Probing Galaxies through Quasar Absorption Lines
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Local galaxies as damped Lyman-α absorber analogues

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Abstract. We calculate in detail the expected properties of low redshift DLAs under the assumption that they arise in the gaseous disks of galaxies like those in the $z \approx 0$ population. A sample of 355 nearby galaxies were analysed, for which high quality H I 21-cm emission line maps are available as part of an extensive survey with the Westerbork telescope (WHISP). We find that expected luminosities, impact parameters between quasars and DLA host galaxies, and metal abundances are in good agreement with the observed properties of DLAs and DLA galaxies. The measured redshift number density of $z = 0$ gas above the DLA limit is $dN/dz = 0.045 \pm 0.006$, which compared to higher z measurements implies that there is no evolution in the co-moving density of DLAs along a line of sight between $z \sim 1.5$ and $z = 0$, and a decrease of only a factor of two from $z \sim 4$ to the present time. We conclude that the local galaxy population can explain all properties of low redshift DLAs.

1. Introduction

The highest column density intervening Lyman-α absorbing systems known as damped Lyman-α systems or DLAs are characterised by H I column densities larger than $N_{\rm HI} = 2 \times 10^{20}$ cm^{-2}. The range of H I column densities found in these DLAs is very similar to that seen in routine 21-cm emission line observations of the neutral gas disks in nearby galaxies. An attractive experiment would therefore be to map the H I gas of DLA absorbing systems in 21-cm emission, and measure the DLAs' total gas mass, the extent of the gas disks, and their dynamics. This would provide a direct observational link between DLAs and local galaxies, but unfortunately such studies are impossible with present technology (see Kanekar *et al.* 2001). The transition probability of the hyperfine splitting that causes the 21-cm line is extremely small, resulting in a weak line that can only be observed in emission in the very local ($z < 0.2$) Universe. On the other hand, the identification of DLAs as absorbers in background QSO spectra is, to first order, not distance dependent because the detection efficiency depends mostly on the brightness of the background source, not on the redshift of the absorber itself. In fact, the lowest redshift ($z < 1.7$) Lyman-α absorbers cannot be observed from the ground because the Earth's atmosphere is opaque to the UV wavelength range in which these are to be found. Furthermore, due to the expansion of the Universe the redshift number density of DLAs decreases rapidly toward lower redshifts, rendering them extremely rare along a random sight line at $z \approx 0$. (The mean free path between low-z DLAs is ≈ 88 Gpc! [Zwaan *et al.*

2005b]). Consequently, there are not many DLAs known whose 21-cm emission would be within the reach of present-day radio telescopes.

So, we are left with a wealth of information on the cold gas properties in local galaxies, which has been collected over the last half century, and several hundreds of DLA absorption profiles at intermediate and high redshift, but little possibility to bridge these two sets of information. Obviously, most observers resort to optical wavelengths to study DLAs, but attempts to directly image their host galaxies have been notably unsuccessful (see e.g. Warren *et al.* 2001; Møller *et al.* 2002 for reviews). A few positive identifications do exist, mostly the result of HST imaging. Possibly the best high redshift data to date are available for three objects imaged with STIS by Møller *et al.* (2002). They found emission from three DLA galaxies with spectroscopic confirmation and concluded that the objects are consistent with being drawn from the population of Lyman-break galaxies.

Although the absolute number of DLAs at low z is small, the success rate for finding low-z host galaxies is better for obvious reasons: the host galaxies are expected to be brighter and the separation on the sky between the bright QSO and the DLA galaxy is likely larger. Early surveys for low-z DLA host galaxies consisted of broad-band imaging and lacked spectroscopic follow-up (e.g. Le Brun *et al.* 1997). Later studies aimed at measuring redshifts to determine the association of optically identified galaxies with DLAs, either spectroscopically (e.g. Rao *et al.* 2003), or using photometric redshifts (Chen & Lanzetta 2003). All together, there are now ~ 20 DLA galaxies known at $z < 1$. The galaxies span a wide range in galaxy properties, ranging from inconspicuous LSB dwarfs to giant spirals and even early type galaxies. Obviously, it is not just the luminous, high surface brightness spiral galaxies that contribute to the H I cross-section above the DLA threshold. As explained above, we cannot study these galaxies in the 21-cm line on a case-by-case basis, but we can do a study of a statistical nature to see if the properties of DLAs and DLA galaxies agree with our knowledge of H I in the local Universe.

