The Evolution of Galaxies on Cosmological Timescales
ASP Conference Series, Vol. 3×10^8*, 1999*
J. E. Beckman, and T. J. Mahoney, eds.

Nature and evolution of Damped Lyman alpha systems

G. Vladilo

Osservatorio Astronomico di Trieste, Via Tiepolo 11, 34131 Trieste, Italy

Abstract. The main properties of Damped Lyman alpha (DLA) systems are briefly reviewed with the aim of studying the nature and evolution of the galaxies associated with this class of QSO absorbers. Candidate DLA galaxies identified at $z \leq 1$ in the fields of background QSOs show a variety of morphological types without a predominance of spirals. Most properties inferred from spectroscopic studies at $z \geq 1.65$ differ from those expected for spiral galaxies. The observational results instead suggest that a significant fraction of DLA systems originate in low-mass and/or LSB galaxies. Evolution effects are generally not detected in DLA systems. This fact suggests that the differences between the properties of present-day spirals and those of high-z DLA systems may not be ascribed to evolution. Several selection effects can bias the observed population of DLA absorbers. Analysis of these effects indicates that the fraction of spiral galaxies tends to be underestimated relative to the fraction of low-mass or LSB galaxies.

1. Introduction

The redshifted Lyα absorptions observed in the spectra of QSOs originate in intervening clouds with wide-ranging HI column densities. When $N(\mathrm{HI}) \geq 2 \times 10^{20}$ atoms cm^{-2} the Ly α line shows a broad profile with extended 'radiation damping' wings. Damped Ly α (DLA) absorption lines are always accompanied by narrow metal lines at the same redshift, $z_{\rm abs}$. These absorption line systems are quite rare, the number per unit redshift interval being the lowest among all types of QSO absorbers ($n(z) \simeq 0.2$ at $z_{\rm abs} \simeq 2$; Wolfe et al. 1995). About a hundred DLA systems are currently known as a result of several surveys, most of them performed in the optical spectral range (Wolfe et al. 1986, 1995). Owing to the dramatic drop of QSO counts at high z, only a reduced number of absorbers have been detected at $z > 4$ (Storrie-Lombardi et al. 1996a). At $z \leq 1.65$ Ly α absorptions can only be observed with space-born UV telescopes and the number of systems identified is quite limited (Lanzetta, Wolfe & Turnshek 1995; Jannuzi et al. 1998 and refs. therein; Turnshek 1998). DLA systems have also been detected as redshifted 21 cm absorption in the continuum of radio loud quasars (Carilli et al. 1996 and refs. therein).

Several reasons suggest that DLA systems originate in interstellar clouds within galaxies located in the direction of the QSO: (i) the high values of HI column density, typical of the interstellar medium of gas-rich galaxies; (ii) the presence of low ionization species of metals, observed in Galactic HI regions; (iii) the line-of-sight velocity dispersion, consistent with the typical values expected for galactic disks; (iv) the evolution of the comoving mass density of gas in DLA absorbers, which is suggestive of gas consumption due to star formation (Wolfe et al. 1995). DLA systems have low metallicities, typically $Z/Z_\odot \approx 10^{-1}$ and, in some cases, as low as $Z/Z_\odot \approx 10^{-2}$ (Pettini et al. 1997a, 1999). Therefore the galaxies hosting DLA clouds must be chemically young and, in some cases, must be in the very first stages of their chemical enrichment.

Studies of DLA absorbers allow us to probe young galaxies at high redshift from the observation of only one line of sight though each galaxy. This kind of investigation is complementary to studies of Ly-break galaxies, which allow us to probe high redshift galaxies from the observation of their integrated emission. The advantage of DLA absorption studies is the intrinsic brightness of the background QSO which can be used to obtain spectra of unparalleled resolution and signal-to-noise ratio at a given redshift. The quality of these spectra allows us to study the chemical and physical properties of young galaxies in unrivaled detail.

Even if the link between DLA absorbers and intervening galaxies is commonly accepted, there is no general agreement on the nature of the galaxies hosting the DLA clouds (also called DLA galaxies hereafter). The traditional working hypothesis is that DLA galaxies are the progenitors of present-day spirals (Wolfe et al. 1986), but alternative interpretations have also been proposed (e.g. Tyson 1988). While it is possible to study the evolution of DLA systems *per se*, understanding the nature of DLA galaxies is fundamental to put the phenomenon in the general context of galactic evolution and to constrain theories of structure formation. The observational clues to the nature of DLA galaxies are summarized in the next section of this contribution. Selection effects are considered in Section 3, while the evolution properties are discussed in Section 4. Finally, the results are summarized in Section 5.

2. Clues to the nature of DLA galaxies

One approach to cast light on the nature of DLA galaxies is to estimate the number of galaxies of a specific morphological type T expected along a random line of sight. At $z \simeq 0$ the number per unit distance interval is

$$n_\circ^T = \int \Phi_\circ^T(M) < A_\circ^T(M) > dM \quad (1)$$

where $\Phi_\circ^T$ is the optical luminosity function of the galaxies of type T in terms of the absolute magnitude M; $A_\circ^T$ is the effective cross section of the column density contour $N_{\rm HI} \geq N_{\rm min} = 2 \times 10^{20}$ cm^{-2} and the angled brackets indicate a weighted average over all possible galaxian inclinations. Estimates of the HI content within galaxies at the present epoch indicate that most of the observed absorptions should originate in spirals (Rao & Briggs 1993). This prediction, however, is not confirmed by studies of candidate DLA galaxies at low redshift (Section 2.1). Considering the lack of understaning at $z = 0$ it is clear that estimating the fraction $n_\circ^T / \sum_T n_\circ^T$ at high z is highly speculative until we know the effects of evolution and merging on morphology and galaxian sizes.

Observations are the key to understanding the nature of DLA galaxies. Spectroscopic data are used to study chemical and physical properties. Imaging data are used to study the morphology of candidate DLA galaxies. Imaging and spectroscopic data have a poor redshift overlap: while the imaging is most effective at $z \leq 1$ — the confusion with the QSO source is more critical at high z — the spectroscopy is mostly performed at $z_{\rm abs} \geq 1.65$.

