A&A 422, L33–L37 (2004)
DOI: 10.1051/0004-6361:20040194

Astronomy & Astrophysics

Letter to the Editor

Detection of Lyman-α emission from a DLA galaxy: Possible implications for a luminosity-metallicity relation at $z = 2$–3⋆

P. Møller[1], J. P. U. Fynbo[2,3], and S. M. Fall[4]

[1] European Southern Observatory, Karl-Schwarzschild-Straße 2, 85748 Garching by München, Germany
e-mail: pmoller@eso.org
[2] Department of Physics and Astronomy, University of Århus, Ny Munkegade, 8000 Århus C, Denmark
[3] Astronomical Observatory, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen Ø, Denmark
[4] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

Received 20 February 2004 / Accepted 11 June 2004

Abstract. In an ongoing programme to identify a sample of high z DLA galaxies we have found the long sought for case of a Lyα emitter seen in the centre of a broad DLA trough. This is the predicted "textbook case" of an intervening DLA galaxy if DLA galaxies are small, but would not be expected if intervening high redshift DLA galaxies have large gaseous disks. The Lyα flux is $5.4^{+2}_{-0.8} \times 10^{-17}$ erg s^{-1} cm^{-2} similar to what has been found in previously known high z DLA galaxies. The impact parameter is found to be $0\farcs3 \pm 0\farcs3$. This is smaller than what was found in previous cases but still consistent with random sight-lines through absorbers with mean impact parameter $\approx 1''$. Of the 24 DLAs targeted in the NICMOS imaging survey five have now been identified as Lyα emitters. The DLA galaxies with detected Lyα emission tend to have higher interstellar metallicities than those with undetected Lyα emission. This is plausibly explained as a consequence of a positive correlation between the Lyα line luminosities of the galaxies and their metallicities, although the present sample is too small for a definitive conclusion. The available observations of high-redshift DLA galaxies are also consistent with a negative correlation between Lyα equivalent widths and metallicities, as seen in nearby star-forming galaxies and usually attributed to the preferential absorption of Lyα photons by dust grains.

Key words. galaxies: formation – galaxies: high-redshift – quasars: absorption lines – quasars: individual: PKS 0458-02

1. Introduction

Shortly after publication of the first sample of Damped Lyα Absorbers (DLAs, Wolfe et al. 1986) it was suggested that Lyα emission from the absorbing galaxies should be detectable as a central spike in the trough of the damped Lyα line (Foltz et al. 1986). Two conflicting views on the nature of high redshift DLA galaxies were in disagreement on this prediction. Wolfe (1986) and Smith et al. (1986) both suggested that the 5 times higher cross-section of high-redshift DLAs relative to local spirals indicated that DLAs were fully formed disks with radii $\sim \sqrt{5}$ times larger than locally. Tyson (1988), on the other hand, argued that DLAs could be gas-rich dwarf galaxies. Two observing strategies were adopted reflecting the two views. Under the assumption that the DLA is small its impact parameter relative to the QSO shall also be small, and therefore a long-slit centred on the QSO should have a high probability of also covering the DLA (e.g., Hunstead et al. 1990). If on the other hand DLAs are large disks they may have large impact parameters relative to the QSOs and narrow band imaging would be a better approach (Smith et al. 1989; Wolfe et al. 1992).

At redshifts ≤ 1 photometric redshifts are now known for 11 DLA galaxies (Chen & Lanzetta 2003) but evolutionary models predict that DLA galaxies at higher redshifts are of a different nature (Lanfranchi & Friaca 2003).

In this paper we present the detection of Lyα emission from the $z = 2.0395$ DLA towards PKS 0458-02 at $z = 2.286$. This detection was obtained in the course of a spectroscopic investigation of three candidate DLA galaxy counterparts reported by Warren et al. (2001). The Lyα emission from the DLA towards PKS 0458-02 does not correspond to any of the candidates at projected distances $0\farcs86$–$4\farcs17$, on the contrary it is found almost exactly in the centre of the DLA absorption line, thereby presenting itself nicely as a "textbook example" of Lyα emission from a high-redshift DLA.

2. Observations and data reduction

Long-slit spectroscopy of PKS 0458-02 was obtained during two dark nights at the ESO Very Large Telescope in October 2000. We used FORS1 with the G600B grism and a $1\farcs31$ wide slit providing a spectral resolution of about

⋆ Based on observations collected at the European Southern Observatory, Paranal, Chile (ESO Programme 66.A-0386(A)).

