Gas and Star Formation in Galaxies and QSO Absorption Line Systems

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Abstract

The statistical properties of damped Lyα systems (DLAs) and the H I disks in local galaxies are in very good agreement. We infer from this that DLAs arise in normal spiral galaxies. DLAs contain most of the neutral gas in the Universe and, as such, provide the reservoir of fuel for star formation. However, molecular detections in DLAs are rare and the implied star formation rate density from DLAs is much lower than the value measured from emission lines. In this talk I argue that the molecules do exist in DLA galaxies, but are locked up in small regions not necessarily cospatial with the high column density H I. If the molecules are taken into account, DLA galaxies can probably account for most of the star formation rate density at high z.

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1 The Universe's cold gas content

Our abilities to map and characterize the Universe's cold gas content through emission line surveys have been limited. The emission lines of simple molecules (e.g., CO) are so weak that at present they can only be detected at large distances if they are agglomerated in monstrous quantities found in rare supermassive galaxies (e.g., Walter et al. 2004, Maiolino et al. 2005). H I 21cm hyperfine line emission has so far only been detected out to a redshift of $z = 0.2$ (Zwaan et al. 2001). Measuring the individual gas masses of normal galaxies at large distances is impossible with present technology.

Yet, in the local Universe we know that these normal Milky Way-type galaxies dominate the gas mass density (Zwaan et al. 1997) and the stellar mass density (Cole et al. 2001), and it is expected that this situation is not completely reversed at earlier times (e.g., Abdalla & Rawlings 2005). The measurements

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of the cold gas mass density at $z = 0$ stem from blind 21-cm emission line surveys, carried out with single dish radio telescopes such as the Arecibo and Parkes telescopes. The largest scale blind 21-cm survey, the H I Parkes All Sky Survey (HIPASS), covered two thirds of the sky out to a redshift of 12,700 km/s and detected 5317 extragalactic H I emission line signals (Meyer et al. 2004, Wong et al. 2006). The cosmic H I mass density at $z = 0$, $\Omega_{\rm HI}$, can be measured very accurately from these kind of surveys, but as stated in the opening paragraph, at higher redshifts these measurements are presently impossible.

Despite this disability to directly detect the gas in emission, we have learned much about the global neutral gas content over cosmic time from a different observational technique. Intervening gas clouds between us and background quasars leave their imprint in the quasar spectra as Lyman α absorption features. These studies give nearly unbiased sightlines through the Universe. The frequency distribution of H I column density N of the absorbers goes roughly as $f(N) \propto N^{-1.5}$, making the highest column densities extremely rare at all cosmic times. However, it is these scanty high column density clouds that contain by far most of the neutral hydrogen mass in the Universe. Traditionally, the absorption systems with N exceeding 2×10^{20} atoms/cm^2 are referred to as Damped Lyman α systems (Wolfe et al. 1986), or DLAs, because they exhibit strong damping wings in the absorption profile. Recent observations have shown that some 80% of the cosmic neutral hydrogen mass is in these systems, both at the present epoch (Zwaan et al. 2005) and at earlier times (Péroux et al. 2005).

2 The distribution of column densities

The H I column densities seen in these DLAs agree very well with those that are typically observed in 21-cm emission line observations of the neutral gas disks in nearby galaxies. Therefore, a detailed analysis of a large sample of 21-cm maps can help in interpreting DLA statistics. Such an analysis was recently carried out by Zwaan et al. (2005) based on the WHISP sample of some 350 WSRT 21-cm maps of local galaxies. Figure 1 shows the resulting H I column density distribution function $f(N)$ at $z = 0$ as black dots with errorbars, and superimposed the measured $f(N)$ from DLAs at high z from Prochaska et al. (2005), Péroux et al. (2005) and Rao et al. (2006).

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 $z \sim 4$ to the present. Furthermore, the shape of the $f(N)$ distribution is identical at high redshift and at $z = 0$. This is particularly remarkable given the completely independent observational techniques that were used to derive the two distri-

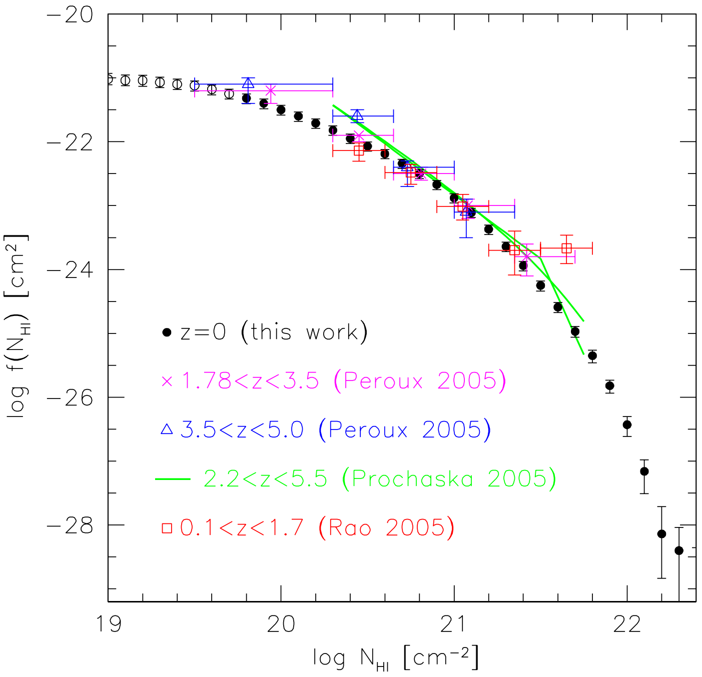

Fig. 1. The H I column density distribution function in the local Universe (black dots) and that measured at higher redshifts.