2. 140,000 "DLAs" at $z = 0$

Blind 21-cm emission line surveys in the local Universe with single dish radio telescopes such as Parkes or Arecibo have resulted in an accurate measurement of $\Omega_{\rm HI}(z = 0)$, which can be used as a reference point for higher redshift DLA studies. $\Omega_{\rm HI}$ is simply calculated by integrating over the H I mass function of galaxies. The shape of the H I mass function has not changed significantly since the early measurements from the late 1990, but the accuracy of the measurement has improved tremendously with HIPASS (Zwaan *et al.* 2005a). However, due to the large beam widths of the single dish instruments, these surveys at best only barely resolve the detected galaxies and are therefore not very useful in constraining the column density distribution function of $z \approx 0$ H I. Hence, for this purpose we use the high resolution 21-cm maps of a large sample of local galaxies that have been observed with the Westerbork Synthesis Radio Telescope. This sample is known as WHISP (van der Hulst *et al.* 2001) and consists of 355 galaxies spanning a large range in H I mass and optical luminosity. In total, the equivalent of more than one year of continuous observing has been devoted to obtain H I data cubes of these galaxies. The total number of independent column density measurements above the DLA limit is $\sim 140,000$, which implies that the data volume of our present study is the equivalent of $\sim 140,000$ DLAs at $z = 0$!

Each galaxy in the sample is weighted according to the H I mass function of galaxies, which expresses the space density of galaxies as a function of their H I mass. We can now calculate the column density distribution function $f(N_{\rm HI})$, which is defined such

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that $f(N_{\rm HI})dN_{\rm HI}dX$ is the number of absorbers with column density between $N_{\rm HI}$ and $N_{\rm HI}+dN_{\rm HI}$ over an absorption distance interval dX. At $z=0$ we can equate dX to dz, such that $f(N_{\rm HI})$ can be expressed as

$$f(N_{\rm HI}) = \frac{c}{H_0}\frac{\int \Phi(M_{\rm HI})\Sigma(N_{\rm HI}, M_{\rm HI})\, dM_{\rm HI}}{dN_{\rm HI}}, \qquad (2.1)$$

where $\Sigma(N_{\rm HI}, M_{\rm HI})$ is the area function that describes for galaxies with H I mass $M_{\rm HI}$ the area in $\rm Mpc^{-2}$ corresponding to a column density in the range $N_{\rm HI}$ to $N_{\rm HI}+dN_{\rm HI}$, and $\Phi(M_{\rm HI})$ is the H I mass function. The integral sign denotes a summation over the whole range of $M_{\rm HI}$ of the galaxies in the sample. Finally, c/H_0 converts the number of systems per Mpc to that per unit redshift. For the weighting we choose to use the morphological type-specific H I mass functions as published by Zwaan *et al.* (2003).