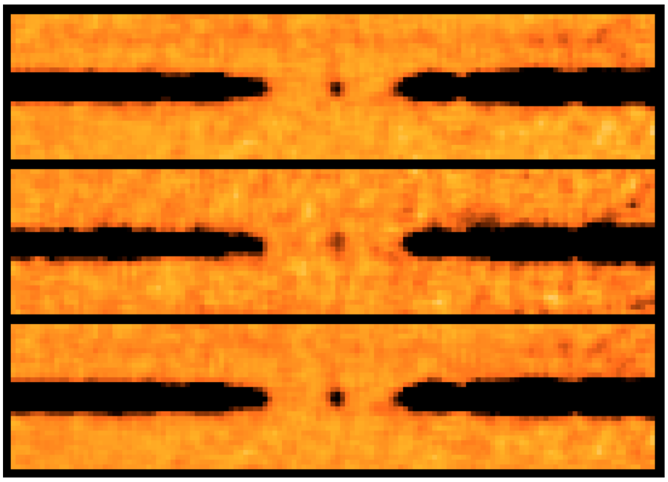

Fig. 1. 2D spectra of the DLA at z = 2.0395. The top spectrum is obtained with the slit at PA = 55°.0 (E of N), the middle spectrum at PA = 28°.8, the bottom spectrum is the weighted sum of the two. In all three blue is to the left red to the right, upwards is roughly NE. The emission peak is clearly seen in the centre of the broad absorption feature.

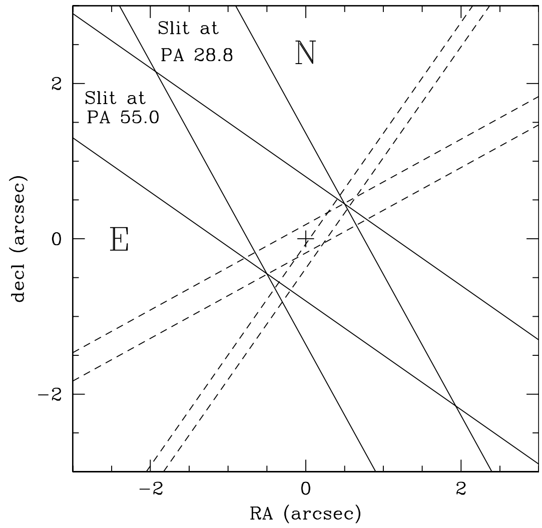

Fig. 2. Layout of the slits (full drawn lines) and determined 1σ ranges of the position of the DLA galaxy DLAg0458-02 (dashes). The position of PKS 0458-02 is marked by the "+".

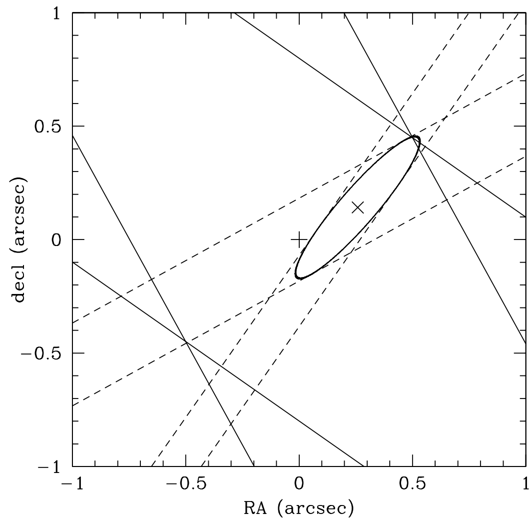

Fig. 3. Inner 2″ by 2″ of the field around PKS 0458-02. The ellipse marks the combined 1σ contour of the position of DLAg0458-02. The most likely position is marked by an "×" at PA = 300°, $b_{\rm DLA}$ = 0″.30.

7 Å *FWHM* for objects wider than the slit. During read-out we binned the data 2 by 2 providing final pixels of size 0″.4 by 2.22 Å. The conditions during observations were photometric and the seeing ranged from 0″.6 to 0″.9 resulting in a resolution of 4−5 Å for point sources. A total integration time of 11 400 s was split as follows: three 2000 s and one 1400 s exposures at a slit position angle of +55°.0 (East of North); two 2000 s exposures at a slit position angle of +28°.8. The two position angles were chosen to be lined up with three candidate galaxies N-6-1D, N-6-4C, and N-6-5C (Warren et al. 2001). The individual spectra were bias subtracted following standard techniques, but after extensive testing we found that the spectroscopic daytime flats were of inferior quality and that better flat fielding was obtained with a combination of a U band imaging flat and a 1D "along slit efficiency curve", both obtained during twilight. Acquisition images were taken in R-Bessel and we found R(Bess) = 18.43 ± 0.05 for PKS 0458-02.