butions: 21-cm emission line maps of galaxies at $z = 0$ versus Lyα absorption line profiles of DLAs at high z. This similarity must at least be telling us that the processes that shape the $f(N)$—ionization of H I at the low N end and formation of H_2 at the high N end—must be very similar at these different moments in the history of the Universe.

From the $f(N)$ 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 and high z, this implies that the comoving 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) .

3 Cosmic gas mass density

The integral under the $f(N)$ curve gives us the total H I mass density $\Omega_{\rm HI}$. Therefore, the very modest evolution of the vertical offset of $f(N)$ immediately implies that $\Omega_{\rm HI}$ has evolved very little over the last 12 Gyrs. This situation contrasts with what was the accepted picture several years ago. Up to that time, the data were interpreted such that all the baryons locked up in stars today, were once contained in neutral hydrogen reservoirs associated with DLAs (e.g., Lanzetta et al. 1995). This idea was supported by the observation that the H I mass density in DLAs at $z \sim 3$ was equal to the mass density in stars today (e.g., Storrie-Lombardi et al. 1996). Furthermore, the mass in H I slowly declined in time, consistent with a gradual conversion of gas to stars. This simplistic but convenient interpretation was troubled by *i)* more modern cosmological parameters (Spergel et al. 2003) that caused the high redshift gas density measurements to drop, and *ii)* a better measurement of the stellar mass density at the present epoch, which came out higher than before (e.g., Rudnick et al. 2003). This now indicates that there was not nearly enough H I mass at earlier times to make up for all today's stellar mass.

In hindsight, this may not be surprising. First, a large fraction of the gas at high z is hot and ionized and therefore undetectable as Ly-α or 21-cm absorption (see, e.g., Davé et al 1999). This gas can cool and condense onto galaxies thereby generating a continuous flow of fuel for the build up of stellar mass.

Furthermore, there is still the possibility that we miss a fraction of the H I gas mass at high redshift due to the 'dust bias'. Obscuration in foreground absorbing clouds causes the apparent luminosity of the background QSOs to drop below the detection limit of the QSO survey. The jury is still out on the importance of this effect. For example, Vladilo & Peroux (2005) argue that the dust bias could lead to an underestimation of the gas mass density at high z of a factor two. Dissenting views are presented by e.g. Murphy & Liske (2005), who claim that the dust bias is likely insignificant.

Finally, an often overlooked contribution to the cool gas content at high redshift is the molecular gas. At present we have now measurement of $\Omega_{\rm mol}$ beyond $z = 0$.

4 Where are the molecules?

It was stated before that DLAs contain most of the neutral gas in the Universe, and as such are associated with the reservoir of fuel available for star formation. Star formation is believed to occur in molecular clouds, so one would logically expect that many DLAs contain molecular gas. Yet, there have been no positive detections of CO and other absorption lines in millimeter wavelength absorption line searches (e.g., Curran et al. 2004). Searches for H_2 absorption in DLAs (via the Lyman and Werner bands) show a success rate of only 20%, and even these sight lines have low molecular fractions (Ledoux et al. 2003).