Fig. 1 shows the resulting $f(N_{\rm HI})$ on the left, and the derived H I mass density per decade of $N_{\rm HI}$ on the right. For comparison with higher redshift observations, we also plot the results from three other studies. The Péroux (2005) measurements of $f(N_{\rm HI})$ below the DLA limit are the result of their new UVES survey for "sub-DLAs". The lines are Schechter and a double power-law fit to the new data of Prochaska *et al.* (2005), based on an automatic search for $z > 2.2$ DLA systems in SDSS-DR3. The intermediate redshift points from Rao *et al.* (2005) are based on Mg II-selected DLA systems. All calculations are based on a $\Omega_{\rm m} = 0.3$, $\Omega_\Lambda = 0.7$ cosmology. The surprising result from this figure is that there appears to be only very mild evolution in the intersection cross-section of H I from redshift $z \sim 5$ to the present. From this figure we can determine the redshift number density of $\log N_{\rm HI} > 20.3$ gas and find that $dN/dz = 0.045 \pm 0.006$, in good agreement with earlier measurements at $z = 0$. Compared to the most recent measurements of dN/dz at intermediate z (Rao *et al.* 2005) and high z (Prochaska *et al.* 2005), this implies that the co-moving number density (or the "space density times cross-section") of DLAs does not evolve after $z \sim 1.5$. In other words, the local galaxy population explains the incidence rate of low and intermediate z DLAs and there is no need for a population of hidden very low surface brightness (LSB) galaxies or isolated H I clouds (dark galaxies). This agrees well with the measured low space densities of LSB galaxies (e.g. Driver *et al.* 2005) and the fact that blind 21-cm surveys have not turned up a single instance of an isolated dark galaxy.

The right hand panel shows that at $z = 0$ most of the H I atoms are in column densities around $N_{\rm HI} = 10^{21}$ $\rm cm^{-2}$. This also seems to be the case at higher redshifts, although the distribution might flatten somewhat. The one point that clearly deviates is the highest $N_{\rm HI}$ point from Rao *et al.* (2005) at $\log N_{\rm HI} = 21.65$. This elevated interception rate of high $N_{\rm HI}$ Mg II-selected intermediate redshift DLAs is also reported in their earlier work. The figure very clearly demonstrates that this point dominates the $\Omega_{\rm HI}$ measurement at intermediate redshifts. It is therefore important to understand whether the Mg II-based results really indicate that high column densities ($\log N_{\rm HI} \sim 21.65$) are rare at high and low redshift, but much more ubiquitous at intermediate redshifts, or whether the Mg II selection introduces currently unidentified biases.

Traditionally, at high redshifts, only the H I atoms above the DLA limit were counted in estimates of $\Omega_{\rm HI}$. In a series of papers, Péroux *et al.* (e.g. 2003, 2005) have discussed the contribution of sub-DLA systems to the total atomic gas mass density, and the most recent conclusion is that sub-DLAs host some 20% of the H I atoms at all redshifts $z > 2$. The $\Omega_{\rm HI}$ measurements at $z = 0$ are based on blind 21-cm surveys and might include a substantial contribution from column densities below the DLA limit. Therefore, potentially, when comparing $\Omega_{\rm DLA}$ at high redshift with $\Omega_{\rm HI}$ at $z = 0$, we are not comparing like with like. However, if we add up all the H I atoms in Fig. 1 below the DLA limit, we

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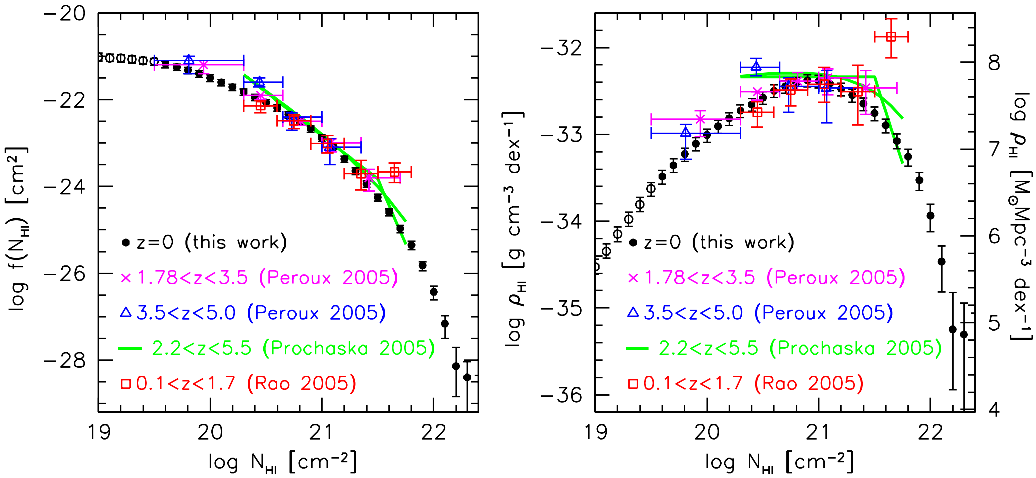