3. Results

We did not detect emission lines in any of the three targeted candidates (at impact parameters 0″.86, 2″.98, and 4″.17) but at both PAs we clearly detect an emission line in the centre of the DLA absorption line, and at close to zero impact parameter (Fig. 1). Since this object does not appear in any candidate list we shall in what follows name it DLAg0458-02.

At PA = 55°.0 and PA = 28°.8 we find impact parameters of b_{55} = 0″.13 ± 0″.09 and $b_{28.8}$ = 0″.00 ± 0″.16 respectively. In Fig. 2 we show the layout of the slit positions (solid lines) and the 1σ ranges of the position of DLAg0458-02 inferred from the two independent detections. In principle two different slit PAs is enough to triangulate for the exact position of the DLA galaxy, but unfortunately the two PAs are rather close to each other so there is still uncertainty about the exact impact parameter.

In Fig. 3 we show an enlargement of the inner 2″ by 2″ where we have calculated the combined 1σ contour. The best fit position of DLAg0458-02 is at PA = 300°, $b_{\rm DLA}$ = 0″.3, but the entire PA range from 175° to 315° is allowed to within 1σ. The full 1σ range on $b_{\rm DLA}$ is from 0″.0 to 0″.6. There is a hard upper limit of $b_{\rm DLA} \leq$ 0″.8 as a larger impact parameter would cause the object to fall outside the slit. We conclude that $b_{\rm DLA}$ = 0″.3 ± 0″.3. An impact parameter of b = 0″.3 is too small for a detection in the NICMOS survey of Warren et al. (2001).

In Fig. 4 we show the 1D extraction of the spectrum (optimally weighted sum of both PAs) and the Lyα emission line is clearly seen in the centre of the Damped absorption line. We determine the centroid of the emission line to be at 3696.86 Å corresponding to a redshift of 2.0410 which is 148 km s^{-1} higher than that of the DLA. However, this is only correct if one assumes $b_{\rm DLA}$ = 0. For our best fit value of $b_{\rm DLA}$ = 0″.3 we must

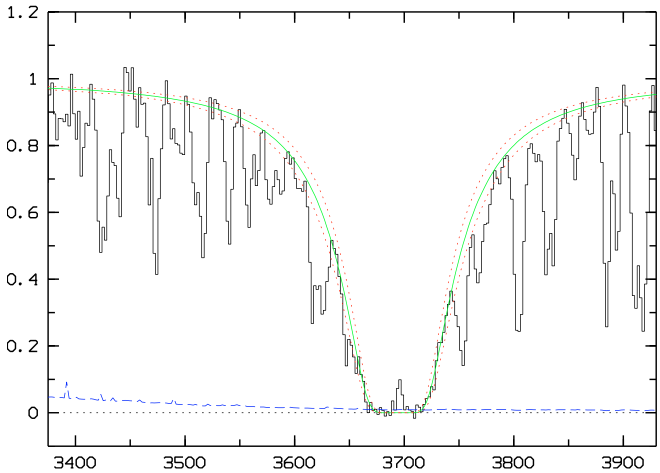

Fig. 4. FORS1/G600B spectrum of the z = 2.0395 Damped Lyα line. Calculated Lyα lines with columns of 6×10^{21} cm^{-2} (full green line), 5 and 7×10^{21} cm^{-2} (dotted red lines) are also shown. Lyα emission from the DLA galaxy is seen in the centre of the absorption line. The 1σ noise spectrum (per 5 Å resolution element) is shown as a dashed line (blue). The emission line is detected at 9.3σ.

correct the redshift for the offset of the object inside the slit and we then obtain a redshift of 2.0396 which is identical to that of the DLA. We shall adopt this latter redshift as the best fit value. The emission line is unresolved at our resolution and we find an upper limit of *FWHM* $\leq$ 5 Å corresponding to an upper limit of 400 km s^{-1} *FWHM*.

