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Faint resonantly scattered Lyα emission from the absorption troughs of damped Lyα systems at $z \sim 3$

Michael Rauch[1]⋆ and Martin G. Haehnelt[2]⋆

[1] *Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101, USA*
[2] *Kavli Institute for Cosmology and Institute of Astronomy, Cambridge University, Madingley Road, Cambridge CB3 0HA*

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ABSTRACT

We demonstrate that the Lyα emission in the absorption troughs of a large sample of stacked damped Lyα absorption systems (DLAS) presented by Rahmani et al. is consistent with the spectral profiles and luminosities of a recently detected population of faint Lyα emitters at $z \sim 3$. This result supports the suggestion that the faint emitters are to be identified with the host galaxies of DLAS at these redshifts.

Key words: line: profiles – radiative transfer – galaxies: dwarf – galaxies: formation – galaxies: high-redshift – quasars: absorption lines.

1 INTRODUCTION

An ultra-deep spectroscopic blind survey (Rauch et al. 2008, hereafter R08) has revealed the existence of numerous, faint, spatially extended Lyα emitters at $z \sim 3$. The inferred rate of incidence of the emitters and the observed signatures of resonant radiative transfer suggest that the emission originates from regions corresponding to high column density H I quasi-stellar object (QSO) absorption systems. R08 proposed that these objects may thus be identified with the elusive host galaxies of damped Lyα absorption systems (DLAS) and Lyman limit systems (LLS). Their study showed that even objects with the low luminosities and low masses characteristic of high-redshift dwarf galaxies are surrounded by extended gaseous haloes, whose intrinsic Lyα emission can typically be traced out to radii of at least 4 arcsec.

Rahmani et al. (2010) recently published a high signal-to-noise ratio (S/N) composite spectrum of the absorption trough of high-redshift DLAS from the Sloan Digital Sky Survey (SDSS), to search for Lyα emission from the underlying galaxies giving rise to the DLAS. Their sample represents low-resolution ($R = 2000$) spectra of 341 DLAS, with column densities exceeding $\log N_{\mathrm{H\,I}} = 20.62$. The DLAS were shifted to the rest frame and then averaged according to various prescriptions. The individual QSO spectra used represent the integrated light of fibres with 3-arcsec diameter. Since many of the R08 objects have relatively compact cores of Lyα emission (on top of more extended low light level emission), a significant fraction of the Lyα luminosity of such galaxies should occur close enough to the line of sight to be recorded within the fibre radius, *assuming that these emitters are in fact associated with DLAS*. Rahmani et al. establish upper limits on the flux in a central wavelength region of the stacked absorption troughs. Based on this result they conclude that the low mean flux permitted by their analysis contradicts, at the 3σ level, the suggestion that DLAS could correspond to a population of Lyα emitters with a mean flux as high as found by R08. We argue here that this conclusion is based on an inappropriate model of the emission profile used by Rahmani et al. When allowance is made for the resonant scattering of the Lyα photons with their inherent wavelength shifts and asymmetries, their combined DLA profile is consistent with substantial Lyα flux and supports, rather than contradicts, the correspondence between DLAS and Lyα emitters proposed by R08.

2 THE EXPECTED Lyα EMISSION PROFILE

Rahmani et al. searched for Lyα emission at the centre of the DLA line, assuming a Gaussian velocity distribution with a width of 200 km s^{-1}. This model would be appropriate for optically thin emission, broadened only by galactic velocity dispersion and the instrumental profile. However, numerous theoretical studies of radiative transfer through the very optically thick DLAS (e.g. Zheng & Miralda-Escudé 2002; Dijkstra, Haiman & Spaans 2006; Verhamme, Schaerer & Maselli 2006; and references therein) have shown that the generic emission line profile is double-humped, with apparent velocity shifts of hundreds of km s^{-1} between the blue and red components, and little emission at all at the systemic redshift. The profile is further modified by the motion of the gas. Observationally, in high-redshift galaxies the red peak dominates, and the blue peak is highly reduced in size. This pattern can be accomplished by Lyα propagating through an expanding halo, partial absorption by intervening Lyα forest clouds, or a combination of both (e.g. Dijkstra et al. 2006; Barnes & Haehnelt 2010; Laursen, Sommer-Larsen & Razoumov 2010). The pattern of a dominant red peak, absorption trough and faint blue peak is clearly seen in the brighter of the sources found by R08, and a similar pattern (with

