Chemical evolution of damped Lyα systems

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Abstract. High redshift DLA systems suggest that the relative abundances of elements might be roughly solar, although with absolute abundances of more than two orders of magnitude below solar. The result comes from observations of the [SII/ZnII] ratio, which is a reliable diagnostic of the true abundance, and from DLA absorbers with small dust depletion and negligible HII contamination. In particular, in two DLA systems nitrogen is detected and at remarkably high levels (Vladilo et al. 1995, Molaro et al. 1996, Green et al. 1995, Kulkarni et al. 1996). Here we compare the predictions from chemical evolution models of galaxies of different morphological type with the abundances and abundance ratios derived for such systems. We conclude that solar ratios and relatively high nitrogen abundances can be obtained in the framework of a chemical evolution model assuming short but intense bursts of star formation, which in turn trigger enriched galactic winds, and a primary origin for nitrogen in massive stars. Such a model is the most successful in describing the chemical abundances of dwarf irregular galaxies and in particular of the peculiar galaxy IZw18. Thus, solar ratios at very low absolute abundances, if confirmed, seem to favour dwarf galaxies rather than spirals as the progenitors of at least some of the DLA systems.

Key words: galaxies: abundances – galaxies: evolution – Galaxy: halo – cosmology: observations

1. Introduction

Absorption line systems detected in the spectra of Quasi Stellar Objects (QSO) originate in intervening galaxies or protogalaxies. Among the different classes of absorbers, the damped Lyman α systems (DLA) are those characterized by N(HI) $\geq 10^{20}$ cm^{-2} and by showing many low ionization species such as FeII, SiII, CrII, ZnII and OI, which are in their dominant ionization stage for a HI region. The high accuracy in the hydrogen column density determination derived from the damped wings and

the absence of significant ionization corrections allow accurate absolute abundance determinations of the gas phase elements. Since DLA systems are observable up to the highest redshift they provide a unique tool for the study of the cosmic chemical history of the early universe. Such observations are complementary to the Hubble Deep Field ones (Mobasher et al. 1997) which show that high redshift galaxies have a large variety of morphological types including many peculiar objects with traces of interaction and merging: interestingly, a large fraction are starburst galaxies, as suggested by their colors.

The relative elemental abundances rather than absolute ones are a valuable diagnostic of the first elemental buildup. This is because absolute abundances are affected by all the model assumptions, whereas abundance ratios generally depend only on the assumed nucleosynthesis and stellar lifetimes. The way of using the information contained in abundance ratios is to compare the observed ratios with predictions from chemical evolution models which take into account detailed stellar nucleosynthesis and lifetimes. As in the Milky Way, we hope to distinguish halo-like abundances, produced by type II SNe and characterized by enhancements of α elements with respect to the iron-peak elements, from disk-like abundances, produced by the cumulative effect of both type Ia and type II SNe, where the abundance ratios become progressively solar. The halo abundance pattern follows from the fact that Fe arises mostly from type Ia supernovae with some contribution from type II, while the reverse is true for Si and O. The longer lifetimes of the SNIa, which are believed to have progenitors with masses of 1-8 M$_\odot$, result in a delayed iron enrichment compared to the major SNII products such as α-elements (Tinsley, 1980; Greggio and Renzini, 1983a; Matteucci and Greggio, 1986). Therefore, the behaviour of the [α/Fe] ratios is mainly dependent on the relative lifetimes of type Ia and II supernovae. Another key element is nitrogen and the ratio N/O. This element, in fact, is thought to originate mainly from low and intermediate mass stars and to be a "secondary" element, in the sense that it is produced proportionally to the initial stellar metallicity. As a consequence nitrogen is restored into the interstellar medium with a large temporal delay relative to oxygen, which is produced in massive stars and is a "primary" element, namely its production is independent of the initial stellar metallicity. For this reason, the

α/Fe and N/O ratios can be used as cosmic clocks and represent a clue in understanding the nature of high redshift objects such as QSO (Hamman and Ferland, 1993; Matteucci and Padovani, 1993) and DLA systems (Matteucci, 1995).

The DLA systems are generally believed to be the progenitors of the present-day spiral galaxies (Wolfe et al. 1986). However, it has also been suggested that they could be dwarf galaxies, since they have a large amount of gas, low metallicities and low dust-to-gas ratios (Pettini et al. 1990;Meyer and York 1992; Steidel 1994). Whether DLA are proto-spirals or proto-dwarfs can be indicated by their observed abundance pattern. To this purpose in this paper we will present models of chemical evolution for galaxies of different morphological type and compare them with the observed abundances in DLA.

2. Observed abundances in damped Lyα systems

So far chemical abundances have been measured in a set of DLA systems and with a variety of resolutions and accuracies by Black et al. (1987), Meyer & York (1987), Chaffee et al. (1988), Meyer et al. (1989), Meyer & Roth (1990), Rauch et al. (1990), Pettini et al. (1990), Meyer & York (1992), Pettini et al. (1994), Fan & Tytler (1994), Wolfe et al. (1994), Pettini et al. (1995), Lu et al. (1995a), Steidel et al. (1995), Lu et al (1995b). Here, we would like to focus on the abundances which could be used to compare with chemical evolution models and in particular with the few nitrogen detections so far reported in the literature. A summary of the abundances for the systems for which nitrogen detection or upper limits are available are reported in Table 1 and 2. All the original abundances have been renormalized to the solar abundances of Anders & Grevesse (1989), with the exception of $\log(Fe/H)_\odot = -4.52$ taken from Hannaford et al. (1992) ([M/H] $\equiv \log$(M/H)-$\log$(M/H)$_\odot$). The abundances in the Tables are derived from column density ratios of different atomic and ionic species in the gas phase, and can be translated to elemental abundances only if ionization effects and dust depletion are negligible or can be accounted for. In the following we discuss shortly these two effects.