Figure 1. *Left:* The H I column density distribution function $f(N_{\rm HI})$. The solid dots are from our analysis of 21-cm maps of local galaxies, the other points are from various surveys at higher redshifts as indicated in the legend. *Right:* The contribution of different column densities (per decade) to the integral H I mass density. Note the very weak evolution in $\Omega_{\rm HI}$ from high z to the present.

find that their share in $\Omega_{\rm HI}$ is only 14%. Even if we make a correction for the column densities below our sensitivity limit, and assume that in this $N_{\rm HI}$ range the distribution function goes as $f(N_{\rm HI}) \propto {N_{\rm HI}}^{-1.5}$, we conclude that sub-DLA H I gas at $z = 0$ adds up to only $\sim$ 19% of the total H I mass.

3. Expected properties of low-z DLAs

Now that we have accurate cross-section measurement of all galaxies in our sample, and know what the space density of our galaxies is, we can calculate the cross-section weighted probability distribution functions of various galaxy parameters. In other words, we can calculate the probability distribution of parameters of galaxies whose gas disks are encountered along random lines of sight in the local Universe. Fig. 2 shows two examples. The left panel shows the B-band absolute magnitude distribution of cross-section selected galaxies above four different H I column density cut-offs. 87% of the DLA cross-section appears to be in galaxies that are fainter than L_*, and 45% is in galaxies with $L < L_*/10$. These numbers agree very well with the luminosity distribution of $z < 1$ DLA host galaxies. Taking into account the non-detections of DLA host galaxies and assuming that these are $\ll L_*$, we find that 80% of the $z < 1$ DLA galaxies are sub-L_*. The median absolute magnitude of a $z = 0$ DLA galaxy is expected to be $M_B = -18.1$ ($\sim L_*/7$). The conclusion to draw from this is that we should not be surprised to find that identifying DLA host galaxies is difficult. Most of them (some 87%) are expected to be sub-L_* and many are dwarfs.

A similar cross-section weighted distribution function can be constructed for the impact parameter between the position of the observed H I column density and the centre of the galaxy this gas belongs to. Based on our analysis, we find that the expected median impact parameter of $\log N_{\rm HI} > 20.3$ systems is 7.8 kpc, whereas the median impact parameter of identified $z < 1$ DLA galaxies is 8.3 kpc. Assuming no evolution in the

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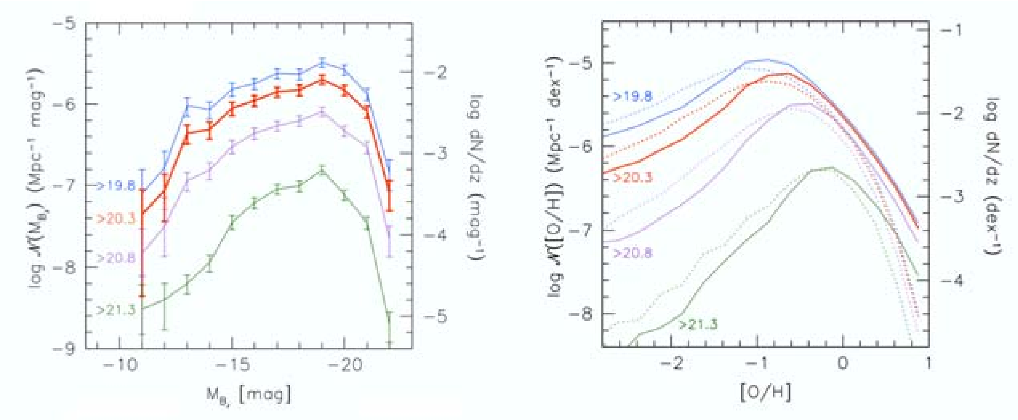

