

# Ly $\alpha$ EMISSION FROM A $z = 2.61$ DAMPED Ly $\alpha$ ABSORBER

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## ABSTRACT

While investigation of the high-redshift Universe and the discovery of distant objects are still in their infancy, several techniques to uncover galaxies at redshifts larger than  $z \sim 1$  have been improved during the last years. However, although it is generally accepted that galaxies selected through their absorption are not intrinsically distinct from those selected through emission, the exact relation between the two is still not fully understood. The detection of Ly $\alpha$  emission in a damped Ly $\alpha$  absorber (DLA) indicates the origin of galaxies, the fundamental building blocks of our Universe. However, only for a handful of the DLAs Ly $\alpha$  emission has been observed.

In the case of quasar Q2348-011, with two DLAs in its line of sight, there was strong evidence to assume the presence of this emission: the discovery of a narrow band (H $\alpha$ ) source at the redshift of the first DLA (Mannucci et al. 1998) and the intense UV radiation at the same redshift (Noterdaeme et al. 2007). Detection of Ly $\alpha$  emission associated with either one or both of the DLAs would significantly improve our understanding of the connection between absorption and emission selected galaxies.

Unfortunately, the anticipated emission was only detected at low significance ( $\sim 3.5\sigma$ )... Rats!

*Subject headings:* galaxies: formation — galaxies: high-redshift quasars: absorption lines — quasars: individual (Q2348-011)

## 1. INTRODUCTION

Damped Ly $\alpha$  systems (DLAs) are huge clouds of neutral hydrogen, characterized by column densities  $N_{\text{HI}} \geq 10^{20.3}$  cm<sup>-2</sup>. Identified by their ability to cause broad absorption lines in the spectra of background quasars, DLAs offer a unique window to the high-redshift Universe, providing us with valuable information about the neutral hydrogen content of the Universe, metallicity evolution, and the formation of galaxies.

The Lyman-break technique (Steidel et al. 1996), i.e. the detection of galaxies due to their fall-out in wavelengths blueward of the Lyman-break, significantly moved forward the frontier of galaxy surveys. The fact that DLAs are in their very nature self-shielded against the ubiquitous meta-galactic UV field implies that the gas is able to cool sufficiently to initiate star formation. This makes them obvious candidates for present day galaxies, and a prime goal of modern cosmology should be to unveil the nature of DLAs. In spite of this, little is known about the relation between emission and absorption selected systems.

Due to the high luminosity of the background quasars, detecting galaxies associated with DLAs is, in general, a strenuous task. Both observations and numerical simulations indicate that a characteristic impact parameter for the line of sight through the hydrogen cloud responsible for the absorption is, at most, a few tens of kpc, corresponding at a typical redshift of  $z \sim 3$  to a few arcseconds. Consequently, even under very good seeing conditions, detection of a galaxy against a bright quasar will be extremely difficult.

Of the  $\sim 1000$  DLAs found so far, in only 6 cases associated Ly $\alpha$  emission has been detected (Tab. 1). This generally displays itself as a small peak in the bottom of

the trough caused by the DLA in the spectrum of the background quasar.

The spectrum of the quasar Q2348-011 ( $z = 3.01$ ) features *two* DLAs, situated at  $z = 2.61$  and 2.43, respectively, with evidence for an excess of UV flux associated with the latter (Noterdaeme et al. 2007). However, as yet searches for a galaxy responsible for the absorption have proved fruitless. Several emitters have been identified in the immediate vicinity of the QSO. In particular, from the excess of H $\alpha$  narrowband to broadband, Mannucci et al. (1998) find an emitter located 11" NW of the QSO (Fig. 1), at the same redshift as the second absorber.

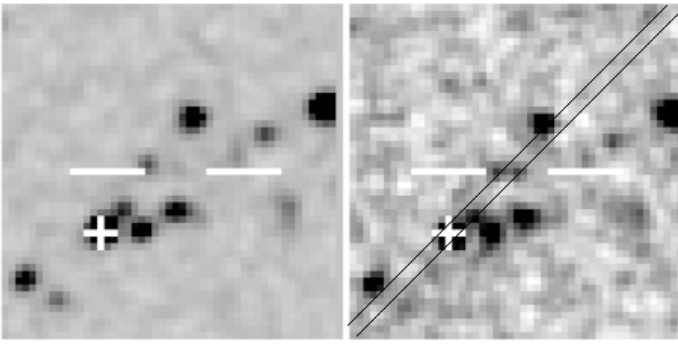
In order to search for Ly $\alpha$  emission, deep, intermediate-resolution spectroscopy of Q2348-011 was carried out at the Nordic Optical Telescope (NOT), with the slit of spectrograph positioned at an angle such that also the spectrum of the emitter at 11" distance should be obtained, thus enabling its redshift to be determined spectroscopically.