Table 1. Summary of searches for candidate DLA galaxies

QSO	$z_{\rm abs}$	$z_{\rm gal}$	ρ^a (kpc)	M_B or Luminosity	Type	Ref.
Ton 1480	0.0039	0.0039	12	—	S0	1
OI 363	0.0912		—	$\geq$–15.9^b	[dw/LSB]	2
0850+4400	0.1638	0.1635	33	$L_B = 0.4\,L_B^*$	S0	3
OI 363	0.2212		—	$\geq$–17.8^b	[dw/LSB]	2
PKS B1127–145	0.3127	0.3121	22	$m_R = 22.3$	—	4
1229–021	0.3950		9.9	–18.9	LSB	5
3C 196	0.437		12.5	-22.1	Giant Sbc	5
PKS 0118–272	0.5580		14	$\approx -21.3^b$	—	6
1209+107	0.6295		14.6	–22.0	Spiral	5
3C 336	0.6563		—	$L < 0.05\,L_K^*$	[dw/LSB]	7
1328+307	0.692		8.5	–20.5	LSB	5
1331+170	0.7443		37.7	-22.9	Spiral	5
0454+039	0.8596		8.3	–20.5	Compact	5
0302–223	1.0095		12.0	–20.4	Semicomp.	5
			27.4	–22.0	Compact	5
1331+170	1.776		20.0	–22.7	Compact	5

^{a} All impact parameter have been converted in units of h_{50}^{-1} kpc.
^{b} Derived by assuming $B - R = 1$ (Rao & Turnshek 1998)
REFERENCES.— (1) Miller, Knezek, & Bregman 1999; (2) Rao & Turnshek 1998; (3) Lanzetta et al. 1997; (4) Lane et al. 1998; (5) Le Brun et al. 1997; (6) Vladilo et al. 1997; (7) Steidel et al. 1997.

2.1. Morphology of candidate DLA galaxies

The galaxies responsible for the DLA absorption can be identified by studying the field of the background QSO. Galaxies with impact parameter compatible with the expected extension of the HI disk are considered as candidate absorbers. The impact parameter, ρ ($h_\circ^{-1}$ kpc), is estimated at the redshift of the absorber and, in order to confirm the identification, one should also measure the redshift of the galaxy and check if $z_{\rm gal} = z_{\rm abs}$. When galaxies are not detected within a reasonable value of ρ, an upper limit to the (surface) brightness of the intervening galaxy can still be derived. The results of searches for DLA galaxies in QSO fields are summarized in Table 1. Although the sample is limited and only a few galaxies have a redshift measurement, an important conclusion can already be derived: DLA galaxies at $z \leq 1$ show a variety of morphological types (S0, spirals, dwarfs) and different levels of surface brightness, including low surface brightness (LSB) galaxies. In other words, the population of DLA galaxies is not dominated by any specific type of galaxies and, in particular, spirals constitute a small fraction of the sample, contrary to the predictions based on the HI content of nearby galaxies (Rao & Briggs 1993). The selection effects discussed in Section 3 may be responsible for this unexpected result.

2.2. Elemental abundances

Abundances of DLA systems can be measured with accuracy and are already available for about 50 systems (Lu et al. 1996; Prochaska & Wolfe 1999; Pettini et al. 1999; see also refs. in Vladilo 1998). The HI column density can be easily constrained within $\pm$ 0.1 dex, or even better, by fitting the damping wings of the Ly α profile. The most common metals show unsaturated transitions which allow column densities to be accurately determined. Ionization corrections are generally negligible thanks to the presence of neutrals or ions with IP $\geq$ 13.6 eV which are dominant ionization stages in HI regions. Dust probably represents the main source of uncertainty in abundance determinations since an unknown fraction of the elements is probably depleted into dust grains (Section 2.3). Studies of the intrinsic abundances of DLA systems in the presence of dust have been performed by Lauroesch et al. (1996) and by Kulkarni, Fall & Truran (1997). In these studies the dust-to-gas ratio, k, is considered a free parameter with same value in all systems. However, the level of depletion scales with k, and it is essential to estimate k for each DLA cloud in order to properly correct the abundances (Vladilo 1998).

Abundances of metal-poor Galactic stars are often used as a reference for DLA studies since they reflect the abundance pattern of the Milky-Way gas at the time in which the first stellar generations were formed. By comparing abundances of DLA systems at redshift z with abundances of Galactic stars formed at look-back time $t(z)$, we can test whether DLA galaxies undergo a chemical evolution similar to that of the Milky Way. The comparison between the two sets of abundances can also be made at a given metallicity, which measures the level of chemical enrichment attained by each system.

Metallicities. The absolute abundance of zinc, [Zn/H][1], is generally used to study the metallicities in DLA systems since zinc is expected to be unaffected by dust depletion (Pettini et al. 1997a; 1999). Observed metallicities span the interval $-2 <$ [Zn/H] < 0, with a column-density weighted mean value [<Zn/H>] $\simeq -1$. The metallicity distribution is different from that found in the stellar populations of the Milky Way, a result that casts doubts on the relationship between high-z DLA systems and present-day spirals (Pettini et al. 1997b; see, however, Wolfe & Prochaska 1998).