As seen in Fig. 4 the absorption profile is well fitted by a damped Lyα line with an HI column density of $6 \pm 1 \times 10^{21}$ cm^{-2}. This is slightly larger than, but consistent with, the values found by Wolfe et al. (1993) (5×10^{21} cm^{-2}) and Pettini et al. (1994) ($4.5 \pm 1 \times 10^{21}$ cm^{-2}).

The flux of the Lyα emission line, as well as other relevant measurements, are summarised in Table 1. The listed +1σ on the Lyα flux is mostly due to the uncertainty of the correction for slit-losses (which are linked to the error on $b_{\rm DLA}$), the listed -1σ is mostly due to the uncertainty of the flux calibration. The Lyα flux of DLAg0458-02 is within the range found for Lyα selected galaxies at the same redshift (Fynbo et al. 2002). The continuum of the DLA galaxy is for the most part hidden under the QSO spectrum but a small fraction of it could be visible in the DLA trough. To place a limit on the equivalent width of the emission line we proceeded as follows. On the best fitting Lyα absorption line profile (6×10^{21} cm^{-2}) we determined the interval in which the calculated absorption line was completely black (i.e. residual flux below 1/5 of the rms in the data). This is the case over an interval of 38 Å. The central 15 Å are taken up by the emission line, the rest we summed up to see if a galaxy continuum could be detected. We did not detect any continuum, and we find a 2σ lower limit on the observed equivalent width of 47 Å or a rest equivalent width of $W_{\rm r} \geq 15.3$ Å (2σ limit).

A long slit spectrum taken at PA = 300° should be obtained in order to verify the best fit impact parameter and PA found via triangulation. This is needed to settle all open questions related to the exact position of DLAg0458-02 inside the slit (redshift, velocity relative to absorber, flux correction for slit loss).

Table 1. Data for PKS 0458-02 and DLAg0458-02.

Quasar redshift	2.286[1]	
Quasar R(Bessel)	18.43 ± 0.05	
Absorption redshift	2.0395[1]	
$N_{\rm HI}$	$6 \pm 1 \times 10^{21}$	cm^{-2}
Impact parameter, $b_{\rm DLA}$	$0\farcs3 \pm 0\farcs3$	
Position angle	300^{+15}_{-125}	degrees (E of N)
Lyα emission line redshift	2.0396[2]	
Δv(Lyα - DLA)	10 ± 150[2]	km s^{-1}
Lyα *FWHM*	≤400	km s^{-1}
Lyα flux	$5.4^{+2}_{-0.8} \times 10^{-17}$	erg s^{-1} cm^{-2}
Lyα $EW_{\rm rest}$	>15.3 (2σ limit)	Å

[1] Pettini et al. (1994); [2] after correction for inferred offset in slit.

4. Discussion

The Warren et al. (2001) NICMOS imaging survey targeted a sample of 24 DLAs and sub-DLAs ($N_{\rm HI} \lesssim 2 \times 10^{20}$ cm^{-2}, Dessauges-Zavadsky et al. 2003). That sample was selected to cover a wide range in redshifts and in HI column densities but absorber metallicities were not considered. At the time of sample definition precise metallicities were known for only very few DLAs and the sample therefore has no metallicity preselection biases. Of the 24 systems five have now been identified as Lyα emitters. Three of the five have known metallicities while for one additional system a lower limit to its metallicity has been published. The metallicities and other relevant information for the five identified systems is summarised in Table 2. Metallicities are also known for 13 of the 19 systems for which no Lyα emission has yet been reported (Kulkarni & Fall 2002; Prochaska 2003; Dessauges-Zavadsky et al. 2003).

4.1. A possible luminosity-metallicity relation for DLA galaxies

Figure 5a is a histogram of the interstellar metallicities of the 17 DLA systems in the Warren et al. (2001) NICMOS sample for which the metallicity is known. The subsample of four objects with detected Lyα emission is indicated by solid blue bars, while the subsample of 13 systems without detected Lyα emission is indicated by red hatched bars. Evidently, there is a tendency for the detected objects to have higher metallicities than the undetected objects, although the sample is too small to draw a definitive conclusion from this comparison. Four of the objects in the Warren et al. sample might not be regarded as "bona fide" DLAs in the sense that they are close to the QSO ($\Delta \lesssim 3000$ km s^{-1}) or that they have relatively low HI column densities ($N_{\rm HI} \lesssim 2 \times 10^{20}$ cm^{-2}). Figure 5b shows the metallicity histogram with these objects excluded. Again, the two objects with detected Lyα emission have higher

Table 2. Lyα emission and metallicity data for five $z \geq 1.9$ DLA galaxies. $b_{\rm DLA}$ is the impact parameter, $\log(N)$ is the HI column density, and Δv is the difference between DLA redshift and QSO redshift given in km s^{-1}. The "Type" classifications in the last column are defined as "$z_{\rm a} \approx z_{\rm e}$": $|\Delta v| \leq 3000$ km s^{-1}; "sub-DLA": $\log(N) \leq 20.3$; "DLA": classic intervening non-sub DLAs.