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⋆E-mail: mr@obs.carnegiescience.edu (MR); haehnelt@ast.cam.ac.uk (MGH)

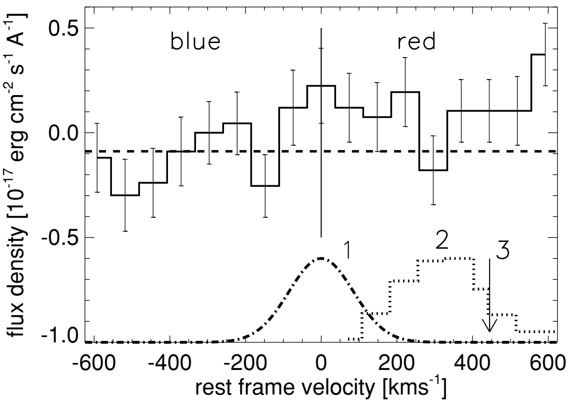

Figure 1. Residuals of the flux density at the bottom of the stacked DLA trough published by Rahmani et al. (2010), obtained by subtracting the DLA model in their Fig. 1 (weighted mean with 5 per cent clipping, their rightmost panel) from the flux histogram. The vertical line is centred on the systemic velocity of the DLAS absorption line. The horizontal dashed line shows the mean flux in the left (blue) half of the absorption line, as a better estimate of the zero level. The bottom of the plot (arbitrary offset with arbitrary units) shows: (1) the shape of the selection window of Rahmani et al. (a Gaussian with full width half-maximum 200 km s^{-1}); (2) for illustrative purposes, a theoretical emission profile for a spherical DLA halo expanding homologously with up to 200 km s^{-1}, with column density 2×10^{20} cm^{-2} and temperature $T = 2 \times 10^4$ K (Zheng & Miralda-Escudé 2002); (3) the mean position (arrow) of the Lyα emission line in the Lyman break galaxy sample by Steidel et al. (2010) (the velocities extend redward beyond the frame of the plot).

even less blue emission) is seen in the much brighter Lyman break galaxies. In the latter objects, the red line suffers a mean shift of 445 km s^{-1} relative to the systemic velocity (Steidel et al. 2010). Similarly large shifts are predicted for Lyα photons passing through simple static slabs of H I gas with column densities typical of DLAS (e.g. Dijkstra et al. 2006; Hansen & Oh 2006). Thus, unless there are many objects where the Lyα escapes through optically thin holes in the H I distribution [as may be produced through photoionization by an active galactic nucleus (AGN)], there should be little flux at the centre of most DLA troughs. Note that the population of Lyα emitters, at least at its bright end, where there are more detailed observations, harbours only a small contamination by AGN (e.g. Ouchi et al. 2008).

Among the non-AGN Lyα emitters, the red peak can occur over a wide range of velocities on the red (right-hand) side of the absorption trough, with the position determined by column density, temperature, kinematics and possibly dust in a not necessarily trivial way. The intensity in the blue half of the trough should generally be weaker in proportion to the ratio between blue and red peaks. Thus we expect an upward jump in the flux density when going from the blue to the red half of the bottom of the DLA line. Such a spectral distribution of the Lyα emission is indeed suggested by the appearance of the stacked spectrum of Rahmani et al. In our Fig. 1 we show the residuals obtained after we subtracted their model of the DLA trough from the flux density in the rightmost panel (weighted mean with 5 per cent clipping) of their fig. 1. We also compare the spectral profile assumed by Rahmani et al. with a more realistic, predicted profile of an individual emitter taking into account the expected resonant scattering of the Lyα emission. We further show the mean observed position of the Lyα line in a sample of Lyman break galaxies. Note that for a large ensemble of emitters, a broad distribution of the location and width of the 'red peak' would be expected. For a stacked spectrum like the one of Rahmani et al., this should lead to a broad emission feature on the red side of the trough, extended over several hundred km s^{-1}. Unfortunately, because of their faintness, we cannot determine the systemic redshifts of the R08 emitters so it is not possible to stack the R08 spectra to directly determine the shape of the combined emission feature.