Iron-peak abundances. Studies of metal-poor stars in the Galaxy indicate that iron-peak elements trace each other with approximate solar ratios (Ryan, Norris, & Beers 1996). Deviations from the solar pattern can be present, but are generally negligible at the metallicity level of DLA absorbers. The [Zn/Fe], [Cr/Fe], and [Ni/Fe] ratios measured in DLA systems show significant deviations from the solar pattern, inconsistent with those observed in metal-poor stars

[1] We adopt the usual notation $[X/Y] \equiv \log(X/Y) - \log(X/Y)_\odot$

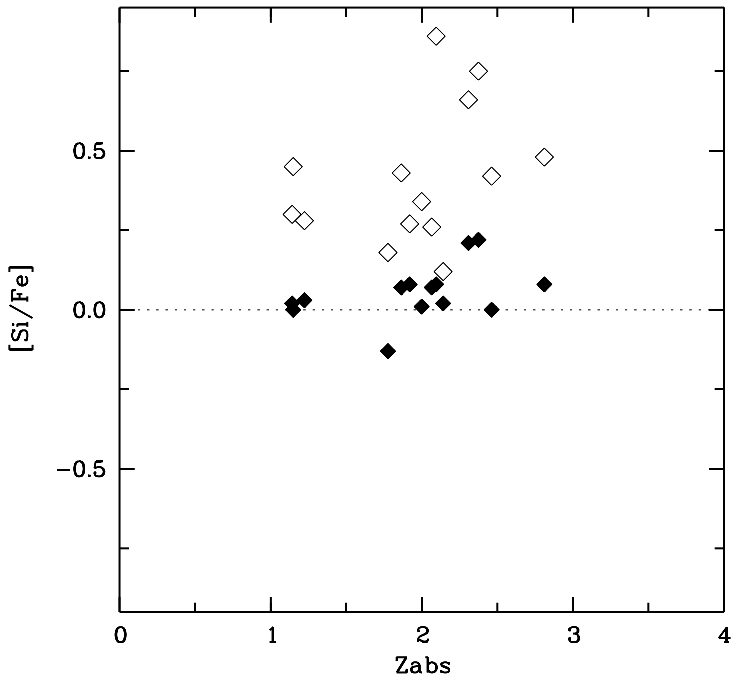

Figure 1. Empty symbols: measurements of the [Si/Fe] ratio in DLA systems. Filled symbols: same measurements corrected for dust depletion. See Vladilo (1998) for more details.

(Lu et al. 1996; Pettini et al. 1997a). All these ratios follow the differential dust depletion pattern observed in the Milky Way interstellar gas (Savage & Sembach 1996), suggesting that the observed abundances are dominated by dust depletion (Section 2.3). The [Mn/Fe] ratio is underabundant, consistent with that observed in metal-poor stars (Lu et al. 1996); however part of this effect can also be ascribed to dust (Vladilo 1998).

[α/Fe] ratios. The ratio between α and iron-peak elements is a well-known tracer of galactic evolution. In the Milky Way it decreases from the value [α/Fe] $\simeq +0.5$ typical of metal-poor stars, down to [α/Fe] $= 0$ at higher metallicities (Wheeler, Sneden & Truran 1989). The temporal delay between the metal injection from SNae Type II, rich in α elements, and SNae Type Ia, rich in iron-peak elements can explain the decrease of [α/Fe] in the course of evolution (Matteucci 1991 and refs. therein). The [Si/Fe] and [S/Fe] ratios in DLA systems show overabundances which resemble Milky-Way metal-poor abundances (Lu et al. 1996). However, the result in itself is not conclusive since the [Si/Fe] and [S/Fe] ratios are also enhanced in the nearby ISM as a consequence of differential depletion (Savage & Sembach 1996). A way to obtain the intrinsic [α/Fe] ratio is to select elements with negligible ISM depletions, such as sulphur and zinc, which trace the α and the iron-peak elements, respectively. The few available measurements give [S/Zn] $\simeq 0$ (Molaro, Centurión, & Vladilo 1998), suggesting that the enhancement of the [Si/Fe] and [S/Fe] ratios is due to differential depletion. This suggestion is confirmed by a re-analysis of abundances in DLA systems corrected for depletion (Vladilo 1998): the resulting [Si/Fe] and [S/Fe]

values are approximately solar (Fig. 1), consistent with the [S/Zn] results. The Magellanic Clouds (Wheeler et al. 1989) and BCGs (Thuan, Izotov & Lipovetsky 1995) are examples of galaxies with [α/Fe] $\simeq 0$ at low metallicity. In general, any galaxy with low SFR at early epochs will be able to produce [α/Fe] $\simeq 0$ at low metallicity because the onset of Type Ia SNae will occur before the galaxy has time to attain solar metallicity (Matteucci 1991).

Nitrogen. Nitrogen abundances can be used to probe the early stages of chemical evolution. However, the relative importance of different production mechanisms — i.e. primary versus secondary production — is not fully understood (Matteucci, Molaro, & Vladilo 1997). Nitrogen abundances have been measured in about ten DLA systems (Molaro et al. 1996; Lu, Sargent & Barlow 1998; Centurión et al. 1998). When the effects of dust are considered, a substantial fraction of [N/Fe] and [N/S] ratios are lower than those observed in Galactic metal-poor stars (Centurión et al. 1998). It is not possible to explain all the observations with a unique production mechanism: some cases suggest a secondary behaviour (i.e. the nitrogen ratios increase with metallicity), whereas others show evidence of primary production (i.e. the ratios are approximately constant with metallicity). Nitrogen ratios in DLA systems show similarities with those measured in nearby metal-poor galaxies, such as the [N/O] ratios in dwarf irregulars (Kobulnicky & Skillman 1996; van Zee et al. 1996) and the [N/Fe] ratios in BCGs (Thuan et al. 1995). In one or two cases there is evidence for an extremely high [N/α] ratio, well above the values found in any astrophysical site (Molaro et al. 1996).

2.3. Dust

The first evidence for dust in DLA systems was provided by a study of QSOs with and without foreground DLA absorption (Pei, Fall & Bechtold 1991). The optical spectral indices of the two samples are significally different and indicate an enhanced reddening of the QSOs with intervening absorption. The dust-to-gas ratios, k, derived from this statistical study are typically between 5% and 20% of the Galactic value.

The observation of different images of gravitationally lensed QSOs with foreground DLA absorption is a powerful technique to study the dust properties of the intervening galaxy. The only case investigated up to now, namely the $z_{\rm abs} = 1.3911$ system toward QSO 0957+561, shows clear evidence of differential dust reddening between the two adjacent images of the QSO (Zuo et al. 1997). The derived k is between 40% and 70% of the Galactic value.

