The Lyman-α emission of high-z damped Lyman-α systems

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ABSTRACT

Using a spectral stacking technique we searched for the average Lyα emission from high-z Damped Lyα (DLA) galaxies detected in the Sloan Digital Sky Survey QSO spectra. We used a sample of 341 DLAs of mean redshift < z > = 2.86 and log N(H i)\geq20.62 to place a 3σ upper limit of 3.0\times10^{-18} erg s^{-1} cm^{-2} on the Lyα flux emitted within ~1.5 arcsec (or 12 kpc) from the QSO line of sight. This corresponds to an average Lyα luminosity of \leq2\times10^{41} erg s^{-1} or 0.03 L_\odot(Lyα). This limit is deeper than the limit of most surveys for faint Lyα emitters. The lack of Lyα emission in DLAs is consistent with the in situ star formation, for a given N(H i), being less efficient than what is seen in local galaxies. Thus, the overall DLA population seems to originate from the low luminosity end of the high redshift Lyα emitting galaxies and/or to be located far away from the star forming regions. The latter may well be true since we detect strong O vi absorption in the stacked spectrum, indicating that DLAs are associated with a highly ionized phase possibly the relics of galactic winds and/or originating from cold accretion flows. We find the contribution of DLA galaxies to the global star formation rate density to be comparatively lower than that of Lyman Break Galaxies.

Key words: galaxies: quasar: absorption line – galaxies: intergalactic medium

1 INTRODUCTION

Damped Lyα (DLA) systems, detected in absorption in the spectra of background quasars are characterized by large neutral hydrogen column densities (N(H i) \geq 2 \times 10^{20} cm^{-2}) and represent the main reservoir of H i at high-z (see Noterdaeme et al. 2009, Fig. 14). The presence of associated heavy elements, the evolution of redshift of the mass density in DLAs, a signature of gas consumption via star formation and the detectability of DLAs over a wide range of redshift make them the appropriate laboratories for studying the cosmological evolution of star formation activity in a luminosity unbiased way.

Though observational studies of DLAs have been pursued over 25 years, one of the most important questions that remain unanswered yet is the connection between DLAs and star-forming galaxies. Measuring the star formation rate (SFR) in DLA-galaxies is very important as DLAs could provide substantial contributions to the global SFR density at high redshifts (Wolfe et al. 2003; Srianand et al. 2003).

At low and intermediate redshifts (z < 1), galaxy counterparts of DLAs have been identified in a number of cases (Burbidge et al. 1996; Le Brun et al. 1997; Rao et al. 2003). They are usually low surface brightness dwarf galaxies (see Rao et al. 2003). On the other hand, searches for the direct emission of the high redshift (i.e. z > 1) DLA galaxies have resulted in a number of non-detections (Lowenthal et al. 1995; Bunker et al. 1999; Colbert & Malkan 2002; Kulkarni et al. 2004; Christensen et al. 2007) and only a few cases have been spectroscopically confirmed through detection of Lyα emission (Warren & Moller 1996; Moller et al. 1998; Møller et al. 2002; 2004; Heinmüller et al. 2006; Fynbo et al. 2010). The difficulty is mainly attributed to the faint nature of the DLA galaxies and their apparent closeness to the bright background QSOs.

One indirect way to address this question is to study the relative populations of different rotational levels of molecular hydrogen (H_2) together with that of fine-structure levels of C i and C ii. The ambient UV flux and therefore the in-situ SFR can thus be derived (e.g. Hirashita & Ferrara 2003; Srianand et al. 2003; Noterdaeme et al. 2007) in a few of the ~10% of DLAs that show detectable amounts of H_2 (Petitjean et al. 2000; Ledoux et al. 2003; Noterdaeme et al. 2008). The rotational excitation seen in these H_2 bearing DLAs is consistent with an ambient UV radiation field similar to or higher than the Galactic one (Srianand et al. 2005). This may not be representative of the overall population however.

Another indirect approach is to derive the SFR through the cooling rate inferred from the C i n’11335 absorption lines as suggested by Wolfe et al. (2003a). They have estimated an average SFR per unit area of 10^{-2.2} M_\odot yr^{-1} kpc^{-2} or 10^{-1.3} M_\odot yr^{-1} kpc^{-2} if DLAs arise in cold neutral medium (CNM) or warm neutral medium (WNM) respectively. However, appreciable contribution
of C iv absorption from the warm ionised medium (WIM) as observed in the diffuse gas of the Milky Way (Lehner et al. 2004) will make the inferred SFR based on C iv absorption lines unreliable.

