*From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution*
*Proceedings IAU Symposium No. 228, 2005*
*V. Hill, P. François & F. Primas, eds.*

doi:10.1017/S1743921305006496

# DLA Systems: their Star Formation History and their Age

**Francesco Calura**[1], **Miroslava Dessauges-Zavadsky**[2] **and Francesca Matteucci**[1]

[1]Dipartimento di Astronomia, Universitá degli studi di Trieste, via G. B. Tiepolo 11-13, 34131 Trieste
email: fcalura@ts.astro.it

[2]Observatoire de Genève, CH-1290 Sauverny, Switzerland

**Abstract.** By means of chemical evolution models for galaxies of different morphological types (i.e. spirals and irregular/starburst galaxies) we study the nature of Damped Lyman-alpha (DLA) systems. By focusing on individual systems, we can derive important constraints on both their star formation history and their age. Our results indicate that the local conterparts of most DLAs are represented by dwarf galaxies having had low star formation rates, but some systems can also be associated to spirals. Some systems are already old, with ages of ∼1 Gyr, and some others are experiencing the very first star formation episodes.

**Keywords.** Galaxies: abundances, galaxies: evolution, galaxies: high-redshift, quasars: absorption lines

## 1. Introduction

Damped Lyman-$\alpha$ (DLA) systems are the quasar absorbers characterized by the highest neutral H column density values ($N(HI) \geqslant 2{\cdot}10^{20} cm^{-2}$). This feature makes DLA the ideal benchmarks to study metal abundances at high redshift, since it allows us to derive very accurate abundance determinations for many chemical species (e.g. SiII, FeII, ZnII). In general, their metallicities can span from ∼1/100 up to ∼1/3 of the solar value, with a weak evolution of their mass-weighted average metallicity across cosmic time (Kulkarni *et al.* 2005). Owing to their large gas content and to their undersolar metallicities, DLAs are believed to represent the progenitors of the gas-rich present-day galaxies, such as irregulars and spirals. In this paper, by means of detailed chemical evolution models for spiral and irregular galaxies (Calura, Matteucci & Vladilo 2003) and by means of very accurate abundance determinations in single DLAs (Dessauges-Zavadsky *et al.* 2004), we aim at inferring crucial information on the nature of these systems. Starting from the study of their abundance ratios, we will show how it is possible to infer their star formation histories and their ages.

In chemical evolution models absolute abundances usually depend on all the model assumptions, whereas the abundance ratios depend only on nucleosynthesis, stellar lifetimes and initial mass function (IMF). Abundance ratios can therefore be used as cosmic clocks if they involve two elements formed on quite different timescales, typical examples being [$\alpha$/Fe] and [N/$\alpha$] ratios. The $\alpha$ elements O, Ne, Mg, Si, Ca, produced on short timescales by type II supernovae (SNe). These ratios, when examined together with [Fe/H], or any other metallicity tracer such as [Zn/H], allow us to clarify the particular history of star formation involved, as shown by Matteucci (2001). In a regime of high star formation rate we expect to observe overabundances of $\alpha$-elements for a large interval of [Fe/H], whereas the contrary is expected for a regime of low star formation. This is due to the different roles played by the supernovae (SNe) of type II relative to the SNe of type Ia. These latter, in fact, are believed to be responsible for the bulk of Fe and Fe-peak element production and occur on much longer timescales than SNe II. For this reason, the analysis of the relative abundances can enable us to have important hints on the nature and age of the (proto-) galaxies which give rise to DLA systems.

## 2. The chemical evolution models

A chemical evolution model allows one to calculate in detail the evolution of the abundances of several chemical species, starting from the matter reprocessed by the stars and restored into the ISM through stellar winds and supernova explosions. The model for a typical spiral galaxy is calibrated on the chemical features of the Milky-Way (MW). The galaxy is assumed to form as a result of two main infall episodes (Chiappini *et al.* 1997, 2001). During the first episode the halo forms and the gas shed by the halo rapidly gathers in the center leading to the formation of the bulge. During the second episode, a slower infall of external gas gives rise to the disk with the gas accumulating faster in the inner than in the outer region ("inside-out" scenario, Matteucci & François, 1989). Dwarf irregular galaxies are assumed to form owing to a continuous infall of pristine gas, until a mass of $\sim 10^9 M_\odot$ is accumulated. The star formation (SF) regimes investigated in this case are two: a regime of continuous SF and a starburst one.