As mentioned above, also the abundances of iron-peak elements provide evidence for dust in DLA systems since the [Zn/Fe], [Cr/Fe], and [Ni/Fe] ratios qualitatively follow the dust depletion pattern seen in the nearby interstellar gas (Savage & Sembach 1996). The observed pattern can be quantitatively explained by assuming that the dust in DLA systems has same the composition as in the Milky Way, but with a different value of k in each system. In fact, one can estimate the dust-to-gas ratio in each system from the condition that the intrinsic iron-peak abundance ratios are solar (Vladilo 1998). The resulting dust-to-gas ratios show a large spread among different DLA absorbers, with k values mostly distributed between 2% and 25% of the Galactic value, consistent with the range found by Pei et al. (1991). In a given DLA system, dust-to-gas ratios estimated from different pairs of iron-peak elements yield consistent results, as expected from the basic assumption of the method. Dust-to-gas ratios estimated in this way are well correlated with metallicity (Fig. 2 in Vladilo 1998). The existence of such a correlation and the evidence for dust obscuration described in Section 3.1 indicate that the k values estimated indirectly from the iron-peak abundances are indeed related to dust present in DLA systems.

2.4. Kinematics

Kinematical properties are derived from the study of the line-of-sight velocity dispersion of the systems, determined from the profiles of unsaturated metal lines. The HI gas is traced by low ions, such as Si^+ or Fe^+, which have very similar profiles in each system and often show multiple absorption components. Since the line of sight samples the absorbers along random directions, a large number of observations is required to test models of DLA kinematics. The most extensive collection of velocity profiles has been obtained by Prochaska & Wolfe (1997, 1998) by means of Keck observations. The velocity widths, ΔV, measured above a given threshold of optical depth, range from about 50 km s^{-1} up to 300 km s^{-1}. When multiple components are present, the most intense one is generally found at one edge of the profile. These "leading-edge" profiles can be naturally produced by the intersection of a rotating disk with an exponential gas density distribution. Analysis of the full set of profiles indicates a consistency with models of fast-rotating ($V_{\rm rot} \simeq 250$ km s^{-1}), thick disks, a result supporting a relationship between high-z DLA systems and present-day spirals; models of slow-rotating, low-mass galaxies are instead ruled out (Prochaska & Wolfe 1997, 1998). However, these conclusions are obtained by assuming that all DLA systems are drawn from a homogeneous population of galaxies, an assumption probably incorrect, given the observational evidence shown in Table 1. In addition, the conclusion that fast rotating disks are the only viable explanation for the observed data has been disproved by Haehnelt et al. (1998). According to these authors, irregular protogalactic clumps can reproduce the velocity profiles distribution equally well. The few profiles with extremely high values of ΔV can be explained with occasional alignment of clumps at the same redshift. An argument against the hypothesis that DLA systems rotate at $V_{\rm rot} \simeq 250$ km s^{-1} comes from an analysis of profile asymmetries performed by Ledoux et al. (1998). According to these authors, there is evidence for regular rotating disks only up to $\Delta V_{\rm rot} \simeq 120$ km s^{-1}, while at higher velocities the kinematics is more complex.

2.5. Spin temperature

For DLA systems that lie in front of a radio loud quasar it is possible to observe the 21 cm absorption in addition to the Ly α line. An analysis of both spectral ranges yields, under suitable assumptions, the harmonic mean along the line of sight of the spin temperature of the gas, $< T_s >$. The typical values found in DLA systems — $< T_s > \approx 10^3$ K (de Bruyn, O'Dea & Baum 1996; Carilli et al. 1996) —, are generally much larger than those observed in the disk of the Galaxy or in nearby spiral galaxies (Braun 1997 and refs. therein). The higher spin temperatures probably indicate that DLA galaxies have a larger fraction of warm gas than nearby spirals. One approach to understanding this difference is through variation of the interstellar pressure: the fraction of warm gas is expected to be higher in regions where the mean pressure is lower (Dickey 1995). Since the mean pressure is determined, in part, by the gravitational potential, a high fraction of warm gas could be a signature of gravitational potential lower than in the Milky Way disk.

3. Selection effects

Selection effects can alter the fraction of specific types of galaxies, or particular regions of galaxies, detected in surveys of DLA systems. Recognizing the role of such effects is fundamental for a correct interpretation of the nature and evolution of DLA galaxies.

3.1. QSO obscuration

The absorbers with the highest dust content will obscure the background QSO and will be missed from magnitude limited samples. This effect of QSO extinction was first investigated by Pei et al. (1991). The possibility of determining the dust-to-gas ratios k in individual systems allows us to estimate the importance of the effect (Vladilo 1998). Evidence for QSO obscuration comes an inspection of Fig. 2: DLA systems for which the product $\mathcal{D} = kN_{\rm HI}$ exceeds a critical threshold are not observed. $\mathcal{D}$ is an estimate of the dust content along the line of sight and the tilted line in Fig. 2 represents the $\mathcal{D}$ value that yields an extinction of 1 magnitude of the QSO in the observer's frame. Absorbers above this line have probably not been detected because they obscure the QSO by more than 1 magnitude. Since dust and metals are strinctly linked, one expects that systems with high metallicity and high column density are missed due to the same selection bias. This effect has indeed been reported by Boissè et al. (1998).

As a consequence of QSO obscuration, DLA absorbers with higher and higher dust content (or metallicity) are only detectable at lower and lower values of column density. In particular, present-day spirals with solar metallicity (and hence $k/k_{\rm Gal} \approx 1$) can be missed when $N_{\rm HI} \geq 10^{20.7}$ cm^{-2}, according to the trend shown in Fig. 2. Dwarf or LSB galaxies, which are characterized by lower metallicities and dust content, should be less affected by this selection bias. In addition, LSB galaxies should be less affected because the column density perpendicular to the disk is typically lower than in high surface brightness (HSB) galaxies.

