasars (DLAs, usually associated with very young galaxies, Pettini et al. 1997a, Lu et al. 1996, 1997); ii) Lyman \( \alpha \) forest (associated with intergalactic gas clouds, e.g. Savaglio 1997) iii) X-ray emitting galactic clusters associated with the intracluster gas (Mushotzky & Loewenstein 1997, Renzini 1997). Though these observations may serve as an additional constraint on cosmic star formation histories, they have to be carefully interpreted to determine what medium is the most representative of the history of star formation as revealed by the spectrophotometric data. Phillips & Edmunds (1996) and Edmunds & Phillips (1997) have considered in detail the cosmic chemical evolution following the evolution of the mean metal abundance of the Universe. They have taken into account all the different classes of galaxies and their internal components. This is certainly the best way to treat the problem though there are many obstacles. In this paper, our main goal is to confront the D history with the luminosity density changes as a function of the redshift. The observations of the present or near present D/H ratio are only available in the solar vicinity (ISM and solar system). Thus, the galactic evolutionary models selected are anchored to the local galactic environment. Even if high redshift estimates exist, they are unfortunately quite uncertain. It is clear that when we will have a broader data set at our disposal, some of these questions can be reassessed. The FUSE satellite developed by NASA in collaboration with France and Canada will be launched at the end of 1998. One of its principle goals is to measure D in
various places: the galactic center and anti-center, the galactic halo and external galactic sites (Vidal-Madjar et al 1997). Though we are making use of models designed for only a part of the Galaxy, whereas the luminosity data are representative of an average over various parts and types of galaxies, it is edifying to confront these models to global constraints at moderate redshift to test, among other things, their local or general character. It turns out that certain models, among the ones studied, lead to a good reproduction of the luminosity density in different wave bands; this convergence is obtained with models similar to empirical ones by Madau (1997). This points to a large variation of the SFR from $z = 2$ to $z = 0$ in agreement with Edmunds & Phillips (1997).

In the context of cosmic chemical evolution, the work by Madau (1997), Madau et al. (1997) is quite illustrative. They have considered three different IMFs: a Salpeter IMF with slope $x = 1.35$, $x = 1.7$ IMF and a Scalo (1986) IMF, the latter yielding a poor fit to the data at the larger wavelengths due to an excess of approximately solar mass stars. In agreement with Lilly et al. (1996), the data are fit better with an IMF which favors the flatter Salpeter IMF. Madau et al. (1997) also considered two different star formation rates, both of which increase from $z = 0$ to $z = 1.5$. Of the two, one decreases at $z \gtrsim 1.5$, while the second remains almost constant at higher redshift. The latter requires dust obscuration which increases with redshift. From the observations of the DLAs alone, they favor the first mode. Such a correction may not be necessary on the basis of the HDF data of Sawicki, Lin, & Yee (1997) which indicates a relatively flat luminosity density between $z = 1$ to about 4.

In what follows, we reassess the problem of tracing the cosmic chemical evolution with the available high redshift data, using the population synthesis model of Bruzual and Charlot (1997). As such, we are presented with a good occasion to enlarge the debate on galactic evolution and promote local arguments to cosmological ones. We will consider several very different star formation rate histories including the relevant metallicity information. We find that the high redshift data is indeed very sensitive to the form of the adopted SFR.

The star formation rate in a chemical evolution model has a strong impact on the degree to which deuterium is destroyed. Given a definite primordial value for D/H, the present day D/H abundance is a prediction of the model. Indeed different models of galactic chemical evolution make very different predictions concerning the total amount of deuterium atraction. Given the current uncertainties in the observations which correspond to the primordial abundance of D/H, several different SFRs have been employed for suitably describing the
evolution of D whether or not the primordial abundance of D/H was high or low. We will consider the consequences of models (Scully et al. 1997, Timmes, Woosley, & Weaver 1995, Tosi 1996 and references therein) corresponding to both high and low D destruction (see table 1), on the comoving luminosity densities in three bands $L(\lambda, z)$ upon extrapolating them to a scale representative of the Universe as a whole.

To this end, we will briefly review the photometric and chemical evolution models considered in section 2. In section 3, we display our results for the models considered and compare these to the data. In section 4, we discuss the consequences of these models on the destruction of Deuterium and the metal enrichment history at high redshift. Finally, in the last section we present our conclusions and perspectives.