The most general equation governing a chemical evolution model is the following:

$$\dot{G}_i = -\psi(t)X_i(t) + R_i(t) + (\dot{G}_i)_{inf} - (\dot{G}_i)_{out} \tag{2.1}$$

$G_i(t) = M_g(t)X_i(t)/M_{tot}$ is the gas mass in the form of an element $i$ normalized to a total initial mass $M_{tot}$. $M_{gas}$ and $M_{tot}$ are substituted by $\sigma_{gas}$ and $\sigma_{tot}$ in the case of galaxy disks. The quantity $X_i(t) = G_i(t)/G(t)$ represents the fractional abundance by mass of an element $i$, with the summation over all elements in the gas mixture being equal to unity. $G(t) = M_g(t)/M_{tot}$ is the total fractional mass of gas present in the galaxy at the time t.

$\psi(t)$ is the star formation rate (SFR), the fractional amount of gas turning into stars per unit time. $R_i(t)$ represents the returned fraction of matter in the form of an element $i$ that the stars eject into the ISM through stellar winds and supernova explosions; this term contains all the prescriptions regarding the stellar yields and the SN progenitor models. The two terms $(\dot{G}_i)_{inf}$ and $(\dot{G}_i)_{out}$ account for the infall of external gas and for galactic winds, respectively.

In general, the SFR $\psi(t)$ (in $Gyr^{-1}$) is given by:

$$\psi(t) = \epsilon G(t) \tag{2.2}$$

The quantity $\epsilon$ is the efficiency of SF, namely the inverse of the typical time scale for SF.

The nucleosynthesis prescriptions are common to all the models and include: the yields of Nomoto *et al.* (1997a) for massive stars (M $> 8M_\odot$). For low and intermediate mass stars ($0.8 \leqslant M/M_\odot \leqslant 8$), we use the yields of van den Hoeck & Groenewegen (1997), but we also investigate the effects of the rotation in low metallicity stars, for which Meynet & Maeder (2002) have calculated yields for N, C, O. The yields for type Ia SNe are from Nomoto *et al.* (1997b). For the evolution of Zn and Ni we adopt the nucleosynthesis prescriptions of Matteucci *et al.* (1993). In the metallicity range interested by DLAs ($-2 \leqslant [Zn/H]$), Zn behaves like Fe, i.e. with its bulk being produced by type Ia SNe. This assumption is in agreement with the recent results of François *et al.* (2004).

We assume a Salpeter (1955) initial mass function (IMF) for irregular/starburst galaxies, and a Scalo (1986) IMF for spirals. We assume that this quantity is constant in time.

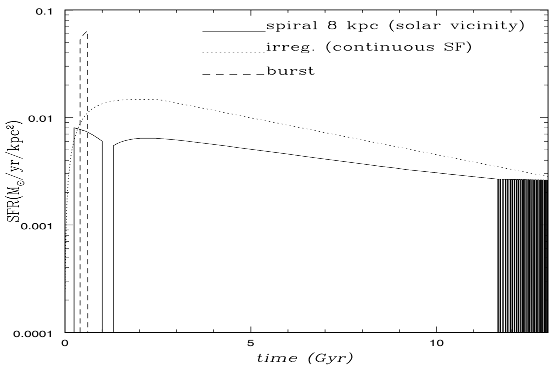


**Figure 1.** Star formation rates as a function of time for the three chemical evolution models used in this work: a spiral galaxy (solid line), an irregular with continuous SF (dotted line) and a starburst (dashed line).

When comparing the spiral model with our observations of DLA systems, we run a set of models each of them corresponding to a different galactocentric radius R. This radius represents the position at which the QSO line of sight crosses the disk of the observed DLA galaxy. This model is calibrated on the Milky Way galaxy and has no free parameter, since every parameter is tuned in order to reproduce the constraints provided by the present day features of our Galaxy (Chiappini *et al.* 2001).

For the comparison of the dwarf irregular or starburst model with our observations of DLA systems, we assume that these high redshift galaxies have undergone a *single* burst of SF. In this case, the free parameters are 2: the burst SF efficiency $\epsilon$ and the burst duration $\Delta t$.