3.2. Surface brightness

Differences in surface brightness between galaxies can be understood if LSB galaxies are hosted in dark halos with values of the spin parameter, λ, larger than those of HSB galaxies (see Jimenez, Bowen & Matteucci 1999 and refs. therein). The cross-sections of individual galactic disks in equilibrium scale as λ^2 and therefore will be dominated by objects with large angular momentum (Mo, Mao & White 1999). As a result, LSB galaxies are expected to dominate the cross-section for DLA absorption. On the other hand, HSB galaxies are expected to dominate the rates of star formation and metal production.

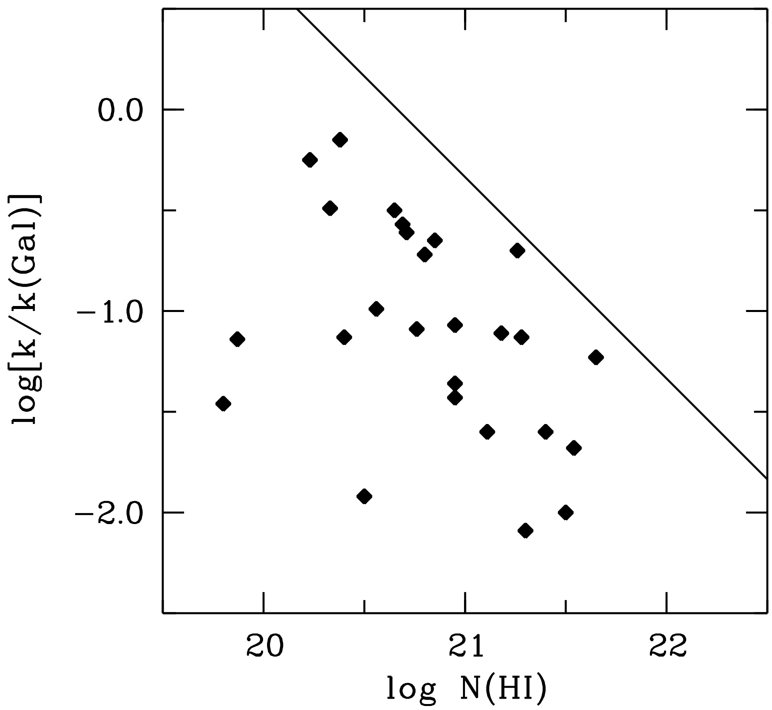

Figure 2. Dust-to-gas ratios (in units of the Galactic value) versus HI column density in DLA systems. Tilted line: line of costant extinction of the QSO (1 magnitude in the observer's frame V band) for an adopted SMC extinction curve (Vladilo, Molaro & Centurión 1999).

3.3. Galactocentric distance

The probability of detecting a galaxy in the interval of galactocentric distances $[r, r+dr]$ is, in general, a function of r. For a galactic disk seen face on, the differential cross section for DLA absorption is $dA_{\circ} \simeq 2\pi r\, dr$, until $N_{\rm HI} \geq N_{\rm min}$. Therefore, galactic regions with larger r have a higher probability of detection, unless the galaxy is seen exactly edge on. Any property which shows spatial gradients will be affected by this bias. In particular, our understanding of chemical evolution properties of DLA systems will be biased since external regions are less chemically evolved than inner regions.

3.4. Gravitational lensing

The galaxy hosting the DLA system can act as a gravitational lens on the image of the background QSO. Smette, Claeskens & Surdej (1997) have developed a formalism to compute the effects of gravitational lensing ('by-pass' effect and 'amplification bias') on the observed number density of DLA systems. The 'by-pass' effect causes the line of sight to avoid the central part of the intervening galaxy and to decrease its effective cross-section for absorption. The 'amplification bias' boosts the apparent magnitude of the QSO and therefore increases the fraction of QSOs with foreground galaxies in magnitude-limited samples. The 'amplification bias' acts in the opposite direction of dust obscuration. However, in order to predict the overall effect one should model dust obscuration and gravitational lensing in a self-consistent way. It is interesting to note that both the 'by-pass' effect, and the 'galactocentric distance' bias conspire to exclude from the surveys the inner regions of galaxies, i.e. the most chemically evolved regions.

4. Evolution of DLA systems

Detecting evolution effects in DLA systems is difficult for several reasons. First, the low number of absorbers identified at low redshift represents a severe limitation, since $z \leq 1.65$ corresponds to a look-back time of about 2/3 of the age of the universe. Second, the selection effects mentioned in the previous section imply that the observed samples are biased. Third, the samples are not homogeneous, since they can include galaxies of different morphological types T, absolute magnitudes M, and redshifts of formation z_f; moreover the line of sight crosses the galaxy at a random radius r. Therefore, observations of any physical quantity Q at different redshifts $z_{\rm abs}$ will yield a data set of the type $Q = Q(z_{\rm abs}; T, M, z_f; r)$, where the redshift dependence of Q will be disguised by fluctuations induced by the other variables.

4.1. Number density and comoving mass density

The number of absorbers per unit redshift interval is given by the product of the absorber cross section, $A_\circ$, times the number density of absorbers per comoving volume, $\Phi_\circ$. The expression for a standard Friedmann universe, $n(z) = \Phi_\circ \, A_\circ \, c \, H_\circ^{-1} \, (1+z) \, (1+2q_\circ z)^{-1/2}$, is usually replaced with

$$n(z) = n_\circ (1+z)^\gamma \,, \tag{2}$$

where γ is determined from the best fit to the empirical data points. In absence of intrinsic evolution $\gamma = 1/2$ ($q_\circ = 0.5$) or $\gamma = 1$ ($q_\circ = 0.$). The work by Lanzetta et al. (1995) yields $\gamma = 1.15 \pm 0.55$, consistent with no evolution. From a combined sample including DLA systems at $z \geq 4$, Storrie-Lombardi, Irwin & McMahon (1996b) find $\gamma = 1.3 \pm 0.5$, also consistent with no evolution. However, these authors do find evolution for the absorbers with $N_{\rm HI} > 10^{21}$ cm^{-2}, which show a decline at $z \geq 3.5$. By combining the sample of DLA systems with the constraints on present-day galaxies, Rao, Turnshek & Briggs (1995) find $\gamma = 2.27 \pm 0.25$. However, this result should not be taken as evidence for evolution until we understand clearly the link between DLA absorbers and nearby galaxies.