2.1. Ionization corrections and dust depletions

The neutral hydrogen in the DLA is optically thick to the ionizing radiation either from the intergalactic background or from starlight inside the DLA, and the abundances derived from species that have ionization potentials in excess of 13.6 eV do not require ionization corrections. This is the case of abundances derived from NI, OI, AlII, SiII and FeII, which are dominant ionization stages in the HI gas in our own Galaxy. Detailed ionization models for intergalactig radiation field at high redshift explored by Lu et al (1995) and Fan and Tytler (1994) show that ionization corrections are indeed minimal for systems with log N(HI)> 20.

Another effect which could affect the abundance determinations is the presence of HII regions within the DLA intercepted by the line of sight (Steigman et al 1975). These regions of warm ($T \simeq 10^4$ K) ionized gas would contribute to the column densities of singly ionized species, such as FeII, SiII and AlII, but not to the HI column density. In the interstellar gas of our Galaxy the column density contribution of HII regions is generally negligible when the HI column density is as high as it is in DLA systems (N(HI) $\gtrsim 10^{20}$ cm^{-2}). If HII regions were more important in DLA than in our Galaxy they would produce different line profiles between neutral and ionized lines, when observed at high resolution. This effect is not observed in the DLA towards QSO 0000-2169 where the b values, velocities and profiles of singly ionized species are the same as those of the neutral species, suggesting that both form in the same slab of HI material. Extra contributions to the absorption from HII regions in this DLA are also constrained by the lack of detection of NII, resulting in NII/NI < 0.4. Viceversa, Green et al. (1995) interpret the abundances of the DLA towards MC3 1331+170 invoking an extraordinary amount of ionized gas, namely six times the neutral gas, which makes rather uncertain the abundances of ionized species.

Highly ionized gas in the form of SiIV and CIV is frequently observed in the DLA. Sometimes the highly ionized gas is found at the same velocities of the neutral one but often is found at different velocities and therefore is very probable that highly ionized gas arises either in regions disconnected from the neutral material, or in the interfaces between neutral material and the intergalactic medium.

Presence of dust will selectively deplete the elements observed in the gas phase. In the dense clouds in the Galaxy the interstellar depletion of Al and Fe can reach $\simeq 2$ dex, that of Si ≈ 1 dex, while, on the other extreme the O depletion is ≤ 0.4 dex, that of N ≤ 0.2 dex and S essentially undepleted (Jenkins 1987). Reddening measurements of QSO with DLA systems suggest a dust-to-gas ratio in the DLA of about 10% of that in our Galaxy (Fall and Pei 1989). In the survey of ZnII and CrII in DLA by Pettini et al. (1994) chromium is typically one dex below zinc, while in the Galaxy is about two dex, showing the presence of dust and a reduced dust depletion in the DLA systems. If some dust were present this would alter the abundance determinations of refractory elements, such as Fe, Si and Al. Much more reliable are the abundances of the non-refractory elements, such as Zn, S, O and N.

2.2. α versus iron-peak elements

Of particular importance for understanding galactic chemical evolution is the comparison between α and iron peak elements. In particular, the ratio between sulphur and zinc is an important diagnostic tool. Both elements show little affinity with dust and their ratio is also safe against possible contributions from HII regions, since these essentially cancel out. Considering that S and Zn have different nucleosynthetic origin with S mainly a product of type II SN and Zn of type Ia SN (Matteucci et al. 1993), the [SII/ZnII] ratio is an ideal diagnostic for understanding the character of the chemical evolution. So far, only few determinations of [S/Zn] ratio in DLA are present in the literature. Meyer et al. (1989) found [S/Zn]=−0.1 in the DLA at $z = 2.8$ towards QSO PKS 0528-250 and Green et al. (1995)

Table 1. Hydrogen column densities and elemental abundances in DLA systems with NI measured. Original abundances have been renormalized to the solar values log (N/H)$_\odot$ = −3.95, log (O/H)$_\odot$ = −3.07, log (Si/H)$_\odot$ = −4.45, log (S/H)$_\odot$ = −4.73, taken from Anders & Grevesse (1989), and log (Fe/H)$_\odot$ = −4.52 from Hannaford et al. (1992).

QSO	z_{abs}	N(HI)	[N/H]	[O/H]	[Si/H]	[S/H]	[Fe/H]	Refs.
0000-26	3.3901	21.30	$-2.77^{+0.17}_{-0.17}$	$-3.13^{+0.17}_{-0.17}$	$-2.48^{+0.19}_{-0.19}$	—	$-2.38^{+0.16}_{-0.16}$	1
1331+1700	1.7765	21.18	$-2.73^{+0.11}_{-0.11}$	$-2.81^{+0.21}_{-0.30}$	—	$-1.35^{+0.11}_{-0.11}$	$-2.25^{+0.11}_{-0.12}$	2[a]
2348-147	2.2794	20.57	< -3.15	$-2.13^{+2.26}_{-0.58}$	$-1.97^{+0.13}_{-0.10}$	$-1.91^{+0.14}_{-0.16}$	$-2.35^{+0.22}_{-0.10}$	3
2344+124	2.5379	20.43	$-3.00^{+0.12\ b}_{-0.22}$	$-2.11^{+2.5}_{-0.36}$	$-1.72^{+0.27}_{-0.13}$	< -1.20	-1.85^{c}	4
1946+7658	2.8443	20.30	$< -3.26^{\ d}$	$-2.65^{+0.15}_{-0.15}$	$-2.16^{+0.10}_{-0.10}$	< -0.89	$-2.41^{+0.10}_{-0.10}$	5[e]

References for Table 1
(1) Molaro et al. (1995) ; (2) Green et al. (1995) ; (3) Pettini et al.(1995);
(4) Lipman, thesis (1995) ; (5) Lu et al. (1995a)

a: Hydrogen column density from Pettini et al. (1994); metal abundance error bars include propagation of the N(HI) error.
b: Nitrogen value derived by using only the main absorption component of the system.
c: Error bar not reported by the author.
d: Upper limit from Lipman (1995; thesis).
e: Column densities from line profile fitting where all the lines are fitted simultaneously; the final choice of Lu et al (1995a) for O is [O/H]> -2.99; metal abundance error bars include propagation of the N(HI) error.

Table 2. Element to element abundances for the DLA systems listed in Table 1.