## 2 Star formation histories in chemical evolution models and population synthesis

Simple models of galactic chemical evolution have enjoyed considerable success in fitting abundance data in the Galaxy and solar neighborhood (Tinsley 1980). To first order, such models require some form for the IMF and SFR as broad averaged quantities. When combined with element abundance yields from supernovae, a simple integration involving the gas mass and yields over the IMF and SFR, gives abundance ratios and total abundances of heavy elements in general agreement with observations. However, unless one has considerable faith in these simple models, it is difficult to make predictions. For example, many simple models of chemical evolution, as well as some more complicated ones which include the infall of matter onto the galactic disk, often “predict” that the total amount of deuterium destruction that has occurred in the solar neighborhood is limited to a factor of 2 – 3 (Tosi 1996). However, it has been shown (Scully et al. 1997) that by including the effects of outflow or galactic winds driven by supernovae heating in the early galaxy, the amount of deuterium destruction can be significantly larger when coupled to a steeply decreasing SFR. That such models exist is clearly of importance if the value of D/H in quasar absorption systems are as high as some observations indicate (Songaila et al. 1994, 1997, Carswell et al. 1994, Wampler 1996, Webb et al. 1997).

The chemical evolution models of Scully et al. (1997) were designed to compare different degrees of deuterium destruction. As such, the models were constructed to first match solar
and present day D/H values of $(D/H)\odot \simeq 2.6 \times 10^{-5}$ (Geiss 1993, Scully et al. 1996) and $D/H_{\text{ISM}} \simeq 1.6 \times 10^{-5}$ (Linsky et al. 1993, 1995) to the high D/H measurements in quasar absorption systems (Songaila et al. 1994, Carswell et al. 1994, Webb et al. 1997) of $\sim 2 \times 10^{-4}$; the low D/H measurements of $2.5 \times 10^{-5}$ (Tytler, Fan, & Burles 1996, Burles & Tytler 1996); and an intermediate value of $D/H = 7.5 \times 10^{-5}$. Parameters of the models were then adjusted so as to fit the abundance ratios $[\text{Fe/H}]$ vs. $t$ and $[\text{O/H}]$ vs. $t$, the present day gas mass fraction, and G-dwarf distribution vs. metallicity in the solar neighborhood.

Because of the increased amount of stellar processing needed to destroy deuterium in the high primordial D/H cases, galactic winds were introduced to avoid the overproduction of heavy elements. The winds generally included two components (Vader 1986), one which is due to the heating of the ISM from the dissipation of energy of the hot supernova remnants (Larson 1974) and a second component which is metal enhanced and is directly proportional to the supernovae rate with an efficiency $\nu$. In all of the models, a single slope IMF with $x = 1.7$ was used. For the high D/H values, two models were constructed. In model 1a, a bimodal model of star formation (Larson 1986) was considered with a massive mode (of stars with masses between $2 - 100$ $M_\odot$) with an exponentially decreasing SFR, $\psi = 0.29e^{-t/2}$ (times in Gyr) and a “normal” mode (stars with masses between $0.4 - 100$ $M_\odot$) with a SFR given by $\psi = 0.29M_G$, where $M_G$ is the mass in gas. In this case $\nu$ was set to 0.81. A second model was constructed for the high D/H case which better matched the local G-Dwarf distribution, because it models a prompt initial enrichment. This case, called model 2, is a sequential model in which the massive mode has a SFR given by $\psi = 0.19e^{-t/1}$ for $t \leq 1$ Gyr, after which it is replaced by the normal mode with $\psi = 0.73e^{-t/2.5}$. The IMF is the same as in 1a and here $\nu = 0.68$.

Models 1b and 1c were designed to match the D/H evolution with primordial D/H = $7.5 \times 10^{-5}$ and $2.5 \times 10^{-5}$ respectively. In these models a single SFR was used. For model 1b, $\psi = 0.28M_G$ with the normal mode IMF of models 1a and 2 and $\nu = 0.55$, and in Model 1c, $\psi = 0.07$, i.e., a constant SFR with a normal mode IMF which extended down to 0.2 $M_\odot$. In this case, since metal production rather than overproduction is a problem, one sets $\nu = 0$.