The mean comoving mass density of gas in DLA systems is given by

$$\Omega_{\rm dla}(z) = \frac{H_\circ \, \mu \, m_{\rm H}}{c \, \rho_{\rm crit}} \int_{N_{\rm min}}^{\infty} N \, f(N,z) \, dN \,, \tag{3}$$

where μ is the mean molecular weight of the gas, $\rho_{\rm crit}$ is the current critical density of the universe and $f(N,z)$ is the column density distribution function (see Storrie-Lombardi, McMahon, & Irwin 1996c and refs. therein). Analysis of a sample including systems at $z > 4$ indicates that $\Omega_{\rm dla}(z)$ increases from $z = 0$ to $z \approx 2.5$ and apparently declines at $z > 3.5$ (Storrie-Lombardi et al. 1996c). In the lowest redshift bin $\Omega_{\rm dla}(z)$ is roughly equal to the comoving density of neutral gas derived from 21-cm emission surveys of nearby galaxies, i.e.

$\Omega_{\rm dla}(z \simeq 0.64) \approx \Omega_{\rm 21cm}(0)$. At the peak value, $\Omega_{\rm dla}(z)$ is marginally consistent with the mass density in stars in nearby galaxies, i.e. $\Omega_{\rm dla}(z \approx 2.5) \leq \Omega_{\rm star}(0)$. These two facts suggest that the evolution of $\Omega_{\rm dla}(z)$ from the peak value to the present-day value is governed by gas consumption due to star formation, as suggested by Wolfe et al. (1995). However, if the inequality $\Omega_{\rm dla}(z) < \Omega_{\rm star}(0)$ holds true, we are missing part of the gas responsible for the formation of present-day stars. This could be a consequence of the QSO obscuration bias, which affects the absorbers with highest column densities, i.e. the absorbers that give a dominant contribution to $\Omega_{\rm dla}(z)$ (Eq.3).

A new study of DLA systems at low redshift suggests that $\Omega_{\rm dla}(z)$ could be roughly constant from $z \simeq 0.4$ up to $z \simeq 3$, with $\Omega_{\rm dla}(z) > \Omega_{\rm 21cm}(0)$ (Turnshek 1998). This finding would imply that the bulk of star formation took place only relatively recently. However, the result must be considered with caution, since it is based on a very low number of systems and may also be affected by the gravitational lensing bias (Turnshek 1998).

Jimenez, Bowen & Matteucci (1999) have recently computed model predictions of $\Omega_{\rm dla}(z)$ for galaxies with low and high levels of surface brightness. According to these authors, HSB galaxies consume neutral gas at a rate which is too fast to explain the observed evolution of $\Omega_{\rm dla}(z)$; instead LSB galaxies provide a good fit to the data published by Storrie-Lombardi et al. (1996c).

4.2. Metallicity and abundance ratios

Metallicities are expected to increase in the course of evolution. Measurements of the [Zn/H] ratio are now available for 40 DLA systems, including 10 absorbers at $z < 1.5$ (Pettini et al. 1999). The analysis of this sample does not reveal evidence for an increase with time: the column-density weighted mean metallicity is not significantly higher at $z < 1.5$ than at earlier epochs. However, the lack of detection of evolution could be due to the inhomogeneity of the sample and/or to the presence of some selection bias. The QSO obscuration bias may be responsible for missing systems of higher $Z/Z_\odot$ and higher column density (Section 3.1), which are expected to give an important contribution to the metallicity at low redshift. The sample is inhomogeneous for studying the metallicity evolution in the sense that $Z/Z_\odot$ depends on the SFR and on z_f, two parameters that vary in different types of galaxies; in addition $Z/Z_\odot$ can vary with the galactocentric distance r in a given galaxy.

Even if evolution is not directly detected from the data, model predictions of metallicity evolution obtained for different types of galaxies yield results consistent with the observations (Lindner, Fritze & Fricke 1998; Jimenez et al. 1999). The models by Jimenez et al. (1999) show explicitely the dependence of the metallicity on z_f and on r. According to these models, LSB galaxies formed at $z_f = 4$ (but not later) fit well the DLA metallicities; HSB disks can account for the observed data only if they form continuously in the interval $1 \leq z_f \leq 4$.

The [α/Fe] ratio is expected to decrease in the course of chemical evolution (Section 2.2). Measurements of the [Si/Fe] ratio are available for almost 30 DLA systems (Lu et al. 1996; Prochaska & Wolfe 1999), and for part of them it is possible to perform the correction for dust depletion (Vladilo 1998). The mean corrected value is not significantly lower at $z < 2$, where $<$[Si/Fe]$>= +0.01 \pm 0.07$ dex, than at $z > 2$, where $<$[Si/Fe]$>= +0.10 \pm 0.09$ dex (Fig. 1). The lack of evolution could be due to the inhomogeneity of the sample or to the presence of some selection bias, as in the case of the metallicity. In fact, all the selection effects that alter the study of the metallicities will also affect the [α/Fe] ratio, which evolves with metallicity. However, the [α/Fe] ratios do not show evidence for evolution even when plotted versus $Z/Z_\odot$ (Vladilo 1998).

4.3. Dust-to-gas ratios

The dust-to-gas ratios k estimated from the iron-peak abundances do not show any trend with redshift. This is consistent with the fact that k is very well correlated with $Z/Z_\odot$ (Fig. 2 in Vladilo 1998) and the metallicity does not evolve with redshift.