QSO	z_{abs}	[N/O]	[N/Si]	[N/S]	[Si/O]	[S/O]	[O/Fe]	[Si/Fe]
0000-26	3.3901	+0.36	−0.29	—	+0.65	—	−0.75	−0.10
1331+1700	1.7765	+0.08	—	−1.38	—	+1.46	−0.56	—
2348-147	2.2794	< -1.02	< -1.18	< -1.24	+0.16	+0.22	+0.22	+0.38
2344+124 [a]	2.5379	−0.59	−1.14	> -1.32	+0.55	$< +0.73$	−0.59	+0.13
1946+7658	2.8443	< -0.61	< -1.10	—	+0.49	$< +1.76$	−0.24	+0.25

a Values derived by using only the main absorption component

found [S/Zn] = +0.1 in the z=1.775 DLA in Q1331. Thus, in spite of the very poor metallicity of the gas, which in these systems is $\simeq$ -2.0, the ratios of elements non depleted in dust have solar values.

In DLA systems the relative abundances of Si and Fe are often found to be consistent with a halo pattern. Lu et al. (1995a) found [Si/Fe]=+0.31 for the DLA at z = 2.844 towards HS 1946=76 and Pettini et al. found [Si/Fe]=+0.4 for the DLA at z = 2.27 towards QSO 2348-147. However, Si and Fe are dif-

ferentially depleted from gas to dust in our Galaxy. The average value in the compilation of 11 clouds observed with HST made by Lu et al (1995a, their Table 8) is [Si/Fe]=+0.66±0.26. The observed enhancement of Si versus Fe in the DLA would reflect the overabundances of α elements with respect to the iron-peak elements only in complete absence of dust. Since DLA show some amount of dust, a moderate enhancement of Si over Fe cannot be considered as a clear-cut evidence of a halo-like pattern. Moreover, values of [Si/Fe]≥0.6, that would be expected if

differential depletion and intrinsic α enhancement are present, have not yet been observed.

2.3. Nitrogen and oxygen abundances

Nitrogen has been detected in the DLA at z=3.39 towards QSO 0000-26, with [N/H] = −2.77 ±0.17 (Vladilo et al. 1995 and Molaro et al. 1995) and in the DLA at z=1.78 towards MC3 1331+170 with [N/H]=-2.7 (Green et al. 1995). A significant upper limit has been derived by Pettini et al. (1995) in the DLA systems towards QSO 2348-147 NI<-3.15. By means of co-addition technique of the lines of the 1200 Å triplet Lipman (1995) achieved a marginal detection of NI for the main component of the DLA towards QSO 2344+124. By using the data published by Fan and Tytler (1994), Lipman derived also an upper limit of [N/H] < -3.26. These measurements show that a real dispersion in the nitrogen abundances may be present among the DLAs.

In order to understand the nucleosynthetic origin of nitrogen the ideal would be to follow its abundance with respect to that of oxygen. Unfortunately, oxygen abundance is generally given with a large uncertainty. This is because oxygen abundance is derived from the OI 1302.1685 Å line which has log gf=1.804 and is generally saturated. The other line OI 1355.5977, has log gf=-2.772 and is generally too faint to place useful upper limits. The line saturation leaves the line broadening poorly constrained and leads to the large uncertainty in the oxygen abundance. However, the b value can be inferred from other lines under the assumption that they are formed in the same material and that the origin of broadening is not thermal. Lu et al. (1995a) and Molaro et al. (1995) use the b value from the other observed species thus removing the large uncertainty in the oxygen abundance (cfr. Table 1). In Molaro et al. (1996). The broadening value is taken not only from ionized species, which might be sensitive to extra contribution from HII gas along the line of sight, but also from NI which is forming in the same material as neutral oxygen. It is rather striking that in the cases with oxygen abundances with small associated errors, oxygen turns out to be remarkably deficient relatively to the other elements measured, such as Si, S and Fe as it is possible to see in Table 2.

To circumvent the problem of oxygen uncertainty, Pettini et al. (1995) and Lipman (1995) take Si or S as a proxy for oxygen assuming [O/Si] = [O/S]=0. This assumption is about true for the halo stars of our own Galaxy (however see later for silicon), but is rather risky for primeval galaxies which might have experienced a different chemical evolution from that of our own Galaxy. In particular, Si and O do not have the same nucleosynthetic origin, silicon may be affected by dust depletion and SII and SiII may be also affected by HII contribution. Also by adopting the Pettini et al. approach for the case of QSO 0000-2169 we have [N/Si] = −0.3, which stands genuinely high when compared to the other determinations.

3. What chemical evolution?

Some DLA seem to show similarities to dwarf irregular and blue compact galaxies in terms of abundance pattern. These galaxies, in fact, exhibit relatively high N/O, although with a large spread, at a low overall metallicity Z ranging from 1/10 to 1/30 of the solar value (see Matteucci, 1995). In particular, IZw18 is the galaxy with the lowest metal content known locally, and a N/O ratio roughly solar. Recently, a single starburst chemical evolution model has been successfully developed by Kunth et al. (1995) to reproduce the observed abundances of IZw 18. Kunth et al. (1995) applied Marconi's et al. (1994) model where star formation is assumed to proceed in short but intense bursts. The contribution to the chemical enrichment of SNe of different type (II, Ia and Ib) is taken into account. The novel feature is the introduction of differential galactic winds where some elements are preferentially lost from the galaxy relative to others. Recently, more and more observational evidence is growing about the existence of such galactic winds in dwarf irregulars as provided by Meurer et al. (1992), Lequeux et al. (1995) and Papaderos et al. (1994). These winds are found to be a crucial ingredient in the model of Kunth et al. (1995) in order to reproduce the high observed N/O ratio in IZw18. To explain the nitrogen abundance of IZw18 this same model assumes also a primary N production from massive stars, as described in the next section.

In this paper we will show the predictions of models similar to that of Kunth et al. together with the predictions of models for the chemical evolution of the solar region, under different assumptions about the production and nature of nitrogen, and we will compare them with the DLA data.

4. The chemical evolution model for dwarf irregulars

We are using here the same model adopted by Kunth et al. (1995) which is aimed at describing the evolution of IZw18, namely of an object presently having a strong burst of star formation which induces a galactic wind.