Figure 2. *Left:* The expected distribution of B-band absolute magnitudes of $z = 0$ high H I column density systems. The lines plus error bars show the product of cross-sectional area and space density, which translates to the number of expected absorbers per Mpc per magnitude. The right axis shows the corresponding number of absorbers per unit redshift dN/dz. The different lines correspond to different column density limits, as indicated by the labels. The thick line corresponds to the classical DLA limit of $\log N_{\rm HI} > 20.3$. *Right:* The probability distribution of oxygen abundance [O/H] of H I absorbers. The solid lines refer to the approach of assuming fixed [O/H] gradients and the dashed lines refer to varying gradients (see text).

properties of galaxies' gas disks, these numbers imply that 37% of the impact parameters are expected to be less than $1''$ for systems at $z = 0.5$. This illustrates that very high spatial resolution imaging programmes are required to successfully identify a typical DLA galaxy at intermediate redshifts.

The right panel in Fig. 2 shows the probability distribution of oxygen abundance in $z = 0$ DLAs. We constructed this diagram by assigning to every H I pixel in our 21-cm maps an oxygen abundance, based on the assumption that the galaxies in our sample follow the local metallicity–luminosity ($Z - L$) relation (e.g. Garnett 2002), and that each disk shows an abundance gradient of [O/H] of $-0.09\,{\rm dex\,kpc^{-1}}$ (Ferguson *et al.* 1998) along the major axis. The solid lines correspond to these assumptions. We can test the effect of varying metallicity gradients in disks of different absolute brightness by adopting the correlations found by Vila-Costas & Edmunds (1992). These measurements are completely independent of the first set of assumptions and result in the dotted curves in right panel of Fig. 2.

Although the distributions peak at slightly different locations, it is obvious that the global trends are not strongly dependent on our assumptions on abundance gradients in disks. The main conclusion is that the metallicity distribution for H I column densities $\log N_{\rm HI} > 20.3$ peaks around [O/H]=-1 to -0.7, much lower than the mean value of an L_* galaxy of [O/H]≈ 0. The reason for this being that *1)* much of the DLA cross-section is in sub-L_* galaxies, which mostly have sub-Solar metallicities, and *2)* for the more luminous, larger galaxies, the highest interception probability is at larger impact parameters from the centre, where the metallicity is lower. Furthermore, we see a strong correlation between the peak of the [O/H] probability distribution and the H I column density limit: for H I column densities in excess of $\log N_{\rm HI} = 21.3$, the expected peak of the distribution is at [O/H]=-0.2. This correlation is expected, since our assumed radial abundance gradients impose a relation between $N_{\rm HI}$ and [O/H]. Taking into account uncertainties in the H I mass function, in the $L-Z$ relation, and in the abundance gradients in galaxies, we adopt a value of [O/H]$=-0.85\pm0.2$ (1/7 Solar) as a representative value for the median cross-section–weighted abundance of H I gas in the local Universe above the DLA column density limit. For the mean mass-weighted metallicity of H I gas with $\log N_{\rm HI} > 20.3$ at $z=0$ we find the value of $\log Z = -0.35\pm0.1$.

These numbers are not very different from the $z=0$ extrapolations of metallicity measurements in DLAs. Prochaska *et al.* (2003) recently compiled metallicity measurements in DLAs over a redshift range $0 < z < 4.5$, mostly based on α-elements. The $z=0$ extrapolations of the least-squares fits to these data give an $N_{\rm HI}$-weighted value of $\log Z \approx -0.5$ and median value of $\log Z \approx -0.7$. These numbers are within 1σ of our measurements of -0.35 ± 0.1 and -0.85 ± 0.2 respectively. Therefore, these results are in very good agreement with the hypothesis that DLAs arise in the H I disks of galaxies.

4. Conclusions

The local galaxy population can explain the incidence rate and metallicities of DLAs, the luminosities of their host galaxies, and the impact parameters between the centres of host galaxies and the background QSOs.

This work is presented in much more detail in a forthcoming paper (Zwaan *et al.* 2005b)

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