## 3. Results

In figure 1, we show the time evolution of the SFR for a spiral galaxy (solid line), an irregular galaxy with continuous SF (dotted line) and a starburst (dashed line). This figure is useful to understand the three different kinds of SF regimes used to model DLAs. In this figure, the SFRs are expressed per unit area, hence the irregular model presents higher values, being more compact (for the radius, we assume a value $R = 1kpc$). In the curve for the spiral, the first peak is due to the first infall forming the halo and the thick disk, whereas the thin disk forms later and slowly. The discontinuities present at $t > 12$ Gyrs are due to the fact that we have assumed a threshold for the SF in spiral galaxies, in agreement with Chiappini *et al.* (2001).

The line for an irregular with continuous SF presents a smooth behaviour throughout the whole history of the galaxy. Finally, we show the SFR of a starburst lasting 0.2 Gyr, a model which has turned out to well represent the SF history (SFH) of some DLAs (Dessauges-Zavadsky *et al.* 2004).

To infer the SFH of a DLA, we focus on its measured abundance ratios and we study them as a function of the metallicity, which may be represented by the absolute abundance of various elements (Fe, Zn, Si, S). The absolute abundances depend on the assumed SFR, whereas the relative abundances depend mainly on the nucleosynthesis and on the stellar lifetimes. As a consequence, when analyzed together with the absolute abundances, the abundance ratios can help us to constrain the SFH of a given system. On the other hand, when these abundance ratios are examined as a function of the

https://doi.org/10.1017/S1743921305006496 Published online by Cambridge University Press

redshift, they provide constraints on the age of a galaxy, defined as the epoch at which the galaxy has started to form stars.

This method has already been successfully applied to infer the SFHs and ages of three DLAs (see Dessauges-Zavadsky *et al.* 2004). At the present time, we are expanding our sample analyzing other systems, in order to improve our statistics and to study the contribution of the DLA population to the global SF history of the universe. In figures 2 and 3 we show an example of the application of our analysis.

In figure 2, we show the observed and predicted abundance ratios versus metallicity for the DLA observed at redshift $z_{abs} = 1.86$ towards Q2230+02. The black squares with error bars represent the observed values. In the cases of refractory elements, we have corrected the observed values for dust depletion assuming the corrections by Vladilo (2002). The large symbols with error bars represent the dust-corrected observed values. In each panel, the three curves represent the models for a spiral galaxy calculated at a galactocentric distance of 16 kpc (solid lines), a starburst (dotted lines) and an irregular with continuous SF (dashed lines). To determine which model best reproduces the abundance ratios, we use a statistical method, consisting in calculating for each model the minimal distance between the data point and the curve. Once the minimal distances for all the abundance ratios are derived, we compute their weighted mean, where the weights are represented by the $1\sigma$ errors. The model providing the lowest weighted mean minimal distance is the best one. To this purpose, we have taken into accout only the measures and not the upper/lower limits. In this case, according to the statistical test, the best fit is obtained with the irregular model. Once we have determined the most likely model representing the DLA, we can constrain its age from the analysis of the abundance ratios as a function of the redshift. To transform cosmic time into redshift, we adopt a cosmology characterized by $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$. In a way similar to that describe above, we start from the best model and choose different values for the redshift $z_f$ at which stars start to form. By means of the statistical method described above, we can derive which value of $z_f$ provides the best fit. In figure 3, we show the observed and predicted abundance ratios versus redshift for the DLA towards Q2230+02. The predictions are for the best model, an irregular with continuous SF, assuming two different redshifts of formation: $z_f = 6$ (solid lines) and $z_f = 20$ (dotted lines). In this case, the statistical test has indicated a redshift of formation between $z_f = 10$ and $z_f = 20$, corresponding to an age between 3.2 and 3.5 Gyr.