The main features of this chemical evolution model are the following:

1) one-zone, with instantaneous and complete mixing of gas inside this zone,

2) no instantaneous recycling approximation; i.e. the stellar lifetimes are taken into account,

3) only one intense burst of star formation is assumed to occur,

4) the evolution of several chemical elements (He, C, N, O, Fe) due to stellar nucleosynthesis, stellar mass ejection, galactic wind powered by SNe and infall of primordial gas, is followed in detail.

If G_i is the fractional mass of the element i, its evolution is given by the equations described in Marconi et al. (1994).

$$\dot{G}_i(t) = -\psi(t)(1 + w_i)X_i(t)+$$

$$\int_{M_L}^{M_{Bm}} \psi(t - \tau_m)Q_{mi}(t - \tau_m)\phi(m)dm+$$

$$A \int_{M_{Bm}}^{M_{BM}} \phi(m) \left[\int_{\mu_{min}}^{0.5} f(\mu)\psi(t-\tau_{m2})Q_{mi}(t-\tau_{m2})d\mu \right] dm +$$

$$(1-A) \int_{M_{Bm}}^{M_{BM}} \psi(t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm +$$

$$\int_{M_{BM}}^{M_U} \psi(t-\tau_m)Q_{mi}(t-\tau_m) + \phi(m)dm + \dot{G}_i(t)_{inf} \quad (1)$$

where $G_i(t)=M_{gas}(t)X_i(t)/M_{tot}(t_G)$ is the mass density of gas in the form of an element i normalized to the total mass at the present time t_G. The quantity $X_i(t) = G_i(t)/G(t)$ represents the abundance by mass of the element i and by definition the summation over all the abundances of the elements present in the gas mixture is equal to unity. The quantity $G(t) = M_{gas}/M_{tot}$ is the total fractionary mass of gas, and M_{tot} refers only to the mass present in the form of gas in the star forming region. The possible presence of a dark matter halo is not considered here, given the simple treatment of the development of a galactic wind, as we will see in the following.

The star formation rate we assume during the burst, $\psi(t)$, is defined as:

$$\psi(t) = -\nu \, \eta(t) \, G(t)$$

where ν is the star formation efficiency (expressed in units of Gyr^{-1}), and represents the inverse of the timescale of star formation, namely the timescale necessary to consume all the gas in the star forming region; $\eta(t)$ takes into account the stochastic nature of the star formation processes as in Gerola et al. (1980) and Matteucci and Tosi (1985), where a detailed description can be found.

The galactic wind is assumed to be simply proportional to the star formation rate (namely to the rate of explosion of type II SNe). This is a reasonable choice since the duration of the burst is so short that it does not allow the explosion of type Ia SNe, which occur all after the burst. The simplicity of the treatment of the galactic wind avoids also the introduction of other unknown parameters such as the efficiency of energy tranfer from stars and supernovae to the ISM. The rate of mass loss via a galactic wind is defined as follows:

$$\dot{G}_{iw}(t) = -w_i \psi(t) X_{iw}(t)$$

where $X_{iw}(t) = X_i(t)$ and w_i is a free parameter containing all the information about the energy released by SNe and the efficiency with which such energy is transformed into gas escape velocity (note that Pilyugin (1992;1993) defines a wind parameter which is the inverse of w_i, namely the ratio of the star formation rate to the wind rate). The value of w_i has been assumed to be different for different elements. In particular, the assumption has been made that only the elements produced by type II SNe (mostly α-elements and some iron) can escape the star-forming regions. We have made this choice following the conclusions of Marconi et al. (1994) and Kunth et al. (1995), who showed that models with differential wind can explain better the observational constraints of blue compact galaxies in general and IZw18 in particular. The justification for the existence of differential galactic winds can be found in the fact that

during short starbursts type II SNe dominate. Since SNII explode in association, they are likely to produce chimneys which will eject metal enriched material (De Young and Gallagher, 1990). On the other hand, type Ia SNe are not likely to trigger a wind since they explode mostly during the interburst phase and have a large range of explosion times (from $3 \cdot 10^7$ to a Hubble time) inducing them to explode in isolation.

The terms on the right side of equation (1) represent, respectively, the rate at which the gas is lost via astration and galactic wind and the rates at which the matter is restored to the interstellar medium (ISM) by:

(a) single stars with masses between $M_L = 1.0 M_\odot$, which is the lowest mass contributing to the galactic enrichment, and $M_{Bm} = 3.0 M_\odot$, which represents the minimum mass for which a binary system (with the minimum mass ratio μ_{min} defined as in Greggio and Renzini 1983b) produces a type Ia SN,

(b) binary systems producing type Ia SNe, within the range of masses $M_{Bm}=3M_\odot$ and $M_{BM}=16M_\odot$ [the assumed progenitors of type Ia SNe are binary systems of C-O white dwarfs(Whelan and Iben, 1973)] the parameter A, defined in Greggio and Renzini (1983b), represents the fraction of binary systems in the IMF which can give rise to type Ia SNe;

(c) single stars in the mass range M_{Bm} - M_{BM} which end their lives either like white dwarfs or type II SNe,

(d) single stars in the mass range M_{BM} and M_U, where M_U is the maximum stellar mass contributing to the galactic enrichment (100 $M_\odot$ in our models). These stars can either end their lives as type II or type Ib SNe.

The initial mass function (IMF) by mass, $\phi(m)$, is expressed as a power law with an exponent x=1.35 over the mass range $0.1 - 100 M_\odot$.

The chemical evolution equations include also an accretion term:

$$\dot{G}_i(t)_{inf} = \frac{(X_i)_{inf} e^{-t/\tau}}{\tau(1 - e^{-t_G/\tau})}$$

where $(X_i)_{inf}$ is the abundance of the element i in the infalling gas, assumed to be primordial, τ is the time scale of mass accretion and t_G is the galactic lifetime. This accretion term may simulate the formation of dwarfs as the result of mergers of smaller subunits. The parameter τ has been assumed to be the same for all blue compact galaxies and short enough to avoid unlikely high infall rates at the present time ($\tau = 0.5 \cdot 10^9$ years). It is worth noting that a shorter timescale would not produce a noticeable effect on the results.