The rest of the paper is organized as follows: In §2 and §3 we describe the observations and the reduction of the resultant data, in §4 the results of our analyses are presented, and in §5 these results are discussed.

Background QSO	Reference
PKS0528-250	Møller & Warren (1993)
2233+131	Djorgovski et al. (1996)
Q0151+048	Møller et al. (1998b), Fynbo et al. (1999)
Q2059-360	Leibundgut & Gorden (1999)
Q2206-19A	Møller et al. (2002)
PKS0458-02	Møller et al. (2004)

**Table 1.** List of quasars, in the spectra of which Ly $\alpha$  emission has been detected (and published) in the trough of a DLA.

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**Figure 1.** Broadband (*left*) and narrowband (*right*) images of candidate (center of both images)  $11''$  from the quasar Q2348-011 (marked by the white cross). The dimension of each image is  $40'' \times 40''$ . North is up and east is left. The image is taken from Mannucci et al. (1998), and the width and position angle of the slit used in this study are indicated by black lines.

## 2. OBSERVATIONS

The observations of the two DLAs were carried out with the Nordic Optical Telescope (NOT) on La Palma. To acquire the spectra, the ALFOSC (Andalucia Faint Object Spectrograph and Camera) instrument together with the  $2K \times 2K$  CCD on the NOT was applied. The two DLAs are located at redshifts  $z = 2.43$  and  $z = 2.61$ , and their corresponding Ly $\alpha$  absorption troughs are thus located at wavelengths  $\lambda = 4158 \text{ \AA}$  and  $\lambda = 4389 \text{ \AA}$ , respectively. To acquire the spectra, grism #16 of the ALFOSC was therefore used. The wavelength coverage of this grism is in the range  $3500 \text{ \AA} - 5060 \text{ \AA}$  and its absolute efficiency is around 50 percent at the according wavelength. It is particularly sensitive and has a resolution of  $R = 2000$  if used with a  $0.5''$  slit. However, since high resolution was not the goal of these observations, a slit of width  $1.3''$  was used, resulting in a resolution of  $R \simeq 770$ , with no 2nd order light in the wavelength range.

Previous searches (Mannucci et al. 1998) have measured the narrow band magnitudes of the candidate objects at the H $\alpha$  line to be approximately 18.8. In order to obtain a satisfactory signal-to-noise ratio of such a faint object, an exposure time of at least 5 hours was needed. This was based on our calculations but also on previous experience of such detections reported in the literature (e.g., Møller et al. 2004). This total time was divided in shorter exposures of 1800 seconds. Since for the chosen grism the dispersion is  $0.77 \text{ \AA}$  per pixel, the read out noise could be reduced by a binning of the CCD at  $2 \times 2$  without any loss of information, providing final pixels of size  $0.39''$  by  $1.54 \text{ \AA}$ .

In order to get spectra of all known candidate objects, the  $1.3''$  long-slit was aligned at position P.A. =  $45^\circ$  with respect to the E-W direction (Fig. 1). The quasars were observed on three distinct nights. During the first night the conditions were not optimal, with relatively high seeing and airmass. However, this improved radically during the last two nights (Tab. 2).

Date	UT	Exp./s	Airmass	Seeing/''
08.18.2007	23 <sup>00</sup> -01 <sup>15</sup>	3 $\times$ 1800	1.48-2.05	2.0-2.4
08.19.2007	02 <sup>00</sup> -04 <sup>30</sup>	3 $\times$ 1800	1.15-1.19	0.8-2.4
08.21.2007	02 <sup>30</sup> -05 <sup>00</sup>	4 $\times$ 1800	1.15-1.20	0.6-1.0

**Table 2.** Observational information for the 3 nights

For the flux calibration, spectra of the standard star Feige 110 (SP2317059) was obtained, using the same grism and slit. This standard star was a perfect choice due its close alignment on the sky with O2348-11. For the wavelength calibration and flat-fielding, a He and a halogen lamp was used, respectively.