ID	NICMOS ID	$z_{\rm DLA}$	$b_{\rm DLA}$ $''$	Emission refs.	$\log(N)$ cm^{-2}	[M/H]	M	[M/H] refs.	$z_{\rm QSO}$	Δv km s^{-1}	Type
DLAg0528–25	N-7-1C	2.8110	1.14(2)	1, 3, 5, 10, 11	21.35	–0.75, –0.76	Si, Zn	14, 15	2.797	–1100	$z_{\rm a} \approx z_{\rm e}$
sDLAg2233+13	N-16-1D	3.1493	2.51(2)	2, 4, 10, 11, 12	20.00	≥–1.04	Si	16	3.298	10 500	sub-DLA
DLAg0151+04	–	1.9342	0.93	6, 7, 8, 9	20.36				1.922	–1200	$z_{\rm a} \approx z_{\rm e}$
DLAg2206–19	N-14-1C	1.9205	0.99(2)	10, 11	20.65	–0.39, –0.42	Zn, Si	15, 17	2.559	58 600	DLA
DLAg0458–02	–	2.0396	0.3(3)	13	21.78	–1.17, –1.19	Zn, Zn	15, 17	2.286	23 300	DLA

(1) Møller & Warren (1993); (2) Steidel et al. (1995); (3) Warren & Møller (1996); (4) Djorgovski et al. (1996); (5) Møller & Warren (1998); (6) Møller et al. (1998); (7) Fynbo et al. (1999); (8) Møller (1999); (9) Fynbo et al. (2000); (10) Warren et al. (2001); (11) Møller et al. (2002); (12) Christensen et al. (2004); (13) this paper; (14) Lu et al. (1996); (15) Kulkarni & Fall (2002); (16) Lu et al. (1998); (17) Prochaska et al. (2003).

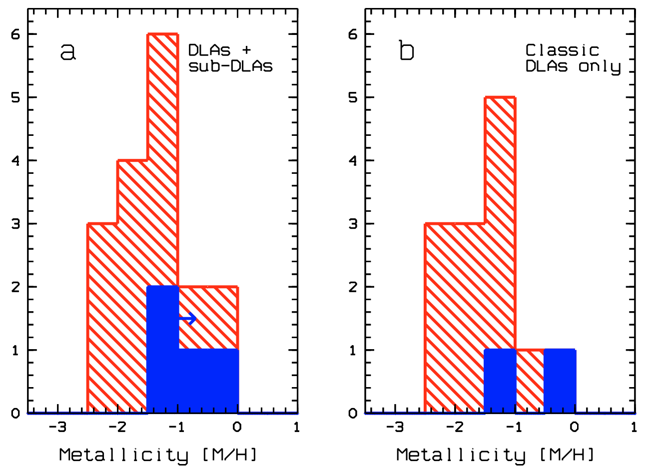

Fig. 5. *Left*: histogram of metallicities of the 17 DLAs of the NICMOS sample for which metallicities are known (hashed red). Of the 17 only 4 have been detected as Lyα emitters (shaded blue). Note that for one of them the metallicity is a lower limit (≥ -1.04, marked by the blue arrow) and may shift towards the right when a final metallicity is determined. *Right:* the same as histogram **a)** but sub-DLAs and $z_{\rm abs} \approx z_{\rm em}$ DLAs have been excluded leaving only 13 objects.

metallicities, on average, than the 11 objects without detected Lyα emission.