4.1. Nucleosynthesis prescription

The term $Q_{mi}(t - \tau_m)$ in equation (1), the so called *production matrix* (Talbot and Arnett, 1973), represents the fraction of mass ejected by a star of mass m in the form of the element i. The quantity τ_m represents the lifetime of a star of mass m and τ_{m2} refers to the mass of the secondary component and τ_{m1} to the mass of the primary component of a binary system giving

rise to a type Ia SN (see Matteucci and Greggio, 1986 for details). For the nucleosynthesis prescriptions we have assumed the following:

a) For low and intermediate mass stars ($0.8 \leq M/M_\odot \leq M_{up}$) we have used Renzini and Voli's (1981) nucleosynthesis calculations for a value of the mass loss parameter $\eta = 0.33$ (Reimers 1975), and mixing length $\alpha = 1.5$. The standard value for M_{up} is 8 $M_\odot$.

b) For massive stars ($M > 8$ $M_\odot$) we have used Woosley's (1987) nucleosynthesis computations but adopting the relationship between the initial mass M and the He-core mass M_{He}, from Maeder and Meynet (1989). It is worth noting that the adopted $M(M_{He})$ relationship does not substantially differ from the original relationship given by Arnett (1978) and from the new one by Maeder (1992) based on models with overshooting and Z=0.001. These new models show instead a very different behaviour of $M(M_{He})$ for stars more massive than 25 $M_\odot$ and Z=0.02, but the galaxies we are modelling never reach such a high metallicity.

c) For the explosive nucleosynthesis products, we have adopted the prescriptions by Nomoto et al. (1984), model W7, for type Ia SNe, which we assume to originate from C-O white dwarfs in binary systems (see Marconi et al. (1994) for details). More recent nucleosynthesis calculation by Thielemann et al. (1993) do not significantly differ from the Nomoto et al. (1984) ones.

4.2. The nucleosynthesis of nitrogen and the N/O ratio

Nitrogen is a key element to understand the evolution of galaxies with few star forming events since it needs relatively long timescales as well as relatively high underlying metallicity to be produced. The reason is that N is believed to be mostly a product of secondary nucleosynthesis, being produced by CNO processing of ^{12}C or ^{16}O from earlier generations of stars. However, a primary component can be obtained when the seed nuclei of ^{12}C or ^{16}O are produced in earlier helium burning stages of the same star. Generally, N is believed to be secondary in massive stars, and mostly secondary and probably partly primary in low and intermediate mass stars. However, some doubts exist at the moment on the amount of primary nitrogen which can be produced in intermediate mass stars due to the uncertainties related to the occurrence of the third dredge-up in asymptotic giant branch stars (AGB). In fact, if Blöcker and Schoenberner (1991) calculations are correct, the third dredge-up in massive AGB stars should not occur and therefore the amount of primary N produced in AGB stars should be strongly reduced (Renzini, private communication).

The only possible way to produce a reasonable quantity of N during a short burst (no longer than 20 Myr), as discussed in Kunth et al. (1995), is to require that massive stars produce a substantial amount of primary nitrogen. This claim was already made by Matteucci (1986) in order to explain the [N/O] abundances in the solar neighbourhood. Recently, calculations by Woosley and Weaver (private communication) seem to support

Table 3. Model parameters: IMF slope: 1.35 (Salpeter); upper mass limit: 100 $M_\odot$; lower mass limit: 0.1 $M_\odot$

MOD	yields	wind	ν (Gyr^{-1})	N_B	duration (Myrs)
1	STANDARD	80	10	1	50
2	N PRIMARY	700	50	1	20
3	N PRIMARY	80	50	1	20
4	N PRIMARY	700	1000	1	20
5	N PRIMARY	1000	50	1	20
6	N PRIMARY	80	50	4	20
7	N PRIMARY	700	50	4	20

the possibility that N is produced by C and O synthesized inside massive metal poor stars as a primary element. Therefore, as in Kunth et al. (1995) we have taken this possibility into account in the present calculation.

5. Theoretical prescriptions for the evolution of the solar vicinity

The model adopted for the evolution of the solar neighbourhood is the same as in Matteucci and François (1992) and the basic equations are similar to Eq (1), the only difference being the absence of a galactic wind, namely all the $w_i = 0$. The main differences between the model for dwarf irregulars and the model for the solar vicinity is that in the latter case the star formation rate is continuous and the IMF for massive stars is steeper than a Salpeter IMF (i.e. Scalo 1986). The time scale for the formation of the disk in the solar region is also different from the timescale assumed for assembling the dwarf irregulars (i.e. $\tau = 0.5$Gyr), namely is $\tau = 3$ Gyr. This choice ensures that the majority of the observational constraints in the solar neighbourhood are reproduced. The nucleosynthesis prescriptions adopted for the solar neighbourhood are exactly the same as for the dwarfs.

6. Results

Besides Model 1 and 5 of Kunth et al. (1995) (model 1 and 3 respectively, in Table 3), we run several models by varying star formation efficiency and/or wind efficiency, all the other parameters being left the same as in Model 5 of Kunth et al. The model parameters are presented in Table 3. In column 1 are the model numbers and in column 2 the nucleosynthesis prescriptions. In particular, "STANDARD" refers to the prescriptions described in section III, whereas "N PRIMARY" refers to the assumption of primary production of N in massive stars, leaving all the rest unchanged.

In column 3 we show the wind parameter w_i as defined in the previous section. This parameter is different from zero only for the elements produced and dispersed during the explosion of SNe II. The value for this parameter given in Table 3 refers only to the α-elements, which are the main outcome of SN II explosions. In particular, for the elements studied here w_i is zero for H, He and N, whereas is different from zero, but smaller

Table 4. Measured (O/H) and (N/O) column density ratios in DLA systems to be compared with the figures.