The mean observed flux density over the entire trough in Fig. 1 is $(3.4 \pm 7.8) \times 10^{-19}$ erg s^{-1} cm^{-2} Å, i.e. consistent with zero, in agreement with Rahmani et al.'s statement that a global correction of the zero level has been performed for each spectrum to account for imperfections in the sky background subtraction. However, the Kolmogorov–Smirnov probability for the residuals in the 16 pixels with error bars in their figure to be consistent with zero flux throughout is only 1 per cent. The probability for the flux density in the blue half and the red half of the DLA trough (the bluest 8 pixels and the reddest 8 pixels of the residuals) to be drawn from the same sample is likewise less than 1 per cent, i.e. the flux levels in the blue and red half of the trough are significantly different, and not consistent with being at the true zero level. The mean flux density in the left-hand side of the trough (bluest 8 pixels plus half of the central pixel) and the right-hand side of the trough (right half of the central pixel and the redward adjacent 8 pixels) are $(-0.87 \pm 0.55) \times 10^{-18}$ and $(1.23 \pm 0.54) \times 10^{-18}$ erg s^{-1} cm^{-2} Å, respectively.

Without any detailed radiative transfer model or statistical distribution of profile shapes, we can still obtain a very simple lower limit to the total flux by *assuming that all the flux emerges in the red half of the profile*. This amounts to ignoring the blue peak entirely and is probably correct to better than 10 per cent (judging from the spectra in R08). The integrated flux in the red half of the trough, covering wavelengths in the range [1215.67, 1218.2] Å or velocities in the range [0, 624] km s^{-1}, i.e. the wavelength region occupying the right-hand half of Fig. 1, is $(3.11 \pm 1.38) \times 10^{-18}$ erg s^{-1} cm^{-2}. This assumes that the zero-level was correctly determined in the spectrum by Rahmani et al. (2010). However, the zero level was adjusted globally for the trough and the flux level is sloping so both halves of the trough cannot be simultaneously at the correct zero level. If we enforce the trivial condition that the flux must be equal or greater than zero in both halves of the DLA trough simultaneously, we are forced to raise the zero level flux density in the entire region at least by the amount of 0.87×10^{-18} erg s^{-1} cm^{-2} Å. This leads to zero flux in the blue side, and to a corrected flux density for the red half of $(2.11 \pm 0.78) \times 10^{-18}$ erg s^{-1} cm^{-2} Å. The total flux in the red side, over the interval [0, 624] km s^{-1} is then $(5.35 \pm 1.97) \times 10^{-18}$ erg s^{-1} cm^{-2}.

The results are robust with respect to different choices in averaging the spectra. Applying the same analysis to the unweighted mean spectrum (Rahmani et al., panel 1 in their fig.1) we get similar numbers, a required upward correction of the zero level by 0.97×10^{-18} erg s^{-1} cm^{-2} Å and a total flux in the red side of $(4.9 \pm 2.6) \times 10^{-18}$ erg s^{-1} cm^{-2}.

The errors here are purely statistical and do not take into account the uncertainty regarding the shape of the true flux density distribution. The flux value given here should systematically underestimate the true flux in several ways. We have ignored any flux in the blue peak, have raised the global continuum level only so far that the blue side is zero and have limited ourselves to take into account only flux within [0, 624] km s^{-1} redward of the rest-frame wavelength. If the emission profiles are similar to those of the brighter observed emitters detected by R08 (or those of typical Lyman break galaxies with detectable Lyα emission), these shortcomings may, however, be relatively unimportant at the level of accuracy achieved here.