The trend displayed in Figs. 5a and 5b is consistent with a positive correlation between Lyα line luminosity and metallicity. This in turn is consistent with a correlation between star formation rate, for which Lyα is an approximate indicator, and metallicity. For nearby galaxies ($z = 0$), there are well known correlations between star formation rate and mass and between metallicity and mass, in the sense that high-mass galaxies tend to have both higher star formation rates and metallicities than low-mass galaxies, albeit with a great deal of scatter in samples that include a wide or full mix of morphological types (Tamura et al. 2001; Prada & Burkert 2002). If the same kinds of correlations also hold at high redshift, they could explain the observed tendency for DLA galaxies with detectable Lyα emission to have higher metallicities than those without detectable Lyα emission. Conversely, the available observations of DLA galaxies could be interpreted as (weak) evidence for luminosity-metallicity and mass-metallicity relations at $z \sim 3$.

The observed trend might, at first sight, appear to contradict the idea that Lyα emission is suppressed in galaxies with high dust content and hence high metallicity. Lyα photons, which scatter resonantly off H atoms, have a much longer path and a much higher probability of absorption on dust grains than continuum photons, an effect that reduces the equivalent width W_α of the Lyα emission line. For nearby star-forming galaxies, the observed Lyα equivalent widths show the expected anti-correlation with metallicity, which is usually interpreted as a consequence of absorption by dust (see Fig. 8 of Charlot & Fall 1993). For DLA galaxies at high redshifts, W_α has been measured in three cases and a lower limit placed on it in another case. We have checked that these equivalent widths and the corresponding metallicities are consistent with the W_α–Z relation for $z = 0$ galaxies and hence with the idea that the Lyα emission is suppressed by dust.

How can we reconcile these two results, one regarding a positive L_α–Z correlation, the other a negative W_α–Z correlation? First, we note that the samples on which these hints are based are still very small, and it is possible they will disappear with more observations. Second, we note that there is no logical contradiction between the two correlations. They can both exist together, as they are observed to do in low-redshift galaxies. The reason this is possible is that dust affects W_α by factors of a few, while L_α spans several orders of magnitude, from low-mass to high-mass galaxies. Thus, a positive L_α–Z correlation can overwhelm a negative W_α–Z correlation. More observations are needed to confirm whether similar relations also hold for high- redshift DLA galaxies. For now, we simply note that the available but meager high-z data are consistent with both low-z relations.

4.2. Sizes and impact parameters of DLAs

The DLA absorber in front of PKS 0458-02 was previously (Wolfe et al. 1985) detected as a 21 cm absorber.

In particular, because PKS 0458-02 has radio structure on a wide range of scales, Briggs et al. (1989) were able to use high-resolution radio interferometry to probe several different paths through the absorbing medium. Using this technique they concluded that the absorber is a disk-like structure that extends across at least 2″. How does this earlier result fit with our detection of an impact parameter of only 0.″3 ± 0.″3?

A measured impact parameter is in each case random and could be anywhere in the range $[0; R]$ where R is the radius of the absorber. Møller & Warren (1998) found that in the mean the measured impact parameter is $0.55R$, so finding a very small $b_{\rm DLA}$ for DLAg0458-02 is therefore not in contradiction to the result by Briggs et al. Four optical (Lyα) impact parameters have been reported previously: 0.″93 (Fynbo et al. 1999); 0.″99, 1.″14, and 2.″51 (Møller et al. 2002). The median of all five is 0.″99 corresponding to a disk diameter of 3.″6, fully consistent with the Briggs et al. result.

4.3. Concluding remarks

We shall not make any strong statement based on the above discussion but simply point out that the data presented in Fig. 5 are certainly consistent with, and are even weekly supporting, the conjecture that a luminosity-metallicity relation is already in place at redshifts 2−3. In further support of a luminosity-metallicity relation we note that Lyman Break galaxies (LBGs) have metallicities as high as or higher than the most metal rich DLAs at similar redshifts (Pettini et al. 2000, 2001) but based on cross-section selection arguments Fynbo et al. (1999) found that typical DLAs have much lower luminosities than LBGs.

Detection of star formation induced Lyα emission from an additional 5−10 DLAs would settle the questions raised above and should therefore be a high priority observational goal. In order to disentangle the dust-attenuation effect from the luminosity-metallicity relation one would need a measure for the galaxy luminosity which is not influenced by dust. This could be obtained via broad band imaging of DLA galaxies with sufficiently large impact parameters, or via detection of Hα/Hβ emission lines.

If it is confirmed that a luminosity-metallicity relation for DLA galaxies is indeed present then this might reflect an underlying mass-metallicity relation. We have already previously shown that a large fraction of DLA galaxies are too small and too faint to be detected under the glare of the quasar point spread function (Fynbo et al. 1999), but if a mass-metallicity relation is indeed present already at high redshifts then we can add to the previous statement that those DLA galaxies most likely to be undetectable are those with the lowest metallicities, a prediction which could greatly improve the efficiency of follow-up observing campaigns. One further observational prediction would also follow immediately from this. Because the less massive DLA systems have smaller radii we predict a correlation between impact parameter and DLA metallicity.