Thanks to the availability of a very large number of moderate resolution QSO spectra in the SDSS data base, it is possible to directly detect emission from the galaxy counterparts within 1.5 arc sec to the line of sight (Noterdaeme et al. 2010) and/or to measure the average SFR in different types of QSO absorption systems by detecting nebular emission in the stacked spectra (Wild et al. 2007; Noterdaeme et al. 2010; Ménard et al. 2009). Here, we tried to measure the average Lyα emission from DLAs using spectral stacking techniques. We describe our DLA sample in Section 2.3, discuss the stacking technique we use and the results in Section 3. We discuss the O vi detections in Section 5 and contribution of DLAs to global SFR density in Section 6. Our conclusions are presented in Section 6.

Throughout this paper we assume a standard flat ΛCDM universe with H0 = 71 km s−1 Mpc−1, Ωm = 0.26, ΩΛ = 0.74.

2 DLA SAMPLE

The sample of DLAs used here mainly comes from an automatic search for DLAs in the Sloan Digital Sky Survey II, Data Release 7 (Noterdaeme et al. 2009). This sample contains 1426 absorbers at 2.15 < z < 5.2 with log N(H i) ≥ 20, out of which 937 systems have log N(H i) ≥ 20.3. We also use additional DLAs found by Prochaska & Wolfe (2009). In total, there are 914 DLAs with redshift measurements based on metal absorption lines. We notice that the poor background subtraction leaves some spikes in the locations of strong sky lines. To avoid any systematics due to these features we have excluded systems located in regions of strong sky lines.

In order to establish the presence or absence of any Lyα emission, we need the bottom of the DLA absorption profile to be defined by enough pixels with zero flux. We will use only those DLAs for which the core (with zero flux) extends over at least three FWHM elements. Since the spectral resolution of SDSS spectra is about R = 2000, the rest FWHM of an unresolved Lyα emission is ∼ 0.61 Å. The above condition translates to a lower limit on the H i column density of log N(H i) ≥ 20.62.

By visual inspections of the individual spectra, we rejected systems showing a double absorption feature in either their Lyβ or metal absorption profiles. Indeed some of these systems may not be real DLAs as the high Lyα equivalent width may be the result of the blend of several components. We also rejected proximate DLAs located within 5000 km s−1 from the QSO redshift and ensured that there is no contamination of the sample by broad absorption lines. After applying all these conditions we are left with 341 systems with log N(H i)≥20.62 that forms our sample to be used in the stacking exercise.

3 SPECTRAL STACKING

The observed SDSS spectra were first shifted to the rest frame of the DLA conserving the flux per unit wavelength interval. The residual flux level in the core of the DLA absorption profile generally shows some non-zero off-set probably related to sky subtraction errors. We correct this off-set using the median flux in the absorption trough before stacking. While this exercise makes our stacked spectrum insensitive to the presence of continuum light from the DLA galaxy, it will not affect the detectability of the Lyα line.

The flux in each pixel of the combined spectrum is calculated by averaging the fluxes of all spectra at this position. Arithmetic mean and weighted mean are both used. In the case of weighted mean the i-band signal-to-noise ratio (SNR) is used as the weighting factor for each spectrum. We calculate the uncertainty in each pixel of the combined spectrum as the standard deviation around the mean value. We obtain a third average spectrum from the weighted mean of the values in each pixel after rejecting the 5% extreme values on either positive and negative sides.

The stacked spectra obtained using simple mean, weighted mean, and weighted mean with clipping together with associated errors are shown in Fig. The stacked DLA spectra in the corresponding samples as red continuous curves. The dashed blue curves are the synthetic profiles obtained using the lower and upper limits on N(H i) obtained in individual systems. To calculate the Lyα emission flux, in each stacked spectrum, we restrict ourselves to the wavelength range covered by the core of synthetic spectrum obtained from the lower limits on N(H i) (i.e inner dotted profiles in Fig. We obtain the limit on the Lyα emission line flux by integrating the observed flux over a gaussian function with FWHM of 200 km s−1. This value corresponds to the mean velocity widths of low ionization lines in DLAs (Ledoux et al. 2006) convolved with the SDSS instrumental broadening. The observed FWHM of the low ionization lines in our composite spectrum is consistent with this value.