At the present time, the same kind of analysis as described above has been applied to study 8 systems. In figure 4 we show the global picture obtained so far, concerning the ages (left panel) and the SFRs (right panel) of these 8 DLAs (Dessauges-Zavadsky *et al.*, in prep.). In the left panel, the solid circles represent the age values obtained by means of our analysis. DLAs may be very young galaxies, with ages between 50–250 Myr, but also old systems with ages >1 Gyr (Dessauges-Zavadsky *et al.* 2005). In the left panel of figure 4, for purposes of comparison with our data, we show also age determinations obtained by other authors with different techniques, such as integrated spectra (stars, Bruzual 2002). The empty square is the estimated age for the Lyman break galaxy (LBG) MS1512-cB58 by Pettini *et al.* (2000). In the right panel of figure 4, we show our SFR determinations for the set of DLAs considered here (solid circles). The values derived by means of our method span between $6.3 \cdot 10^{-4} M_\odot yr^{-1} kpc^{-2}$ and $4 \cdot 10^{-2} M_\odot yr^{-1} kpc^{-2}$, in good agreement with the determinations by Wolfe, Prochaska & Gawiser (2003), obtained with a completely different method (dotted area in figure 4, right panel). It is interesting to note how the SFRs in DLAs appear much lower than the values obtained for active star forming galaxies observed at high redshift by Savaglio *et al.* (2004, dashed area) and

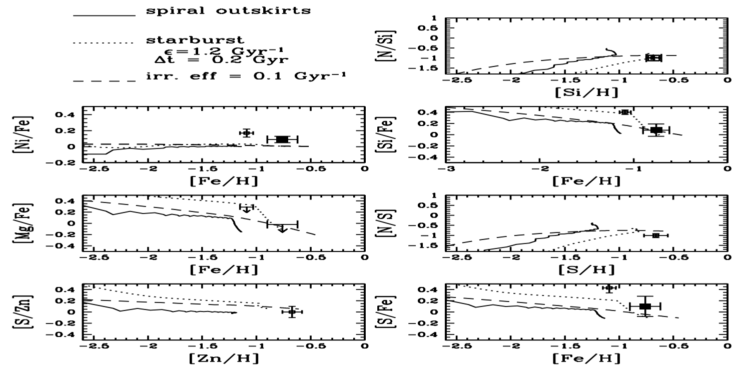


**Figure 2.** Predicted and observed abundance ratios vs metallicity for DLA towards Q2230+02 observed at redshift $z = 1.86$. Small squares and arrows: uncorrected data. Large squares and arrows: data corrected for dust-depletion according to Vladilo (2002). The solid, dotted and dashed lines represent the predictions for the spiral, starburst and irregular with continuous SF models, respectively.

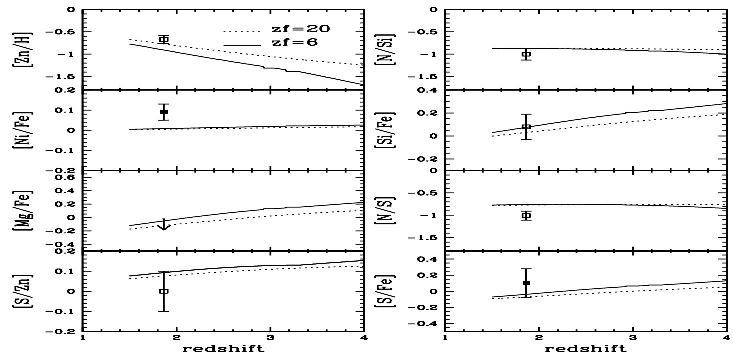


**Figure 3.** Observed and predicted abundance ratios versus redshift for the DLA towards Q2230+02. Here we show predictions for the best model, an irregular with continuous SF, assuming two different redshifts of formation: $z_f = 6$ (solid lines) and $z_f = 20$ (dotted lines).

the LBG (empty square). The solid triangles are SFRs in DLAs measured directly from the emission lines (see Dessauges *et al.* 2005 and references therein).

## 4. Conclusions

By means of chemical evolution models for spiral, dwarf starburst and dwarf irregular galaxies, we have studied the abundance ratios measured in single DLA systems. The study of the abundance ratios versus metallicity and redshift turned out to be very useful to constrain the star formation history and the age of a given DLA, respectively. Our results indicate that some abundance patterns observed in DLAs, in particular the ones characterized by solar $[\alpha/Fe]$ values, can be compatible with the star formation histories typical of the external regions ($R > 8kpc$) of spiral disks and of the dwarf irregular galaxies, presenting a continuous and low star formation rate. On the other hand, some $\alpha$-enhanced sytems can be associated to galaxies observed during (or immediately after) a starburst episode (Dessauges-zavadsky *et al.* 2004, Dessauges-Zavadsky *et al.*, in preparation). The derived ages for the DLAs can span throughout a wide range, from 50 Myr

https://doi.org/10.1017/S1743921305006496 Published online by Cambridge University Press