Since metallicity is an indicator of chemical evolution, the good correlation between k and $Z/Z_\odot$ can be considered as evidence for evolution in DLA systems. The regular increase of the dust content with metallicity, however, constrasts with the lack of any correlation with redshift. We deduce that DLA systems do evolve in a regular fashion, but they attain a given level of metallicity (or dust-to-gas ratio) at different redshifts. This conclusion confirms that the sample of DLA systems must include galaxies with different formation redshifts z_f and/or different SFRs.

4.4. Kinematics

From the analysis of a sample of 16 absorbers, Ledoux et al. (1998) find that the maximum ΔV at a given z increases at lower redshifts. This result, if confirmed, would indicate that neutral regions exhibit increasingly faster motions with cosmic time. However, analysis of the set of 28 measurements of ΔV obtained by Prochaska & Wolfe (1997, 1998) does not confirm the existence of such a trend.

Wolfe & Prochaska (1998) find that the maximum ΔV measured at a given [Zn/H] increases with metallicity. According to these authors this effect can be explained by the passage of the lines of sight through rotating disks with radial gradients in metallicity. An alternative explanation is that DLA galaxies with higher metallicities exhibit faster motions than DLA galaxies with lower metallicities. This interpretation would fit nicely in a general trend of increasing metallicity with increasing mass (i.e., velocity dispersion). In any case, the statistics are still insufficient to confirm the existence of this trend.

4.5. Spin temperature

As mentioned in Section 2.5, the spin temperatures measured in high-z DLA systems are higher than those measured in present-day spirals. The difference could be ascribed, in principle, to an effect of evolution. However, recent measurements in two DLA systems at $z_{\rm abs} = 0.221$ and $z_{\rm abs} = 0.091$ yield $< T_s > \approx 10^3$K, consistent with the values found at high redshifts (Chengalur & Kanekar 1999). This suggests that evolution may not be crucial and confirms that DLA galaxies have properties intrinsically different from those observed in nearby spirals.

5. Summary

The nature of the galaxies hosting DLA clouds is still a subject of debate. However, some important conclusions can be inferred by comparing the results obtained from different observations. At low redshifts, candidate DLA galaxies in the fields of the background QSOs show a variety of morphological types and different levels of surface brightness. Spirals are not the dominant contributors, contrary to the predictions based on the HI content of the nearby universe. At high redshift, the hypothesis that DLA absorbers originate in (proto)spirals is not supported by spectroscopic studies of metallicities, abundance ratios, dust-to-gas ratios and spin temperatures. In particular, [α/Fe] ratios and nitrogen abundances hint at an origin in galaxies with properties similar to those observed in nearby, low-mass galaxies. Studies of kinematics are consistent with an origin both in massive disks (proto-spirals) and in low-mass galaxies.

Evolution effects are generally not detected in DLA systems. A possible exception is the number density of $N_{\rm HI} > 10^{21}$ cm^{-2} absorbers, which seems to decline at $z \geq 3.5$. The comoving mass density $\Omega_{\rm dla}(z)$ apparently peaks at $z \approx 2.5$ and decreases at lower redshifts, but this decrease is not corroborated by recent observations. At the peak value $\Omega_{\rm dla}(z) < \Omega_{\rm star}(0)$, suggesting that we are missing part of the gas responsible for the formation of present-day stars. Model predictions of LSB galaxies seem to better fit $\Omega_{\rm dla}(z)$ than models of HSB galaxies.

Metallicities, abundances ratios, dust-to-gas ratios, line-of-sight velocity dispersions, and spin temperatures do not show evidence of redshift evolution. As a consequence, the differences between the properties of present-day spirals and those of high-z DLA systems cannot be ascribed to evolutionary effects: DLA galaxies appear to be intrinsically different from nearby spirals.

Dust production follows metal production in a very regular fashion in DLA systems. While this regular behaviour is proof of evolution, the lack of any correlation between metallicity and redshift suggests that DLA galaxies attain a given level of metallicity at different cosmic epochs, i.e. DLA galaxies must have different formation redshifts z_f and/or different SFRs.

Several selection effects conspire to bias the observed population of DLA absorbers. In particular, high column density clouds located in environments with relatively high metallicity can be missed owing to the QSO obscuration effect. This bias tends to decrease the fraction of spirals detected in the surveys. In general, the contribution of the most chemically evolved galactic regions tends to be underestimated. On the other hand, selection effects tend to favour the detection of LSB galaxies and the fraction of low-mass galaxies does not seem to be underestimated. In spite of their small sizes, low-mass galaxies can be detected if the faint end of the luminosity function is sufficiently steep (Tyson 1988), a condition supported by results obtained at low z (Zucca et al. 1997).

In conclusion, DLA absorbers appear to be associated with a composite population of galaxies without strong effects of evolution and with a prominent representation of low-mass and/or LSB galaxies. A significant number of massive galaxies can be detected in absorption by increasing the statistics of DLA surveys and by pushing the observational limits down to fainter magnitudes in order to contrast selection effects.

References

Boissé, P., Le Brun, V., Bergeron, J., & Deharveng, J.M. 1998, A&A, 333, 841

Braun, R., 1997, ApJ, 484, 637

Carilli, C.L., Lane, W., de Bruyn, A.G., Braun, R., Miley, G.K. 1996, AJ, 111, 1830

Centurión, M., Bonifacio, P., Molaro, P., & Vladilo, G. 1998, ApJ, 509, 620

Chengalur, J.N., & Kanekar, N. 1999, MNRAS, 302, L29

de Bruyn, A.G., O'Dea, C.P., Baum, S.A. 1996, A&A, 305, 450

Dickey, J.M. 1995, in The Physics of the Interstellar and Intergalactic Medium, eds. A. Ferrara et al., A.S.P. Con. Ser. Vol. 80, 357

Haehnelt, M.G., Steinmetz, M., & Rauch, M. 1998, ApJ, 495, 647

Jannuzi, B.T., Bahcall, J.N., Bergeron, J., Boksenberg, A., Hartig, G.F., Kirhakos, S., Sargent, W.L.W., Savage, B.D., Schneider, D.P., Turnshek, D.A., Weymann, R.J., & Wolfe, A.M. 1998, ApJS, 118, 1