The Lyα flux measurements are summarised in Table 1.1 and the gaussian fits are shown in the insets of Fig. 1. We do see marginal Lyα flux at the expected position at a ≤ 2σ level in the case of simple and weighted mean. In the case of clipped mean the bottom of the Lyα absorption profile is consistent with no Lyα emission. We estimate the 3σ upper limit (F 3σ (Lyα) given in Table 1) by using the gaussian fitting errors. As expected, the 3σ limit from the clipped mean is smaller than that from the other two methods. As this is the case with less contamination by outliers, we use the upper limit from the clipped mean composite spectrum, F 3σ (Lyα) > 3.0×10−19 erg s−1 cm−2, for all further discussions. For the SDSS fibre diameter, 3 arcsec, this limit translates to a limiting 1σ surface brightness limit of 1.4×10−19 ergs s−1 arcsec−2. This is only 1.7 times higher than that achieved in the very deep long slit spectroscopic observations by Rauch et al. (2008).

The flux limit we have achieved in the stacked spectrum is almost one order of magnitude smaller than the flux measured in the case of direct detections of Lyα emission from DLA galaxies (see Möller et al. 2004; Fynbo et al. 2010) and the typical flux limits reported for individual measurements (see Christensen et al. 2007). In addition the flux limit we have reached is much deeper than the one reached in typical blind narrow band searches for Lyα-

Table 1. Lyα measurement in the stacked spectrum.

| Stacking method              | F(Lyα) (erg s⁻¹ cm⁻²) | F 3σ (Lyα) (erg s⁻¹ cm⁻²) | L 3σ (Lyα) (erg s⁻¹ cm⁻²) |
|------------------------------|------------------------|---------------------------|---------------------------|
| simple mean                  | 0.21±0.13              | 0.39                      | 28.3                      |
| weighted mean                | 0.26±0.13              | 0.39                      | 28.3                      |
| weighted mean with clipping  | 0.13±0.10              | 0.30                      | 21.8                      |

a in units of 10⁻¹⁷ ergs s⁻¹ cm⁻²
b in units of 10⁻¹⁸ ergs s⁻¹ cm⁻²
emitters (see Ouchi et al. 2008) and comparable to the deepest limit achieved in the VVDS-LAE survey by Cassata et al. (2010).

For the mean redshift of our sample, < z > = 2.86, our limiting flux corresponds to a Lyα luminosity of $2 \times 10^{43}$ erg s$^{-1}$ (see Table 1) or $\sim 0.03 L^*$(Lyα) if we use the Schechter function parameter $L^* = 5.8 \times 10^{42}$ erg s$^{-1}$ from the narrow band Lyα search by Ouchi et al. (2008). Thus it appears that on an average, DLAs at z ~2.8 trace the faint end luminosity of Lyα emitters.

4 STAR FORMATION

We estimate the average SFR in DLAs assuming that Lyα photons mainly originate from H II regions around massive stars and case B recombination (Osterbrock 1989). Then the Lyα luminosity is related to the SFR ($\dot{M}_{\text{SF}}$) by,

$$L_{\text{Ly}\alpha} = 0.68 h v_\alpha (1-f_{\text{esc}}) N_\gamma \dot{M}_{\text{SF}}.$$  \hspace{1cm} (1)

Here, $h v_\alpha = 10.2$ eV and $f_{\text{esc}}$ are, respectively, the energy of a Lyman-α photon and the escape fraction of Lyman continuum photons. We use $f_{\text{esc}} \approx 0.1$ as measured from stacked spectra of high-z LBGs (Shapley et al. 2006). Further, $N_\gamma$ is the number of ionizing photons released per baryon of star formation. This is mainly a function of the metallicity and the stellar initial mass function (see Table 1 of Samui et al. 2007). As high-redshift DLAs have generally low metallicities, $[Z/Z_\odot] \sim -1.5$ (see Fig 3 of Noterdaeme et al. 2008), we interpolate values of Table 1 of Samui et al. (2007)'s for $[Z/Z_\odot] = -1.5$ and a Salpeter initial mass function with $\alpha = 2.35$. Lyα photons are sensitive to different kinds of radiation transport effects including resonant scattering (within the ISM as well as the intergalactic medium (IGM)) and attenuation via dust. Hence, the observed Lyα luminosity can be related to the emitted luminosity by