QSO	z_{abs}	12+log(O/H)	log(N/O)
0000-26	3.3901	5.80	−0.52
1331+1700	1.7765	6.12	−0.80
2348-147 [a]	2.2794	6.80	< −2.20 [a]
2344+124 [a]	2.5379	6.82	−2.0 [a]
1946+7658 [a]	2.8443	6.28	< −2.0 [a]

(a) Values taken from Lipman (1995).

than for α-elements, for C and Fe. The parameter w_i for these elements is chosen in such a way to account for the fact that Fe and C are produced both in massive and in intermediate mass stars (type Ia SNe and AGB stars, respectively).

In column 4 is shown the star formation efficiency ν (in units of Gyr^{-1}), as defined in the previous section. In column 5 is shown the number of bursts and in column 6 the duration of each burst in Myr. Such a duration is constrained by results of population synthesis models (Mas-Hesse and Kunth, 1991) suggesting a maximum duration for the present burst in IZw18 of 20 Myr. The starting time of the burst is not important for models 1-5 since we assume that it is the only event of star formation and it could happen at any time (i.e. at any redshift). It is worth noting that the assumed range of variation of ν and w_i is quite large but reasonable. In order to reproduce the star formation rate of IZw18 a value of $\nu=50\,Gyr^{-1}$ (note that for the solar neighbourhood $\nu=0.5\,Gyr^{-1}$) is preferred since it predicts a star formation rate of $\simeq 0.03 M_\odot yr^{-1}$, in very good agreement with observational estimates (see Kunth et al., 1995). An efficiency of star formation of $1000\,Gyr^{-1}$ is also plausible for starburst galaxies since it predicts a star formation rate of $\simeq 0.1 M_\odot yr^{-1}$. Such star formation rates are quite reasonable for objects suffering only few bursts of star formation (may be only one) and having a large amount of gas. The wind parameter also spans a quite large range of values and this is possible under the assumption of enriched galactic wind, when only metals are lost. On the other hand, in the case of normal wind the value of w_i is constrained by the condition of not destroying the galaxy. However, it is worth noting that even a totally disruptive wind, could in principle be considered. The initial mass of gas involved in the burst is assumed to be $6 \cdot 10^6 M_\odot$.

The N/O versus O/H distribution is shown in Fig. 1 where the models with only one burst together with the models for the solar neighbourhood are shown. The dot-dashed curve is from model N. 5 from Kunth et al. (1995) (model 3 of table 3) and it can reproduce the observations of IZw 18. Incidentally, we note that this model can fit very well the N/O upper limit by Pettini et al. (1995) but for a burst age shorter than 20 Myr. On the other hand, Pettini's et al.'s point, as well as the other points from Lipman (1995), could be marginally reproduced also by the evolution of a disk galaxy in the earliest phases of
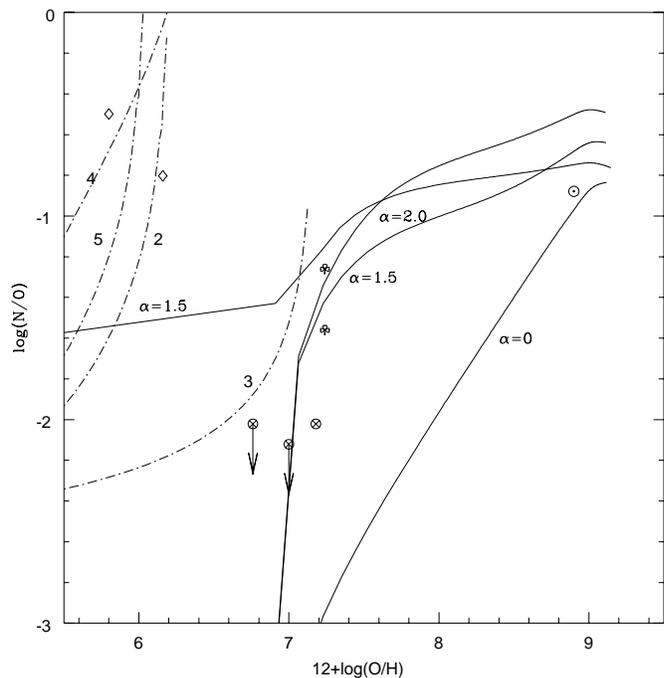

Fig. 1. Log(N/O) vs. 12+log(O/H) as predicted by different models of chemical evolution. In particular, the continuous lines refer to a model for the solar neighbourhood, as described in the text, for different prescriptions concerning the nucleosynthesis of N. The value of the α parameter in Renzini and Voli (1981) is indicated on each curve; $\alpha=0$ means only secondary N in low and intermediate mass stars, $\alpha=1.5$ and 2.0 indicate different amounts of primary N produced during the third dredge-up according to the efficiency of convection. The line with a plateau and labelled $\alpha=1.5$ represents a model where N is assumed to be primary in massive stars (in all the other models is secondary) plus primary N from intermediate mass stars with $\alpha=1.5$. The dash-dotted lines are the predictions of starburst models with only one burst, as described in Table 3. The symbols refer to measurements of N/O and O/H ratios in the sun and in the DLA shown in Table 4. In particular, the romb with the highest N/O is the system observed by Molaro et al. (1996) whereas the other romb is the DLA system observed by Green et al. (1995). The clovers refer to different measurements for IZw18, the one with the highest N/O is from Skillman and Kennicutt (1993), whereas the other is from Dufour et al. (1988). The crossed circles are the DLA systems discussed in Pettini et al. (1995) and Lipman (1995).

its evolution; in particular during the halo phase, as it is shown in the figure.