We emphasize that the above result is only a marginal detection. The method of stacking many low S/N spectra from the SDSS still falls short by a factor of 4–6 (Rahmani et al. erroneously give a factor of 1.7) of the sensitivity reached by R08 in detecting individual Lyα emitters. Much larger samples of DLAS spectra (or larger S/N of individual spectra) will be required to match the R08 detection threshold.

Finally, we would like to note that the selection criteria for the emitters in R08 and Rahmani et al. (2010) are rather different. The stacking of DLA troughs by definition is sensitive to the flux from DLAS host galaxies within 1.5 arcsec (or at least a significant fraction of the flux for the less extended objects). The emitters of R08 were instead detected when part of their Lyα emission intersected a randomly positioned long slit. H I ionizing photons can be efficiently converted into Lyα at column densities below those characteristic of DLAS (e.g. Gould & Weinberg 1996) and the Lyα can be scattered into the line of sight at even lower column densities (e.g. Barnes & Haehnelt 2010). Some of the Lyα photons received from the R08 emitters should thus originate from regions with column densities characteristic of sub-DLA or LLS. In consequence, sometimes only a minor fraction of their total luminosity may be recorded by the resulting spectrum. Most of these galaxies are still likely to host DLAS, but their luminosities may (in some cases) be severely underestimated by only part of their light falling through the slit. Note further that the redshift distribution of the Rahmani et al. sample extends to higher redshift. A more precise quantitative comparison will need to take these observational differences into account.

3 CONCLUSIONS

Lyα emitters associated with optically thick gaseous haloes show asymmetric and mostly redshifted line profiles that, in aggregate, can produce a tilt of the flux level at the bottom of a DLA absorption profile. We identify such a pattern in the stacked DLAS spectrum presented by Rahmani et al. (2010) and estimate the flux emerging from the trough. Taking into account the expected effects of resonant scattering on the spectral distribution of the emission and the probable oversubtraction of the sky background at the bottom of the profile, we arrive at a much higher (but still only marginally significant) estimate for the average Lyα flux than Rahmani et al. Our lower limit of Lyα flux emerging at the bottom of the stacked DLAS profile (clipped weighted mean) gives $(5.35 \pm 1.97) \times 10^{-18}$ erg s^{-1} cm^{-2}. This value is within one standard deviation of the mean flux of the R08 emitters, 3.7×10^{-18} erg s^{-1} cm^{-2}, in reasonable agreement with that independent estimate. The average luminosity of Lyα emitters causing DLAS in the line of sight to background QSOs is similar or perhaps even somewhat larger than the average luminosity of faint Lyα emitters in the R08 sample. Thus, contrary to the claim by Rahmani et al, our present analysis lends additional support to the conclusions by Rauch et al. (2008) that their Lyα emitters largely overlap with the host galaxies of DLAS.

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REFERENCES

Barnes L. A., Haehnelt M. G., 2010, MNRAS, 403, 870
Dijkstra M., Haiman Z., Spaans M., 2006, ApJ, 649, 14
Hansen M., Oh S. P., 2006, MNRAS, 367, 979
Gould A., Weinberg D. H., 1996, ApJ, 468, 462
Laursen P., Sommer-Larsen J., Razoumov A. O., 2010, preprint (arXiv:1009.1384)
Ouchi M. et al., 2008, ApJS, 176, 301
Rahmani H., Srianand R., Noterdaeme P., Petitjean P., 2010, MNRAS, 409, 59
Rauch M. et al., 2008, ApJ, 681, 856
Steidel C. C., Erb D. K., Shapley A. E., Pettini M., Reddy N., Bogosavljevic M., Rudie G. C., Rakic O., 2010, ApJ, 717, 289
Verhamme A., Schaerer D., Maselli A., 2006, A&A, 460, 397
Zheng Z., Miralda-Escudé J., 2002, ApJ, 578, 33

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