It is also of interest here to compare our results based on the above models along with galactic chemical evolution models which use infall to progressively form the galactic disk. We will therefore consider two models of this type: the model of Timmes, Woosley, & Weaver (1995) hereafter TWW; and a model representative of the compilation in Tosi (1996) which
includes models of Carigi (1996), Galli et al. (1994); Matteucci & Francois (1989); and Prantzos (1996). The latter set of models, all have similar star formation histories as well as D/H evolution. They differ more in their galactic radial dependence which does not concern us here. All of these models including that of TWW (1995) all employ infall and they are dependent on the gas density, $\sigma$. While the model of TWW has a relatively strong dependence ($\sigma^2$), the others have a more moderate dependence (closer to a linear dependence as in models 1a,b above).

In Figure 1, we show all of the SFRs (as a function of redshift) of the models considered. The various curves are labeled 1a,b,c and 2 corresponding to the models of Scully et al. (1997), TWW, and T corresponding to a SFR representative of the models taken from the compilation of Tosi (1996). For comparison, we also show the two star formation rates from Madau et al. (1997). They have all been normalized at $z = 0$ so that log(SFR) = 0.

In what follows in the next section, we will assume that the adopted star formation history is not too different from the history in an average galaxy which contributes to the luminosity density at high redshift. In fact, we know from the work of Madau et al. (1997) that this is not too bad an assumption since the models considered there with respect to the high redshift data resemble standard chemical evolution models. Therefore we take each of the models above, assume that the various IMFs and SFRs are in fact universal and extract the luminosity density as a function of time (or redshift for a given cosmological model) as described below. This luminosity function is then compared to the available data.

We compute the spectrophotometric properties of model galaxies using new population synthesis models by Bruzual & Charlot (1997). These span the range of metallicities $5 \times 10^{-3} \leq Z/Z_\odot \leq 5$ and include all phases of stellar evolution from the zero-age main sequence to supernova explosions for progenitors more massive than $8 M_\odot$, or the end of the white dwarf cooling sequence for less massive progenitors. The models are based on recent stellar evolutionary tracks computed by Alongi et al. (1993), Bressan et al. (1993), Fagotto et al. (1994a, b, c), and Girardi et al. (1996), supplemented with prescriptions for upper-AGB and post-AGB evolution. The radiative opacities are taken from Iglesias et al. (1992). In the version used here, we adopt the library of synthetic stellar spectra compiled by Lejeune et al. (1997) for all metallicities. This library is based on spectra by Kurucz (1995, private communication; see also Kurucz 1992) for the hotter (O-K) stars, Bessell et al. (1989, 1991) and Fluks et al. (1994) for M giants, and Allard & Hauschildt (1995) for M dwarfs. The
Lejeune et al. spectral library also includes semi-empirical corrections for blanketing, a well-known limitation of synthetic spectra (see, for example, Charlot, Worthey & Bressan 1996, and references therein). The resulting model spectra computed for stellar populations of various ages and metallicities have been checked against observed spectra of star clusters and galaxies (Bruzual & Charlot 1997; Bruzual et al. 1997).

A complete discussion of the differences between the spectrophotometric predictions of these models with those in previous studies will be presented in Bruzual & Charlot (1997). The typical discrepancies between the properties of stellar populations of the same input age and metallicity that are obtained by using the spectral synthesis models constructed by different groups of scientists, have already been illustrated by Charlot, Worthey & Bressan (1996). These can reach up to 0.05 mag in rest-frame $B-V$, 0.25 mag in rest-frame $V-K$ and a 25% dispersion in the $V$-band mass-to-light ratio. With these uncertainties in mind, we will concentrate more on understanding the trends seen in the observations than on obtaining exact fits to the data.

Finally, since our SFRs are all expressed in terms of time, we need a cosmological model to convert time to redshift. The galactic evolution models described above were originally designed to model our Galaxy with a total age 14 Gyr, a shorter time would require a more rapidly changing SFR, particularly for models 1a and 2. The conversion of course is well known

$$H_o t = \int_0^{(1+z)^{-1}} \frac{dx}{\sqrt{1 - \Omega_o - \Omega_\Lambda + \Omega_\Lambda a^2 + \Omega_o / x}}$$  

where $\Omega_\Lambda = \Lambda / 3 H^2$ and $q_o = \Omega_o / 2 - \Omega_\Lambda$. For the simple case of an Einstein-de Sitter Universe ($q_o = 1/2$ and $\Lambda = 0$), the right hand side of Eq. (1) is just $\frac{2}{3}(1 + z)^{-3/2}$. For comparison we will also consider a $q_o = 0.1$ Universe as well.