In fact, the continuous curves in Fig. 1 represent the predictions from the model of chemical evolution of the solar neighbourhood under different assumptions about the nucleosynthesis of N. In particular, the area delimited by those models goes from purely secondary N in stars of all masses (the straight line at the right end) to primary N in massive stars and secondary and primary N in low and intermediate mass stars. On the other hand, the N/O ratios observed by Molaro et al.(1996) and Green et al.(1995) are reproduced by models with a strong starburst and very strong galactic wind (models 4 and 5 in Table 2), so that models for the solar neighbourhood seem to be completely
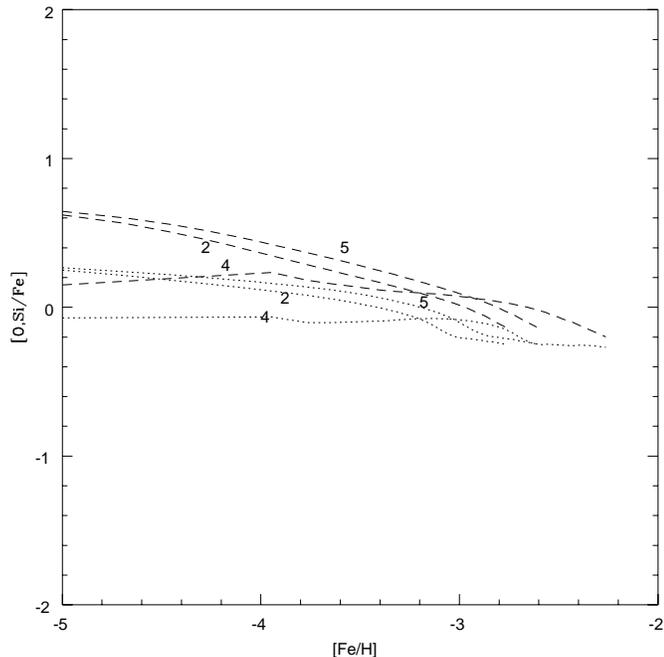
Fig. 2. Predicted and observed [O,Si/Fe] versus [Fe/H]. The long-dashed lines refers to O, whereas the short-dashed lines refers to Si. The model numbers are indicated on each curve.

Fig. 3. The same as Fig. 1 but here are shown only the predictions of models 6 (dashed-dotted line) and 7 (dotted line).

ruled out in explaining these two DLA systems. Thus we show that it is possible to have large N/O ratios even at low O abundances if the nitrogen produced by massive stars, restored on relatively short time scales, is primary and with a strong differential effect in the galactic wind. As shown in Fig. 2 the same model produces solar ratios of alpha-elements (such as S, O and Si) to iron peak elements (such as Fe and Zn), as it is observed at least in few DLA. In particular, in Fig. 2 we show the predictions of the models for O and Si relative to iron to be compared with the data of Table 4. The x-axis does not extend to abundances larger than [Fe/H]=-2.0 since in one-burst models the metallicity does not increase any further. Sulphur is not shown here but it should closely follow oxygen. On the other hand, the predicted [Si/Fe] is lower than [O/Fe] and the reason for this resides in the fact that more Si than O is produced in type Ia SNe (Nomoto et al. 1984; Thielemann et al. 1993) and that we assume the same w_i parameter for Si and O. Studies of abundances in halo stars do not allow us to discriminate clearly on this point (François, 1986; Ryan et al. 1991; Primas et al. 1994; McWilliam et al. 1995). Therefore, it does not seem safe to assume [Si/O]=0 in order to derive oxygen abundances in DLA systems (see Lipman, 1995). However, as indicated in Fig. 2 the observed [O/Fe] is lower than [Si/Fe] for the DLA observed by Molaro et al. (1996). A possible explanation for this is that, in the framework of the differential galactic wind, O, which originates mostly in type II SNe, should be lost from the galaxy in a larger percentage than silicon, which originates also from type Ia SNe. In other words, Si should be treated as we do with C and Fe. H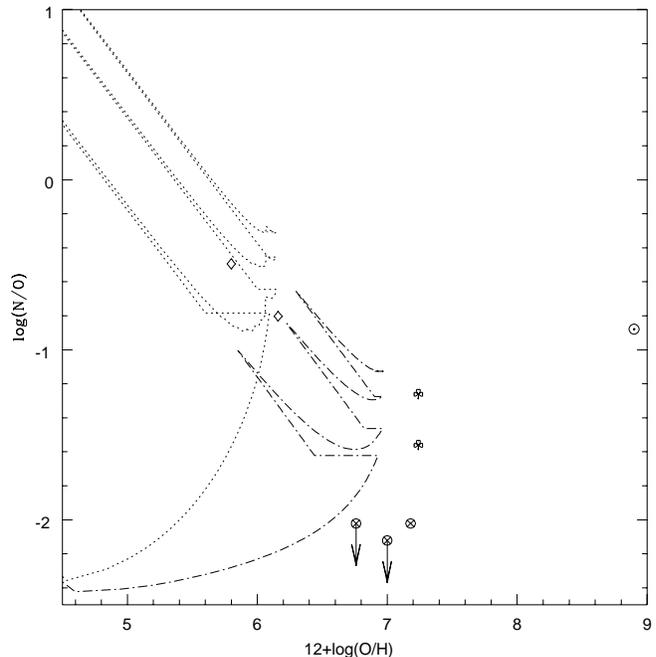owever, numerical experiments show that even in this case is difficult to invert the situation and have [Si/Fe] higher than [O/Fe], as indicated by the data taken at face values!

In Fig. 3 we show the predicted N/O vs. O/H from models with 4 short bursts (20 Myr each) all occurring inside the first Gyr from the start of star formation, so that they can be representative of high redshift objects. In particular, we show the predictions of model 6 and 7 which are similar to model 3 and 2, respectively, but with four bursts of star formation.These models show that in principle the DLA systems from Green et al. (1995) and from Molaro et al. (1996) could be explained by a galaxy like IZw18 experiencing more than one burst of star formation and observed during the interburst period, without invoking an extremely large wind parameter. In fact, during this phase the N/O ratio increases as due to the fact that oxygen is no more produced while N continues to be restored from low and intermediate mass stars. This is a well known effect as shown by Pilyugin (1992;1993).