$$L_{\text{ Ly}\alpha}^{\text{obs}} = f_{\text{esc}}^{\text{Ly}\alpha} L_{\text{ Ly}\alpha}.$$  \hspace{1cm} (2)

where $f_{\text{esc}}^{\text{Ly}\alpha}$ is the escape probability of the Lyα photons. It is well known that only a small fraction of LBGs are Lyα emitters and even in these cases only a small fraction of Lyα photons escape the galaxy (see Kornei et al. 2010). Taking this fact into account it is appropriate to use a volumetric $f_{\text{esc}}^{\text{Ly}\alpha}$ of 0.05 as estimated by Hayes et al. (2010) for high-z galaxies. With these assumptions, the $3\sigma$ upper limit we have obtained above corresponds...
star formation activity in galaxies can lead to supernovae driven outflows of hot gas. Observations of high-$z$ Lyman Break Galaxies (LBGs) frequently show galactic scale superwinds and the mass outflow rate may be intimately related to the star formation rate (Petit [2001]). This hot gas can be traced by O vi absorption. Fox et al. (2007) have detected O vi in at least 34% of the DLAs and suggested that O vi could be present in 100% of them. We confirm this finding by detecting the O vi doublet (with rest equivalent width $W_r$(O vi$\lambda$1032) = 0.4Å) in our composite spectrum (see Fig. 5). The average deconvolved velocity width of the O vi lines (275 km s$^{-1}$) is systematically higher than that of C iv (250 km s$^{-1}$), Si iv (205 km s$^{-1}$) and singly ionization lines (~120 km s$^{-1}$). The velocity range spanned by the hot phase is therefore a factor of two larger than that of the neutral phase. This suggests a connection between actively star forming regions with outflowing and/or infalling hot gas and DLAs.

6 SUMMARY AND DISCUSSION

Using a sample of 341 DLAs with log $N$(H i)$\geq20.62$ we place a 3$\sigma$ upper limit of 3.0$x10^{18}$ erg s$^{-1}$ cm$^{-2}$ on the Ly$\alpha$ flux emitted at the redshift of the DLAs within ~1.5 arcsec (or 12 kpc at z=2.86) to the QSO line-of-sight. This corresponds to an average Ly$\alpha$ luminosity of 2$x10^{41}$ erg s$^{-1}$ or an object with a luminosity of 0.03 $L_\star$(Ly$\alpha$). Thus, the typical DLA population seems to originate from the low luminosity end of the high redshift Ly$\alpha$ emitting galaxies.

At low redshift the star forming galaxies obey the Kennicutt & Schmidt law,

$$\psi_v > \psi_v^c \Rightarrow N_{\alpha} < N_{\alpha}^{\text{crit}}$$

$$= K(N_{\alpha}/N_{\alpha}^c)^\beta, N_{\alpha} \geq N_{\alpha}^{\text{crit}}.$$ (4)

Kennicutt (1998a,b) have found $K = (2.5 \pm 0.5) \times 10^{-4} M_\odot$ yr$^{-1}$ kpc$^{-2}$, $\beta = 1.4 \pm 0.15$, $N_{\alpha}^c = 1.25 \times 10^{20}$ cm$^{-2}$ and log $N_{\alpha}^{\text{crit}} = 20.62$. Using the above equation and the $N$(H i) distribution of our sample we would expect to measure in our experiment a surface SFR of $5.5 \times 10^{-3} M_\odot$ yr$^{-1}$ kpc$^{-2}$. Assuming DLAs have a radius of 10 kpc gives an expectation of $1.7 \pm 0.4 M_\odot$ yr$^{-1}$.