3 Results confronted to photometric observations

As indicated in section 1, we compare the results of our model calculations to the high redshift data of Lilly et al. (1996), Connolly et al. (1997), and Sawicki et al. (1997). Lilly et al. used the CFRS galaxy sample for which both redshift and B,V,K and I band photometry was available. As such, they constructed the co-moving luminosity densities $L(\lambda, z)$ in three redshift bins ($z = 0.2 - 0.5, 0.5 - 0.75, \text{and} 0.75 - 1.0$) and at three wavelengths (0.28,
0.44, and 1.0 $\mu$m). For the local value ($z = 0$) they adopted the value from Loveday et al. (1992) and we will do the same. (We note that there has been considerable discussion in the literature recently, regarding the local value). We also compare our results to the data of Connolly et al. (1997) based on HDF data at 0.28 $\mu$m in the redshift ranges 0.5 – 1.0, 1.0 – 1.5, 1.5 – 2.0. The HDF data of Madau et al. (1996) at 0.15 at $z > 2$, is difficult to use for our purpose here because of the effects of extinction which may range from a factor of $\sim 3$ (Pettini et al. 1997b) to as much as a factor of $\sim 15$ (Meurer 1997). For completeness, we also compare our results with the HDF data of Sawicki et al. (1997) which are at the slightly different wavelengths of 0.3 and 0.45 $\mu$m (we will ignore this difference with the other data) and in the redshift bins, 0.2 – 0.5, 0.5 – 1.0, 1 – 2, 2 – 3, and 3 – 4.

As we discussed in section 2, one of our main goals in this work is to test the various star formation histories employed in several galactic chemical evolution models against the high redshift luminosity density. The SFRs considered are indeed very different and range from a constant SFR which is flat as a function of $z$, to one that is a steeply decreasing exponential with time. These are shown in Figure 1. When run through the population synthesis code (Bruzual and Charlot 1997), it will be clear that the high redshift luminosity data is very sensitive to the input SFR.

In Figures 2 - 7, we show the data taken from Lilly et al. (1996) shown as filled squares for $\lambda = 0.28, 0.44,$ and 1.0 $\mu$m, and from Connolly et al. (1997) shown as open circles for the 0.28 $\mu$m wavelength only. The data of Sawicki et al. 1997 is shown as filled triangles for 0.28 (0.3) and open triangles for 0.44 (0.45) $\mu$m. The points in the highest redshift bin are shown as lower limits due to obscuration as discussed above. The data seem to be in relatively good agreement between the different observations. The figures also show the results of the calculated luminosity density for each of the respective models, 1a, 1b, 1c, 2, and the infall models (Timmes et al. 1995, Tosi 1996). The SFRs we have chosen, are well defined up to a normalization. Rather than normalize the individual SFRs, we can normalize the resultant luminosity density. Thus, in each of the models, we have normalized $L(\lambda, z)$ to fit the observations of Lilly et al. (1996) at $z = 0.35$ at $\lambda = 0.44\mu$m. After making this single normalization, the slopes of $L(\lambda, z)$ with respect to $z$ for each wavelength band as well as the relative magnitudes of $L(\lambda, z)$ with respect to the different wavelengths is a prediction of the model. As is readily seen from the figures, our calculation of $L(\lambda, z)$ is highly sensitive to the chosen SFR.
The figures show the evolution of the luminosity density from a redshift of 5 to the present (if galaxies or their progenitors form at $z_{\text{max}} \leq 5$, a cut should be made at this redshift). For the Einstein-de Sitter Universe ($q_o = 0.5$), this corresponds to times from $t \simeq 1$ to 14 Gyr (for $q_o = 0.1$, it is 1.4 – 14 Gyr). Whereas the bulk of the data which exists for $z < 2$, corresponds to times $t \simeq 2.7 – 14$ Gyr (3.6 – 14 Gyr for the $q_o = 0.1$ model).

In model 1b, the SFR is proportional to gas mass (Scully et al. 1997). The same is true for the late time behavior of model 1a, when the “normal” mode is dominant. In these models the gas mass fraction changes by about a factor of 5 to 10 over the age of the galaxy. This factor is particularly sensitive to the present gas mass fraction chosen and is not precisely known. Because of the proportionality between the SFR and the gas mass fraction, the change in the SFR in these models is also uncertain. However, it is not simply the net change in the SFR that is important when trying to match this high redshift data. Even in case 1a, where the SFR decreases by a factor of about 10, we do not fit the multicolor data and this shows the extreme sensitivity of the results to the exact form of SFR. In both of these cases (1a and 1b), it is clear that the slope of $\mathcal{L}(\lambda, z)$ vs $z$ is too small. While the increase in the luminosity density is sufficient (at least in model 1a), the increase occurs over the redshift range 0 – 5, rather than 0 – 2 as indicated by the data. Even more troublesome is the relative luminosity at the different wavelengths. The models are too blue, particularly the bimodal model 1a. None of these models can be considered good candidates for cosmic chemical evolution. Results for these cases are shown in Figures 2 and 3.