In Figs. 4 and 5 we show the [O,Si/Fe] ratios predicted by model 6 and 7, respectively. Here too we can see the oscillating behaviour due to the alternating burst and quiescent phases. In particular, in both models the [O,Si/Fe] ratios decrease during the interburst phase and increase again during the bursts. The difference between the two models resides in the efficiency of the wind in model 7, which reflects in a stronger variation of the abundance ratios between the burst and the interburst phases. The reason for this variation in model 7 is that the stronger wind acting during bursts is responsible for very low absolute abundances at the end of each burst, so the increase of Fe during the interburst is stronger relatively to model 6 where the absolute abundances at the end of each burst are higher.
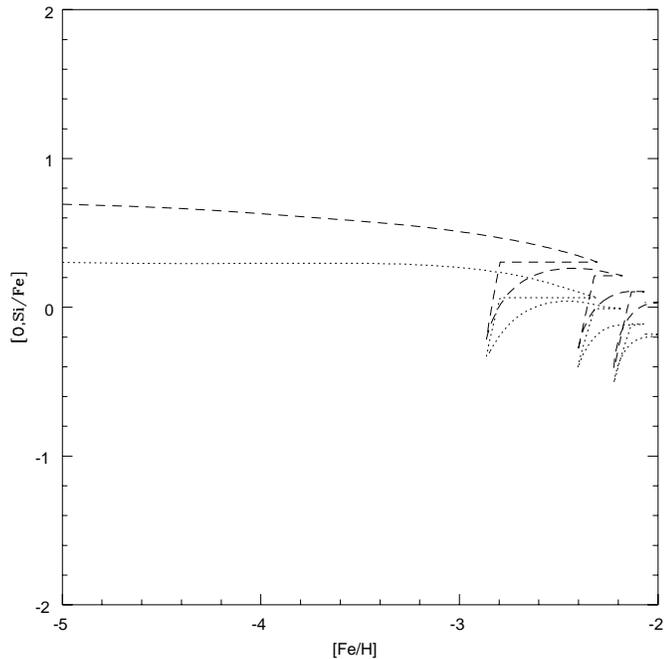
Fig. 4. The same as Fig. 2 but for model 6. The dashed lines refer to O, whereas the dotted lines refer to Si.

Fig. 5. The same as Fig. 2 but for model 7. The dashed lines refer to O, whereas the dotted lines refer to Si.

Finally, it is worth noting that current models for elliptical galaxies (see Matteucci and Padovani, 1993) would never reproduce such the high N/O ratio observed by Molaro et al. (1996) for such low metallicities. In Fig. 1, for example, the predictions of models for an elliptical galaxy of initial luminous mass $10^{11} M_\odot$ would lie at the right side of the solar neighbourhood curve for only secondary nitrogen, and even in the case of primary N from massive stars would be completely outside of the metallicity region where the DLA systems are observed.

7. Conclusions

The abundance pattern of non refractory elements in some primeval DLA systems at high redshift seems not to follow the pattern observed in the halo of the Milky Way. This suggests that these objects had a different chemical evolution than the Milky Way and the spirals in general, at variance with the general belief that DLA are the progenitors of present day spirals. We have shown that the most promising models to explain the observed abundances are those succesfully applied to the dwarf irregular galaxies such as IZw18 (Marconi et al. 1994, Kunth et al. 1995). The conclusion about these DLA systems being dwarf galaxies has also been independently suggested by Meyer and York (1992) and by Steidel et al. (1994) from the low abundances found in the few DLA observed at low redshifts.

In summary, our conclusions are:

- In order to explain the high N/O ratios observed in two DLA systems by Green et al.(1995) and Molaro et al.(1996) one has to assume that these systems are dwarf irregular galaxies experiencing their first or one of their first bursts of star formation.
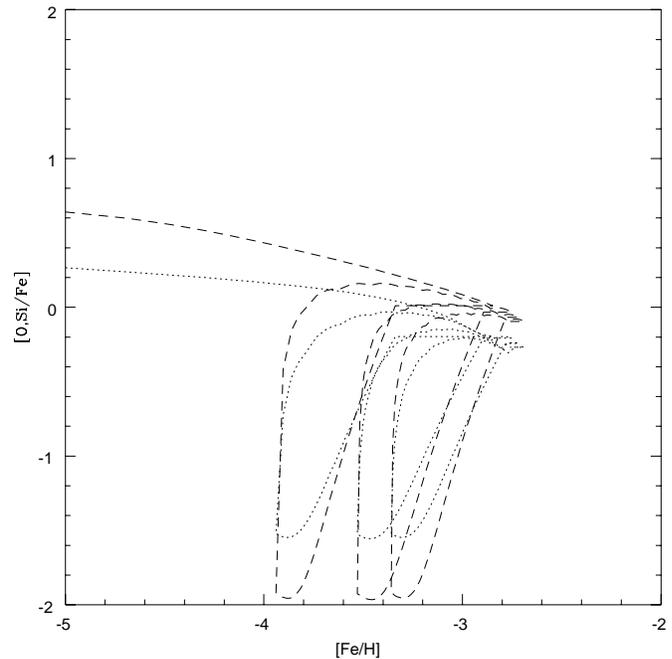
These galaxies should also experience strong enriched galactic winds carrying away mostly the products of SN II explosions such as oxygen and other α-elements. In particular, the high N/O abundance ratios could represent either the situation of an interburst phase where N increases and O does not, or the situation of a burst triggering an extremely strong and enriched galactic wind.

- Nitrogen in massive stars should have a primary origin as already suggested by Matteucci (1986). This seems to be possible but is strongly dependent on the assumed treatment of convection in stellar interiors. The nucleosynthesis of N in stars of all masses, especially in low and intermediate mass stars, which are the main producers of this element, needs revision and a homogeneous set of calculations for stars of all masses is required. New yields, but only for stars below 4 $M_\odot$, have been recently computed by Marigo et al. (1996). Unfortunately, the mass range above that mass limit is very important for nitrogen production and therefore firm conclusions cannot yet be drawn.

- We can exclude, on the basis of current models for elliptical galaxies that any of the systems discussed in this paper could be a proto-elliptical.

- Some of the differences in the abundances observed among different DLA systems could be due to the fact that some of them are proto-spirals (see the systems observed by Pettini et al. 1995 and Lipman, 1995) and some are proto-dwarfs (see the systems observed by Molaro et al. 1996 and Green et al. 1995)

- Abundance ratios between elements produced from stars at different rates such as N/O and α/Fe represent a very useful tool either to date a galaxy or to understand the nature of high red-shift objects.

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