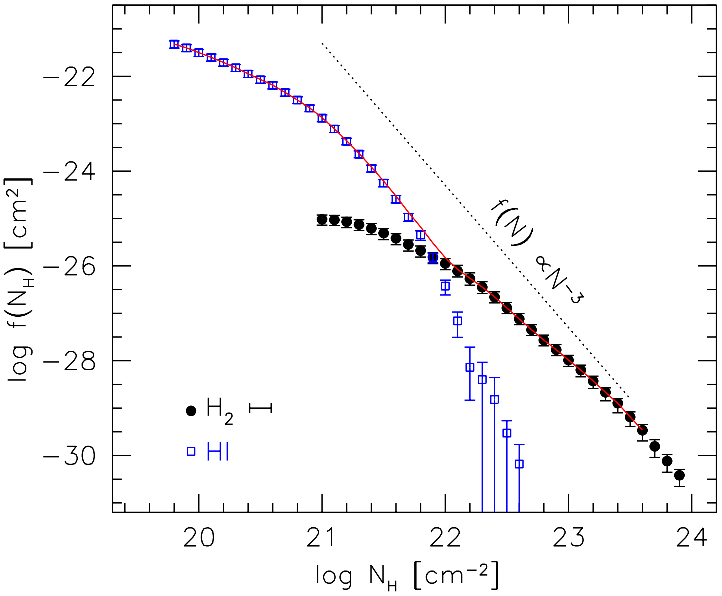

Fig. 2. The H I and H_2 column density distribution functions at $z = 0$

Before adopting the extreme and unphysical conclusion that DLAs are therefore not associated with the bulk of the star formation, it would be worthwhile examining further explanations for the lack of molecular detections in DLAs. To this end Zwaan & Prochaska (2006) analysed a sample of CO maps of nearby galaxies from the BIMA-SONG sample (Helfer et al 2003). From this sample they calculated the H_2 column density distribution function $f(N_{\mathrm{H}_2})$(using the standard CO to H_2 conversion factor X), which we reproduce in Figure 2. The distribution of H_2 column densities seems to follow a natural extension of the H I distribution function, in such a way that the summed distribution roughly follows a power-law with slope $N^{-2.5}$. The two distribution functions cross at $\log N_{\mathrm{H}} = 22$, which is the approximate column density associated with the conversion from H I to H_2 (e.g. Schaye 2001).

From this diagram we can derive that the redshift number density above the limit $\log N_{\mathrm{H}_2} = 21$ is approximately 3×10^{-4}, or a factor 150 lower than that for H I in DLAs at $z = 0$. Yet, approximately 95% of the H_2 mass density is in systems above this column density limit. The low cross sections immediately explain the low detection rate of molecules in DLAs, but there are additional effects. Molecular hydrogen forms on the surface of dust grains. The regions in galaxies containing most of the Universe's H_2 molecules are therefore likely to be dusty, causing a higher optical extinction of the background sources, which, in turn, might lead to them dropping out of magnitude-limited surveys.

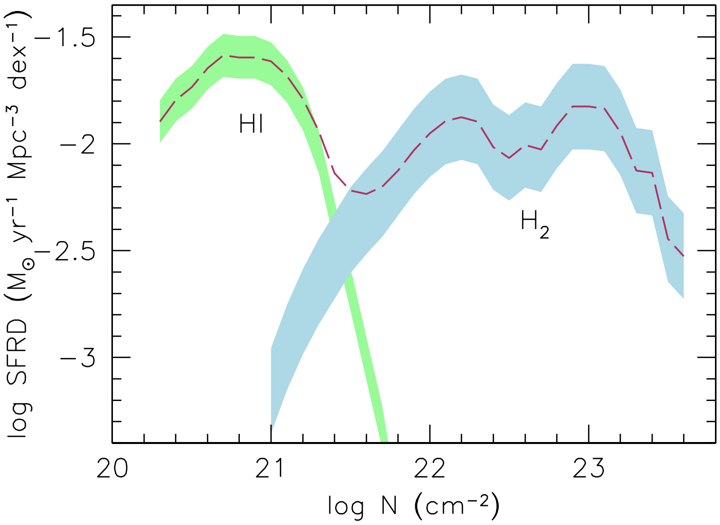

Fig. 3. The implied star formation rate density as a function of face-on H I and H_2 column density as derived from the Kennicutt (1998) star formation law. Grey areas indicate approximate uncertainties.

5 DLAs and star formation

Now back to the issue of DLAs being associated with star formation. Lanzetta et al. (2002) and Hopkins et al. (2005) recently estimated the star formation rate density (SFRD) in DLA systems by applying the 'Schmidt law' of star formation to the H I column density distribution function $f(N_{\rm HI})$. The Schmidt law is defined in local galaxies and states that the star formation rate correlates very well with total neutral gas surface density to the power 1.4, as was demonstrated by Kennicutt (1998). Using this method, it is found that the implied SFRD from DLAs is much lower than that measured directly from Hα and [O II] observations. Here, we estimate what fraction of the SFRD is actually contributed by those regions where the H_2 column is higher than the H I column. To this end, we make use of the Hopkins et al. (2005) method that relates the SFRD to the $f(N_{\rm H})$, and apply it to our measurement of $f(N_{\rm H_2})$ and $f(N_{\rm HI})$. The results are presented in Figure 3, which shows the implied SFRD as a function of H I and H_2 face-on column density. We see that the H I and H_2 column densities contribute approximately equally to the total SFRD.

The implication of this is that the H I column density distribution function from DLAs, combined with the Schmidt law for star formation, does not give a meaningful measurement of the SFRD. Clearly, to evaluate the SFRD contributed by DLAs one should take into account their molecular content, which is, however, very difficult to measure because the molecules are locked up in such small regions that the incidence rate is extremely small. These molecules are therefore probably not always present along the same sightline as the high column density H I gas, but they are present in the same 'DLA galaxy'. When discussing the contribution of DLAs to the star formation rate density it is important to differentiate between to terms: *i)* the DLA absorber, i.e., the thin sightline along which the H I column density is measured, and *ii)* the DLA galaxy, which may include H I and H_2. Star formation and the presence of neutral gas is not necessarily cotemporal and cospatial on small scales.

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