Most problematic as candidates for cosmic evolution models are the constant SFR (model 1c) and the infall models compiled in Tosi (1996). As one can see from Figure 1, these models show very little variation in the SFR and as a result the evolution of the luminosity density does not even come close to matching the data as seen in Figures 4 and 5. If one accepts these models as galactic evolution models, then one must conclude that spiral galaxies such as our own have a star formation history which is not typical of the light producing objects observed at high redshift. We can not exclude this possibility.

In contrast, model 2, the sequential model with a second mode of the form $e^{(-t/\tau)}$ with $\tau = 2.5$ Gyr, gives a good fit both in terms of the slope of the luminosity densities with respect to $z$ and in color as seen in Figure 6. The SFR adopted by Madau et al. (1996, 1997) can also be characterized by an exponential with a time-scale $\tau \simeq 1.8 – 3$ depending on which of their models is used and the assumed age of the Universe. Of course, these models were
designed to closely reproduce the high redshift luminosity density and we do not duplicate their results here. The infall model of Timmes et al. (1995) uses a SFR proportional to the square of the gas mass fraction and also leads to a fairly sharply decreasing SFR, as indicated by their evolution of SN rate (cf. their fig. 39). While this model does somewhat better than the linear infall models (T), it would be hard to argue that it provides a good fit to the data. The result for the TWW model is shown in Figure 7. It is worth noting that the extragalactic background light resulting from our model II will be essentially in agreement with observations since it is similar to that calculated by Madau (1997, see his fig 5).

It is also interesting to compare the derived SFR($z$) with the space density evolution of quasars. After an initial steep rise to $z = 1.5$ the space density flattens and then declines gradually beyond $z = 2$ (Hawkins and Veron 1996, Schmidt et al. 1995). Changes in the space density of quasars may provide important clues to the epoch of the galaxy formation and related questions. The broad similarities between the SFR in galaxies and the quasar evolution rate suggest a scenario in which nuclear starbursts (taking place in elliptical galaxies triggers the quasar phenomenon (Boyle and Telervich 1998).

4 Overall metallicity and D destruction

Element abundances measured in absorbing quasar systems span a large redshift range (1 to about 4). The various clouds sampled also differ by their column densities; DLAs ($10^{20}$ cm$^{-2}$), Lyman forest systems ($10^{14} - 10^{15}$ cm$^{-2}$). We can ask whether or not the objects observed at high redshift are able to place constraints on the early phases of evolution as calculated by simple galactic (sic cosmic) models of the type discussed above. DLAs are generally considered as precursors of present day disk galaxies (e.g. Wolfe et al. 1995). The nature of the protogalactic clumps giving rise to DLAs, however, is still controversial and their morphology remains uncertain. The crucial question is whether DLAs represent a population of already assembled proto-disks, or whether they are still subgalactic fragments in the process of hierarchical assembly. The large HI column densities of DLAs (Lanzetta et al. 1995, Storrie Lombardie et al. 1996) are reminiscent of present day galactic disks, but these column densities together with their complex line profiles can be equally well reproduced by gas-rich merging protogalactic clumps with masses expected from CDM hierarchical structure formation models. Thus, the large rotating disk hypothesis, which has been favored up to
now, can be questioned (Haehnelt et al. 1997).

Recent abundance measurements in DLAs shed new light on the problem (Lauroesch et al. 1996 and references therein). The metal abundances (Fe/H, Zn/H) in DLAs at high $z$ are somewhat lower than expected for the galactic halos at similar ages but moreover much more dispersed (Lu et al. 1996, 1997, Pettini et al. 1997a,c, Vladilo 1997). Moreover, the large abundance spread (by up to 2 orders of magnitude) at the same redshift seems to indicate that we are dealing with objects of different morphologies at different stages of their chemical evolution or that we are dealing statistically with the outer parts or numerous small systems of low metallicity compared to the average metallicity of well formed spirals (Phillips & Edmunds 1996). It is possible that this great dispersion reflects a stochastic phase of star formation which is limited to the very early stages of the cosmic evolution due to the low number and short lifetime of the stars involved or external fringes of disk galaxies not typical of the whole. As such, these systems may not represent the true averaged metallicity to be compared with a cosmic evolutionary model.