This is higher than our 1.2 M$_\odot$ yr$^{-1}$ 3$\sigma$ upper limit derived in the previous Section. This suggests that star formation in DLAs is less efficient compared to what is seen in the H i disks of nearby galaxies. This is consistent with the conclusions by Wolfe & Chen (2006). In the local universe such low star formation efficiencies are seen either in the outer regions of galaxies or in dwarf galaxies (Roychowdhury et al. 2004, Bregel et al. 2010).

Using C iv$^+$ absorption lines, Wolfe et al. (2003a) have estimated the SFR per unit area, $\psi_v^c = 10^{-2.39}$ and $10^{-3.32} M_\odot$ yr$^{-1}$ kpc$^{-2}$ for CNM (cold neutral medium) and WNM (warm neutral medium) models, respectively. The pure WNM solution will require an unphysically low escape fraction ($\leq0.004$) of Ly$\alpha$ photons in order for the model to comply with our upper limit. As DLAs have very little dust content, such low Ly$\alpha$ escape fraction is unlikely. In the case of the CNM solution, for the upper limit we observe to be consistent with the C iv$^+$ measurements, the Ly$\alpha$ escape fraction $f_{\text{esc}}$ should be smaller than 0.03. This value, although low, is similar to that estimated in LBGs (Hayes et al. 2010). Note that the high-cold population of C iv$^+$ as defined by Wolfe et al. (2008) will also require unphysically low values of $f_{\text{esc}}$. In any case, it can be concluded that in situ star formation is low in DLAs.

Using deep long-slit spectroscopy of an empty field, Rauch et al. (2008) have detected extended and weak Ly$\alpha$ emitters at $2.67 \leq z \leq 3.75$ Based on the projected size (a median radius of 0.999 corresponding to a physical size of 7.7 kpc) and a volume density of $3 \times 10^{-5} h_6^3$ Mpc$^{-3}$, they found that the number per unit redshift of these emitters is consistent with that of DLAs. The

5 HIGH-IONIZATION GAS PROBED BY O vi ABSORPTION

If DLAs are associated with star forming regions, they should be associated with hot gas related to galactic outflows and/or infall of primordial gas. Indeed, numerical simulations of cosmological structure formation (e.g. Davé et al. 2001) predict that gas falling onto diffuse large-scale structures will be accelerated to supersonic speeds and become shock-heated to temperatures of $10^5$ to $10^7$ K, creating a phase known as the warm-hot IGM. Similarly a sustained star formation activity in galaxies can lead to super nova driven outflows of hot gas. Observations of high-$z$ Lyman Break Galaxies (LBGs) frequently show galactic scale superwinds and the mass
individual Ly$\alpha$ flux in these objects range from $1.5$ to $15 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ with mean and median fluxes of, respectively, $3.7$ and $3 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$. If typical DLAs were associated with these objects (with sizes less than the projected size of the SDSS fibre), then we should have detected Ly$\alpha$ emission in the stacked spectrum. Thus the analysis presented here does not support the idea that the unresolved or centrally dominated faint Ly$\alpha$ emitters found by [Rauch et al. 2008] are the host-galaxies of DLAs with log $N$(H$i$) $\geq 20.62$. However, our analysis can not rule out DLAs being similar to their amorphous extended class of objects with sizes $\geq 10$ kpc.

In summary, there are strong evidences for DLAs to be associated with regions of star-formation: (i) the median metalliclicity of DLAs is of the order of $10^{-2}$ solar (Noterdaeme et al. 2008) and is always larger than $10^{-3}$ solar (Penprase et al. 2010); (ii) we confirm the findings by Fox et al. (2007) that strong O vi absorption is associated with DLAs with a velocity spread (FWHM $\sim 250$ km s$^{-1}$) about twice larger than the velocity spread of the low-ionization gas suggesting bulk-motions in the hot phase due to kinematical input from supernovae and/or gravitational effects; (iii) C ii$^+$/C i$^+$ is detected in almost half of the DLAs and can only be explained by energy input from star-formation activity (Wolfe et al. 2008). However, we show here that the mean Ly$\alpha$ emission within 12 kpc from DLAs is smaller than the emission in most of the weak Ly$\alpha$ emitters detected by Rauch et al. (2008) and is consistent with very low in situ star formation rates. Therefore, the DL phase could be spread far away from the center of the star forming regions. The hot phase associated with DLAs could then be the relics of past wind episods in the star forming regions.

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