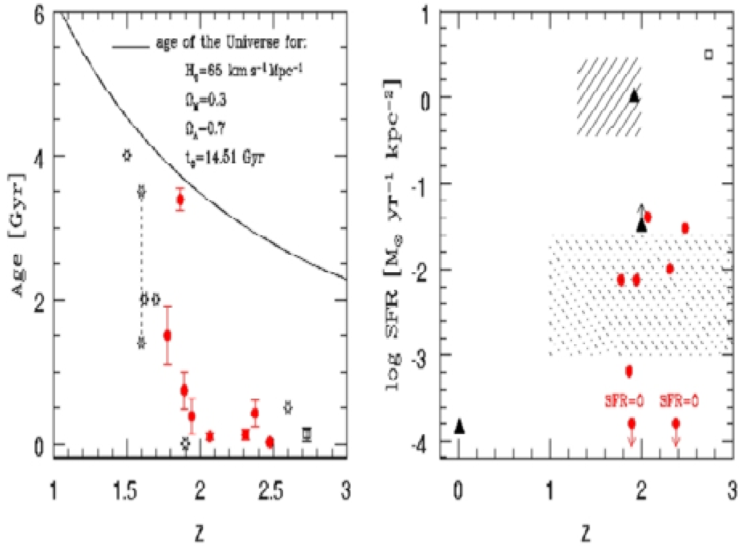


**Figure 4.** Left panel: age vs. redshift for the DLAs studied here (solid circles) and compared to results by other authors with different methods (see text for details). Right panel: SFR versus redshift for our DLA sample (solid circles) compared to values obtained by other authors (see text for details).

to several Gyrs. The determined star formation rates are compatible with the values obtained for DLAs by other authors with different techniques, and are several order of magnitudes lower than the values observed in actively star forming galaxies observed at high redshift and LBGs. These objects are rather young ellitptical galaxies in formation (see for example Matteucci & Pipino 2002). This suggests that DLAs are likely to play a negligible role in the cosmic star formation and metal production history. The bulk of the metals are produced in spheroids and in the innermost regions of spirals, both of which are missing from current DLA samples.

## References

Calura F., Matteucci F., & Vladilo G., 2003, *MNRAS*, 340, 59

Chiappini, C., Matteucci, F., & Gratton, R. 1997, *ApJ*, 477, 765

Chiappini, C., Matteucci, F., & Romano, D., 2001, *ApJ*, 554,1044

Dessauges-Zavadsky, M., Calura, F., Prochaska, J. X., D'Odorico, S., & Matteucci, F., 2004, *A&A*, 416, 79

Dessauges-Zavadsky, M., Prochaska, J. X., D'Odorico, S., Calura, F., & Matteucci, F., 2005, in *Probing Galaxies through Quasar Absorption Lines*, IAU Colloquium 199, (P. R. Williams, C. Shu, and B. Ménard, eds.), in press

Kulkarni V., *et al.*, 2005, *ApJ*, 618, 68

Matteucci, F. & François, P., 1989, *MNRAS*, 239, 885

Matteucci, F., 2001, *The chemical evolution of the Galaxy*, Astrophysics and space science library, Volume 253, Dordrecht: Kluwer AcademicPublishers

Meynet, G. & Maeder, A., 2002, *A&A*, 381, L25

Nomoto, K., Hashimoto, M., Tsujimoto, T., Thielemann, F. K., Kishimoto, N., Kubo, Y., & Nakasato, N., 1997a, *Nucl. Phys. A*, 616, 79

Nomoto, K., Iwamoto, K., Nakasato, N. T., *et al.*, 1997b, *Nucl. Phys. A*, 621, 467c

Pettini, M., Steidel, C. C., Adelberger, K. L., Dickinson, M., & Giavalisco, M., 2000, *ApJ*, 528, 96

van den Hoeck, L. B. & Groenwegen, M. A. T. 1997, *A&AS*, 123, 305

Vladilo, G., 2002a, *A&A*, 391, 407

https://doi.org/10.1017/S1743921305006496 Published online by Cambridge University Press