At $z$ greater than 4, the metallicity of DLAs levels off at $[Fe/H] = -2$ to -2.5. This “plateau” is identical within uncertainties (which can be as much as a factor of ten) to the metallicity inferred from CIV absorption lines associated with the Lyman forest clouds (Cowie et al. 1995, Tytler et al. 1995, Songaila and Cowie 1996). It is worth noting that at $z$ greater than 3 there is a rapid decline in the space density of quasars (Schmidt et al. 1995). Then, at those high redshifts, the formation of structured objects able to trigger intense star formation with associated nucleosynthesis has not started or has just begun. Thus our models should be limited to $z$ less than 3 – 4. To conclude, $z = 4$ seems to be a transition epoch for cosmic chemical evolution.

It has been suggested that intracluster gas is a more appropriate sample with which evolutionary calculations can be compared (Renzini 1997, Mushotzky and Loevenstein 1997). In Renzini (1997) following Madau et al. (1996), it was shown that adopting $H_0 = 50$, a baryonic density $\Omega_B = 0.05$ and the density of luminous matter $\Omega_{lum} = 0.0036$, one obtains a fraction of luminous baryons of 0.07 which is comparable to that obtained (6 – 10 %) in clusters of galaxies whereas the overall metallicity derived from these figures is 7 % solar compared to the metallicity of clusters of galaxies which is about a third solar. Renzini (1997) proposes two possible explanations of cluster-field differences: ram pressure stripping (which he later discards) or a flatter IMF in clusters relative to field galaxies.
Indeed, $\Omega_B = 0.05$ corresponds to an intermediate primordial deuterium abundance, $D/H \sim 6 \times 10^{-5}$ high compared to the lower observed abundances measured in quasar absorbers (Tytler, Fan & Burles 1996, Burles & Tytler 1996). Of course, higher values have also been published, $D/H \simeq 1 - 2 \times 10^{-4}$ (see e.g. Vidal-Madjar, Ferlet & Lemoine 1997 for a recent review) yielding $\Omega_B \simeq 0.02$ for $H_0 = 60$. In this case, the global metallicity of the Universe would be about 0.2 solar which is very close to the observed metallicity of the clusters of galaxies (about a third solar) and thus it would not be necessary to argue that galaxies in and outside of clusters behave differently, or require different IMFs. The efficiency of baryon conversion calculated with $\Omega_B = 0.02$ is within a factor of two compared to the one derived from clusters. Choosing a higher value of $D/H$, one could conclude that the global metallicity of the Universe is close to the one observed in the clusters. The high $D/H$ has the advantage to lead to a unique metallicity evolution in the field and in the clusters, whereas the low $D/H$ requires the supplementary assumption (Renzini 1997) that the IMF is flatter in galactic clusters. (The lower value of $D/H$ would require even a greater distinction between these galaxies.) The global abundance is about constant (of the order of 0.2 – 0.3 solar) from $z = 0$ to $z = 2$ or 3; this constraint, as suggested by Renzini (1997), make sense for the galactic evolutionary models available. The field ellipticals dominate in mass the spirals as in clusters, at low redshift (Persic and Salucci 1992), and it is not surprising that we find similar enrichments in the intergalactic and intracluster medium, due to galactic winds triggered in ellipticals by SNII (e.g. Elbaz et al. 1995).

We turn now to the destruction of deuterium as implied by the various evolutionary models considered. The amount of deuterium destruction is of course very model dependent and can range anywhere from a factor of about 2 to 15 in our Galaxy (Scully et al. 1997). If the observations of $D/H$ in quasar absorption systems relax to a single well defined value, we would indeed have a strong constraint on galactic chemical evolution models. For now, we can simply try to model the different astration factors implied by the existing observations. Nevertheless, among the different models investigated here, a clear trend with respect to the SFR and the luminosity density is evidenced. Models with a star formation rate decreasing exponentially and with a relatively short characteristic time (as in our model 2 and the two models from Madau et al. 1997, M1 and M2) are favored. On the contrary, models with a moderate SFR variation, proportional to the gas mass fraction, such as our models 1a, 1b, or the models compiled in Tosi (1996), similar to model T here, do not fit the photometric
data. Even the TWW model with a SFR proportional to the square of the gas mass fraction is problematic. The constant SFR model 1c fares much worse.