Acknowledgements. We are grateful to S. J. Warren for comments on earlier versions of this manuscript and to C. Ledoux for many helpful discussions concerning metallicities of DLAs.

References

Briggs, F. H., Wolfe, A. M., Liszt, H. S., et al. 1989, ApJ, 341, 650
Charlot, S., & Fall, S. M. 1993, ApJ, 415, 580
Chen, H.-W., & Lanzetta, K. M. 2003, ApJ, 597, 706
Christensen, L., Sánchez, S. F., Jahnke, K., et al. 2004, A&A, 417, 487
Dessauges-Zavadsky, M., Péroux, C., Kim, T.-S., et al. 2003, MNRAS, 345, 447
Djorgovski, S. G., Pahre, M. A., Bechtold, J., & Elston, R. 1996, Nature, 382, 234
Foltz, C. B., Chaffee, F. H., & Weymann, R. J. 1986, AJ, 92, 247
Fynbo, J. U., Møller, P., & Warren, S. J. 1999, MNRAS, 305, 849
Fynbo, J. U., Burud, I., & Møller, P. 2000, A&A, 358, 88
Fynbo, J. U., Møller, P., Thomsen, B., et al. 2002, A&A, 388, 425
Hunstead, R. W., Fletcher, A. B., & Pettini, M. 1990, ApJ, 356, 23
Kulkarni, V. P., & Fall, S. M. 2002, ApJ, 580, 732
Lanfranchi, G. A., & Friaca, A. C. S. 2003, MNRAS, 343, 481
Lu, L., Sargent, W. L. W., & Barlow, T. A. 1998, ApJ, 115, 55
Lu, L., Sargent, W. L. W., Barlow, T. A., et al. 1996, ApJS, 107, 475
Møller, P. 1999, in Astrophysics with the NOT, ed. H. Karttunen, & V. Piirola, University of Turku, 80
Møller, P., & Warren, S. J. 1993, A&A, 270, 43
Møller, P., & Warren, S. J. 1998, MNRAS, 299, 661
Møller, P., Warren, S. J., Fall, S. M., et al. 2002, ApJ, 574, 51
Møller, P., Warren, S. J., & Fynbo, J. P. 1998, A&A, 330, 19
Pettini, M., Smith, L. J., Hunstead, R. W., & King, D. L. 1994, ApJ, 426, 79
Pettini, M., Shapley, A. E., Steidel, C. C., et al. 2001, ApJ, 554, 981
Pettini, M., Steidel, C. C., Adelberger, K. L., et al. 2000, ApJ, 528, 96
Prada, F., & Burkert, A. 2002, ApJ, 564, L73
Prochaska, J. X. 2003, ApJ, 582, 49
Prochaska, J. X., Gawiser, E., Wolfe, A. M., et al. 2003, ApJ, 595, L9
Smith, H. E., Cohen, R. D., & Bradley, S. E. 1986, ApJ, 310, 583
Smith, H. E., Cohen, R. D., Burns, J. E., et al. 1989, ApJ, 347, 87
Steidel, C. C., Pettini, M., & Hamilton, D. 1995, AJ, 110, 2519
Tamura, N., Hirashita, H., & Takeuchi, T. T. 2001, ApJ, 552, L113
Tyson, N. D. 1988, ApJ, 329, L57
Warren, S. J., & Møller, P. 1996, A&A, 311, 25
Warren, S. J., Møller, P., Fall, S. M., & Jakobsen, P. 2001, MNRAS, 326, 759
Wolfe, A. M. 1986, Phil. Trans. Roy. Soc. London, A, 320, 435
Wolfe, A. M., Briggs, F. H., Turnshek, D. A., et al. 1985, ApJ, 294, L67
Wolfe, A. M., Lanzetta, K. M., Turnshek, D. A., & Oke, J. B. 1992, ApJ, 385, 151
Wolfe, A. M., Turnshek, D. A., Lanzetta, K. M., & Lu, L. 1993, ApJ, 404, 480
Wolfe, A. M., Turnshek, D. A., Smith, H. E., & Cohen, R. D. 1986, ApJS, 61, 249