## 3. DATA REDUCTION

The data was reduced with IRAF<sup>2</sup> through a standard image reduction procedure of overscan subtraction, bias subtraction, and flat-fielding. The uneven illumination of the halogen lamp was corrected for, using the tasks **response** and **illumination**.

False signals in the images were removed using the task **lacos\_spec** (van Dokkum 2001) The ten 1800 sec spectra were equally weighted and averaged (although there are alternative ways taking into account the different image variance, seeing, etc.), to obtain one final 2D spectrum.

Subsequently, the background was removed in the following way: two stripes of width  $\sim 10 - 20$  pixels to the left and right, respectively, of the spectrum and sufficiently close to it, were used to compute an average column. This average column, representing the average background per wavelength, was then subtracted from the original image. Due to the bending of the skylines, this way of background subtraction is only accurate in the center of the image, where the spectrum lies.

To obtain 1D spectra, the task **apall** was used. The 1D spectra were wavelength calibrated by use of the task **dispcor**. We obtained one wavelength calibrated 1D spectrum per night (assuming that the wavelength calibration did not change over the course of a single night) and then combined the three 1D spectra with the help of **scombine** to obtain a final 1D spectrum (Fig. 4.2).

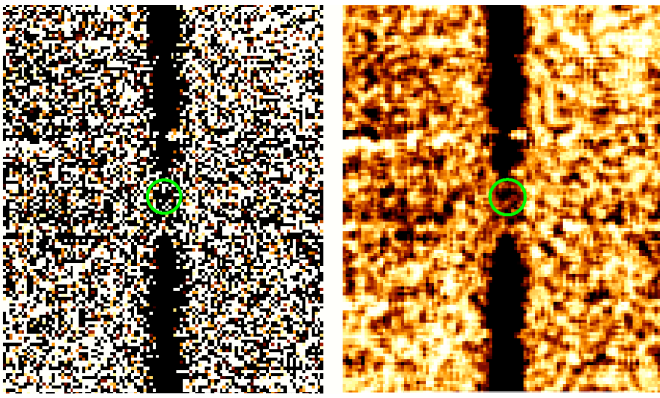
## 4. RESULTS

To estimate the presence (and significance) of Ly $\alpha$  emission in the DLA trough, the two-dimensional, background corrected spectrum (Fig. 4) was used. A quick inspection is enough to reveal that even if this emission is present, it is not as prominent as in Møller et al. (2004). However, there seems to be an excess of counts over the background. The significance of the detection was measured in the following way:

The corresponding image statistics were computed in IRAF with the use of **imexamine**, option **m**. This computes the statistics in an aperture centered at the position of the cursor. A square box covering an area of 25 pixels was used for this purpose.

Clicking in regions sufficiently close to the trough allows us to estimate the local background values. We obtain  $0.61 \pm 0.37$  counts. Here the error is the standard deviation of the mean counts in the aperture averaged over

<sup>2</sup> IRAF is distributed by the National Optical Astronomy Observatory (NOAO), which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.



**Figure 2.** Two-dimensional spectra of the quasar Q2348-011, non-smoothed (*left*) and smoothed (*right*). The emission in the trough of the DLA is marked by a green circle.

20 local regions. In the middle of the trough we get 1.91 counts, implying that the significance of our detection is at the  $3.5\sigma$  level.

#### 4.1. The effect of smoothing

The image in Fig. 4, left, is noisy. The detection can be more clearly seen if smoothed. This was done with the task `boxcar` and a smoothing window  $3 \times 3$  pixels. The resulting image can be seen in the right image of Fig. 4. Computing the corresponding statistics for this image, we get  $0.41 \pm 0.30$  counts for the local background and 1.69 counts for the middle of the trough, implying a  $4.2\sigma$  detection.