Table 1: Deuterium Destruction Factors

<table>
<thead>
<tr>
<th>Model</th>
<th>total destruction factor</th>
<th>from $z = 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>12.5</td>
<td>7.5</td>
</tr>
<tr>
<td>1b</td>
<td>4.7</td>
<td>4.2</td>
</tr>
<tr>
<td>1c</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>12.5</td>
<td>10</td>
</tr>
<tr>
<td>M1</td>
<td>13.1</td>
<td>6.2</td>
</tr>
<tr>
<td>M2</td>
<td>16.0</td>
<td>9.1</td>
</tr>
<tr>
<td>TWW</td>
<td>2.0</td>
<td>1.5</td>
</tr>
<tr>
<td>T</td>
<td>2–3</td>
<td>2–3</td>
</tr>
</tbody>
</table>

Because deuterium is totally destroyed in the star formation process, the deuterium destruction factor will be very sensitive to the models we have considered. In the table below, we show the total deuterium destruction factor, $D_p/D_o$, as well as the factor from $z = 2$ to the present, $D_{z=2}/D_o$. When we compare these deuterium destruction factors with our previous results on the high redshift luminosity data, we see that although the models which fit the photometric data reasonably well (2, M1, M2) all destroy significant amounts of deuterium, the converse is not necessarily true. That is, models which destroy significant amount of $D/H$ will not automatically fit the high redshift data. The case in point is models 1a and 2, which each destroy $D/H$ by more than a factor of 10, yet only model 2 fit the high redshift data well. However, if one compares the evolution of $D/H$ in these two models (see e.g. Scully et al. 1997), one find that the $D/H$ is destroyed later in model 2 than in model 1a (this can be seen from the table as well). Thus the high redshift luminosity data not only prefers a large deuterium destruction factor, but the bulk of the destruction should take place at $z \lesssim 2$. We emphasize that these results can not be used to extrapolate a primordial $D/H$ abundance from observations of $D/H$ in our own galaxy. As we have indicated earlier, the star formation history in our own galaxy may have been very different from that of the typical object which account for the bulk of the observed luminosity density. However, in those systems, we expect that significant amounts of deuterium destruction has occurred.
whatever the primordial D/H ratio may be.

5 Discussion and conclusions

Recent observations of the luminosity density at high redshift (Lilly et al. 1996, Madau et al. 1996, Connolly et al. 1997, Sawicki, Lin, & Yee 1997) are making it possible for the first time to test models of cosmic chemical evolution. Madau et al. (1997) tested several models of cosmic chemical evolution by varying the IMF. Although they found that flatter IMF (those containing more massive stars) were preferred, the luminosity densities were not overly sensitive to the IMF. In this work, we have primarily considered the sensitivity of the high redshift luminosity density to the SFR. We have run the population synthesis code of Bruzual & Charlot (1997) to calculate $L(\lambda, z)$ for a wide variety of SFRs ranging from a constant SFR to ones which are steeply decreasing exponentials in time.

Indeed, the high redshift observations, are very discriminatory with respect to the chosen SFR. Models in which the star formation rate is proportional to the gas mass fraction (these are common place in Galactic chemical evolution) have difficulties to fit the multi-color data from $z = 0$ to 1. This includes many of the successful Galactic infall models. In contrast, models with a SFR proportional to $e^{-t/\tau}$ with $\tau$ between 2 to 4 or to some extent, proportional to $\sigma^2$ are favored. Further consequences of the the adopted histories of star formation could be worked out including a calculation of the brightness of the night sky including the FIR (Guiderdoni et al. 1998).

While we can not conclude that all models with large deuterium destruction factors are favored, it does seem that models which do fit the high redshift data destroy significant amounts of D/H. On the other hand, we can not exclude models which destroy only a small amount of D/H as Galactic models of chemical evolution. In this case, however the evolution of our Galaxy is anomalous with respect to the cosmic average. If the low D/H measurements of Tytler, Fan & Burles (1996) and Burles & Tytler (1996) hold up, then it would seem that our Galaxy also has an anomalously high D/H abundance. That is we would predict in this case that the present cosmic abundance of D/H is significantly lower than the observed ISM value. If the high D/H observations (Songaila et al. 1994, 1997, Carswell et al. 1994, Wampler 1996, Webb et al. 1997) hold up, we would conclude that our Galaxy is indeed representative of the cosmic star formation history.
We note that our detailed results are somewhat dependent on the chosen cosmological model. For example, had we chosen to allow for values of $\Omega_0 < 1$, or a chosen a model with with a cosmological constant, $\Lambda$ consistent with the revised age of the universe and SNIa observations at moderate redshifts (Perlmutter et al. 1997) we could reach somewhat different conclusions. The effect of lowering $\Omega_0$ and $q_0$ was discussed in Lilly et al. (1996).