Jimenez, R., Bowen, D.V., & Matteucci, F. 1999, ApJ, 514, L83

Kulkarni, V.P., S.M., Fall, & J.W. Truran, 1997, ApJ, 484, L7

Lanzetta, K.M., Wolfe, A.M., Altan, H., Barcons, X., Chen, H.-W., Fernández-Soto, A., Meyer, D.M., Ortiz-Gil, A., Savaglio, S., Webb, J.K., & Yahata, N. 1997, AJ, 114, 1337

Lanzetta, K.M., Wolfe, A.M., & Turnshek, D.A. 1995, ApJ, 440, 435

Lauroesch, J.T., Truran, J.W., Welty, D.E., & York, D.G. 1996, PASP, 108, 641

Le Brun, V., Bergeron, J., Boissé, P., & Deharveng, J.M. 1997, A&A, 321, 733

Ledoux, C., Petitjean, P., Bergeron, J., Wampler, E.J., & Srianand, R. 1998, A&A, 337, 51

Lindner, U., Fritze-Von Alvensleben, U., & Fricke, K.J. 1998, A&A, 341, 709

Lu L., Sargent W.L.W., Barlow T.A. 1998, ApJ, 115, 55

Lu, L., Sargent, W.L.W., Barlow, T.A., Churchill, C.W., & Vogt, S. 1996, ApJS, 107, 475

Matteucci, F. 1991, in SN1987A and other Supernovae, ed. I.J. Danziger & K.Kjär, ESO Proc. No. 37, 703

Matteucci, F., Molaro, P., & Vladilo, G. 1997, A&A, 321, 45

Miller, E.D., Knezek, P.M., & Bregman, J.N. 1999, ApJ, 510, L95

Mo, H.J., Mao, S., & White, S.D.M. 1999, MNRAS, 304, 175

Molaro, P., Centurión, M., & Vladilo, G. 1998, MNRAS, 293, L37

Molaro, P., D'Odorico, S., Fontana, A., Savaglio, S., & Vladilo, G. 1996, A&A, 308, 1

Pei, Y.C., & Fall, S.M. 1995, ApJ, 454, 69

Pei, Y.C., Fall, S.M., & Bechtold, J. 1991, ApJ, 378, 6

Pettini, M., Ellison, S.L., Steidel, C.C., & Bowen, D.V. 1999, ApJ, 510, 576

Pettini, M., King, D.L., Smith, L.J., & Hunstead, R.W. 1997a, ApJ, 478, 536

Pettini, M., Smith, L.J., King, D.L., & Hunstead, R.W. 1997b, ApJ, 486, 665

Prochaska, J.X., & Wolfe, A.M. 1997, ApJ, 474, 140

Prochaska, J.X., & Wolfe A.M. 1998, ApJ, 507, 113

Prochaska, J.X., & Wolfe A.M. 1999, ApJ, in press (astro-ph/9810381)

Rao, S.M., & Briggs, F. 1993, ApJ, 419, 515

Rao, S.M., & Turnshek, D.A. 1998, ApJ, 500, L115

Ryan, S.G., Norris, J.E., & Beers, T.C. 1996, ApJ, 471, 254

Savage B.D., & Sembach K.R. 1996, Ann. Rev. Astron. Astrophys., 34, 279

Smette, A., Claeskens, J.-F., & Surdej, J., 1997, New Astronomy 2, 53

Steidel, C.C., Dickinson, M., Meyer, D.M., Adelberger, K.L., & Sembach, K.R. 1997, ApJ, 480, 568

Storrie-Lombardi, L.J., Irwin, M.J., & McMahon, R.G. 1996b, MNRAS, 282, 1330

Storrie-Lombardi, L.J., McMahon, R.G., & Irwin, M.J. 1996c, MNRAS, 283, L79

Storrie-Lombardi, L.J., McMahon, R.G., Irwin, M.J., & Hazard, C. 1996a, ApJ, 468, 121

Thuan, T.X., Izotov, Y.I., & Lipovetsky, V.A. 1995, ApJ, 445, 108

Turnshek, D.A. 1998, in Structure and Evolution of the Intergalactic Medium from QSO absorption Line Systems, ed. P. Petitjean, & S. Charlot (Paris:Editions Frontieres), 263

Tyson, N.D. 1988, ApJ, 329, L57

van Zee, L., Haynes, P.M., Salzer, J.J., & Broeils, A. 1996, AJ, 112, 129

Vladilo, G. 1998, ApJ, 493, 583

Vladilo, G., Centurión, M., Falomo, R., & Molaro, P. 1997, A&A, 327, 47

Vladilo, G., Molaro, P., & Centurión, M. 1999, Proc. of the meeting The Birth of Galaxies, Chateau de Blois, France, June 28th - July 4th (1998), in press.

Wheeler, J.C., Sneden, C., & Truran, J.W.Jr. 1989, Ann. Rev. Astron. Astrophys., 27, 279

Wolfe, A.M., Prochaska, J.X. 1998, ApJ, 494, L15

Wolfe, A.M., Lanzetta, K.M., Foltz, C.B., & Chaffee, F.H. 1995, ApJ, 454, 698

Wolfe, A.M., Turnshek, D.A., Smith, H.E., & Cohen, R.D. 1986, ApJS, 61, 249

Zucca, E., Zamorani, G., Vettolani, G., Cappi, A., Merighi, R., Mignoli, M., Stirpe, G. M., MacGillivray, H., Collins, C., Balkowski, C., Cayatte, V., Maurogordato, S., Proust, D., Chincarini, G., Guzzo, L., Maccagni, D., Scaramella, R., Blanchard, A., & Ramella, M. 1997, A&A, 326, 477

Zuo, L., Beaver, E.A., Burbidge, E.M., Cohen, R.S., Junkkarinen, V.T., & Lyons, R.W., 1997, ApJ, 477, 568