#### 4.2. Alternative way of calculation

The significance can also be calculated in the following way:

$$\sigma = \frac{\text{total counts in aperture}}{\text{total expected standard deviation in aperture}} \quad (1)$$

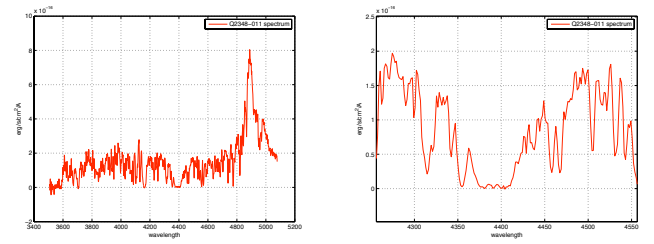
The total counts in the aperture are 47,800 and 42,175 for the unsmoothed and the smoothed image, respectively.

The total expected standard deviation in the aperture is the square root of the total variance in the aperture. This, in turn, is:

$$\text{Var}_{\text{tot}} = N\text{Var}_{\text{pix}} = N\sigma_{\text{pix}}^2, \quad (2)$$

where  $N$  is the number of pixels in the aperture,  $\text{Var}_{\text{pix}}$  is the variance per pixel and  $\sigma_{\text{pix}}$  is the standard deviation per pixel. The last quantity is provided by the `imexamine` statistics and is 2.88 for the unsmoothed image, while in the smoothed case this drops to 0.80. In this case, however, the pixels have been averaged (i.e., they are no longer independent) and this is no longer a “true” standard deviation per pixel. Hence, it should not be used for this computation, unless a much bigger aperture including many more pixels is used.

By applying this calculation to the unsmoothed image we obtain a  $3.33\sigma$  detection which is similar to what we obtained before.



**Figure 3.** Full, one-dimensional spectra of the quasar Q2348-011 (*left*) and zoom-in on the region around the DLA situated at  $z = 2.61$  (*right*). The possible Ly $\alpha$  emission is seen as two small bumps in the trough.

#### 4.3. Emitted flux

The detection of the Ly $\alpha$  emission line (even at this low significance) implies active star formation in the DLA. Using the tool `splot` on our final flux calibrated 1D spectrum (Fig. 4.2), a flux of  $3.57 \times 10^{-17}$  erg s $^{-1}$  cm $^{-2}$  Å $^{-1}$  at a wavelength of 4386 Å is deduced. There is also a second bump in the trough, with an excess over the background of  $2.77 \times 10^{-17}$  erg s $^{-1}$  cm $^{-2}$  Å $^{-1}$  at 4395 Å.

However, flux calibration of spectra might suffer from effects like slit losses, extraction choices, etc. For this reason, to measure the total emitted flux in one more way, we wanted to compare the counts level at the bottom of the trough with another well calibrated line.

For this purpose, we used a spectrum of the quasar obtained by the Sloan Digital Sky Survey (SDSS). This spectrum, although it is not as deep as ours, has the advantage that it comes from a well known pipeline with standard, well understood and trustworthy calibrations.

However, surprisingly enough, in our NOT spectrum we had more flux than the SDSS spectrum. Since the results were very similar however, we chose not to apply this correction.

#### 4.4. A hypothetical $10\sigma$ detection

The Ly $\alpha$  emission was detected at this low significance because it was faint. Here we will investigate how much flux it would have to emit in order to be detected at the  $10\sigma$  level (with the same exposure time). Since the noise (as expressed by the total standard deviation in the aperture) will not change, to obtain such a detection would demand measuring a total number of  $\sim 144$  counts.

This corresponds to an emitted flux of  $10.75 \times 10^{-17}$  erg s $^{-1}$  cm $^{-2}$  Å $^{-1}$

### 5. DISCUSSION AND CONCLUSION

Obviously, the fact that the Ly $\alpha$  emission in the spectrum of Q2348-011 was only detected at a fairly low significance does *not* necessarily imply that the absorber features no, or only very little, intrinsic Ly $\alpha$  emission. Previous identifications were all carried out on telescopes significantly larger, so the result may simply be a consequence of the relatively small mirror of the NOT. Moreover, even though the bulk of the photons may be emitted from a quite small region, due to the resonant nature of Ly $\alpha$  scattering processes they will not escape the host galaxy before having traversed a rather large distance. Numerical simulations (Laursen & Sommer-Larsen 2007) suggest that the

luminous region may be increased to several tens of square arcseconds, thus lowering the surface brightness and making most of the region fall outside the slit. Furthermore, the increased path will increase the probability of being absorbed by dust.

In order to unambiguously detect the emission at a higher significance level and quantify the star formation in the DLA region, more observing time at the NOT has

been applied for.

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