The leading effect is a lowering of the luminosity density data at high redshift. For example for $\Omega_0 = 0.1$ and $\Omega_\Lambda = 0$, $\Delta \log L = -0.43 \log(1 + z)$, while for $\Omega_0 = 0.1$ and $\Omega_\Lambda = .9$, $\Delta \log L = -1.12 \log(1 + z)$. Such a shift can have dramatic consequences on the comparison of the model prediction and data. This effect led Totani, Yoshii, & Sato (1997) to conclude that the high redshift data indicated a non-zero cosmological model. A similar conclusion would be reached if instead of varying the SFRs and hence the chemical evolution models, we varied the cosmological models. In Figure 8, we show the luminosity density for model 1b, in the context of a $\Omega_0 = 0.1$ and $\Omega_\Lambda = .9$ cosmological model. Now the fit is quite reasonable at the expense of introducing a cosmological constant. Thus, several of the models considered which show only a modest rise in $L$ could be made to better fit the data in this case. While we could certainly state that 1b is compatible with the data for non-zero $\Lambda$, we could not claim evidence for a non-zero $\lambda$ on the basis of this model. This distinction is important. Furthermore, it is difficult to imagine a greater increase in $\Lambda$ relative to the one considered, and so it is unlikely that models 1c or T could be brought into agreement with the high redshift data.

We have demonstrated that the observations of the luminosity density at high redshift is a key discriminator among models of cosmic chemical evolution with different star formation rates. Future observations of this type coupled with measurements of D/H in quasar absorption systems will help us understand not only the average cosmic evolution but also whether or not our own Galaxy is typical of that average.

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References

Carigi, L. 1996, Rev. Mex. A. C., 4, 123
Girardi, L. et al., 1996, A & AS, 117, 113
Vidal-Madjar A., Ferlet R., & Lemoine, M. 1997, in “Structure and Evolution of the Inter-
galactic Medium from QSO Absorption Line Systems”, eds. P. PetitJean, S. Charlot,
Frontiere, p. 355
Figure Captions

Figure 1: A comparison of the various SFR histories considered. Model 1a (from Scully et al. 1997, shown as a dashed curve) has bimodal star formation, the late time behavior of the SFR is proportional to the gas mass; Model 1b (from Scully et al. 1997, shown as a solid curve) is more standard with the SFR also proportional to the mass in gas; Model 1c (from Scully et al. 1997, shown as a dotted curve) has a constant SFR; Model 2 (from Scully et al. 1997, shown as a dot-dashed curve) is a sequential model with a late time behavior given as $\psi(t) \propto \exp(-t/2.5)$; Model M1 (from Madau et al. 1997, shown as a thick solid curve) and Model M2 (also from Madau et al. 1997, shown as a thick dot-dashed curve) were both chosen to fit the high redshift photometric data and both have a late time behavior which is well characterized by an decreasing exponential; Model T (shown as a thin solid curve) is a SFR representative of the infall models compiled in Tosi (1996); Model TWW (from Timmes et al. 1995, shown as a thin solid curve) has a SFR proportional to the square of the gas mass fraction.

Figure 2: The tricolor luminosities densities (UV, B and IR) at $\lambda = 0.28, 0.44, 1.0 \mu m$, in units of $(h/0.5) WHz^{-1} Mpc^{-3}$ as a function of redshift for model 1a. The data are taken from Lilly et al. (1996) (filled squares), Connolly et al. (1997) (open circles), and Sawicki et al. (1997) (open squares).

Figure 3: Same as Figure 2 for model 1b.

Figure 4: Same as Figure 2 for model 1c.

Figure 5: Same as Figure 2 for model T.

Figure 6: Same as Figure 2 for model 2.

Figure 7: Same as Figure 2 for model TWW.

Figure 8: Same as Figure 3 for a cosmological model with $\Omega_0 = 0.1$ and $\Omega_\Lambda = 0.9$. 