Identification of a Galaxy
Responsible for a High-Redshift
Damped Lyα Absorption System

S. G. Djorgovski[*], M. A. Pahre[*], J. Bechtold[†], and R. Elston[‡]

[*] Palomar Observatory, MS 105-24, Caltech, Pasadena, CA 91125, USA.

[†] Steward Observatory, University of Arizona, Tucson, AZ 85721, USA.

[‡] Cerro Tololo Interamerican Observatory, NOAO, Casilla 603, La Serena, Chile.

Galaxies believed to be responsible for damped Lyα absorption (DLA) systems in the spectra of high-redshift quasars represent a viable population of progenitors of normal disk galaxies[1]. They appear to contain a substantial fraction of the baryons known to exist in normal galaxies today[2,3]. Here we report on the detection of an object, designated DLA 2233+131, responsible for a previously known DLA system at $z_{abs} = 3.150$ [ref. 4] in the spectrum of a quasar 2233+131 ($z_{QSO} = 3.295$)[5]. This is the first unambiguous detection of a DLA galaxy, in both emission line and stellar continuum. Its properties correspond closely to what may be expected from a young disk galaxy in the early stages of formation, with no sign of an active nucleus. This gives a strong support to the idea that DLA systems represent a population of young galaxies at high redshifts.

Despite considerable efforts, no direct counterpart of a DLA galaxy has been unambiguously detected so far[6,7,8,9]. Clustered companions of DLA objects, all containing AGN, or quasar companions which may be responsible for some associated absorption have been seen, but no normal, isolated DLA systems themselves[10,11,12,13,14]. The closest may be the objects apparently associated with a quasar PKS 0528–250, with $z_{abs} = 2.811 > z_{QSO,em} = 2.77$, but given their association with the quasar, their nature and the source of ionization remain uncertain[13,14].

Our data were obtained on the night of UT 1995 September 28, using the Low Resolution Imaging Spectrograph (LRIS) instrument[15] at the W.M. Keck 10-m telescope on Mauna Kea, Hawaii. The object was found during observations of a candidate for a different DLA system (at $z_{abs} = 2.551$)[4] in the same field, which will be reported elsewhere. It was also selected independently as a DLA candidate on the basis of its broad-band colors by Steidel *et al.* [16], which was unknown to us at the time. We obtained direct images of the field in the Cousins V and R bands, and long-slit spectra using low and moderate resolution gratings, providing spectroscopic resolutions of $FWHM \approx 10$ and 3.5 Å, respectively. The seeing was $FWHM \approx 0.7$ arcsec. Since no photometric standards were observed that night, V and R images of the same field were obtained in photometric conditions at the Palomar 60-inch telescope on the night of UT 1995 October 17, and used to establish the photometric zero point for the Keck images. All data were reduced using standard techniques.

The object is identified with a galaxy 2.3 arcsec away in projection from the quasar, in $PA = 159°$ (Figure 1). Its magnitudes are $V = 25.1 \pm 0.2$ and $R = 24.8 \pm 0.2$, in an excellent agreement with the photometry by Steidel *et al.* [16]. The optical spectrum blueward of the Lyman break is thus nearly flat, with $\langle F_\nu \rangle \approx 0.35$ μJy, typical of actively star forming galaxies. For the quasar itself we obtain $V = 18.29$ and $R = 18.15$.

Our spectra show a prominent Lyα line emission at $z_{em} = 3.1530 \pm 0.0003$, corresponding to the restframe velocity difference of $\Delta V = 209$ km s^{-1} from the absorption system (Figures 2 and 3). The central wavelength of the emission line may be affected by absorption in the ambient gas, which could modify its observed redshift. The observed line flux is $F_{1216} = (6.4 \pm 1.2) \times 10^{-17}$ erg cm^{-2} s^{-1} , where flux zero point uncertainties dominate the error. While no other lines are detected, the close proximity to the known absorber redshift and the consistent colors and magnitudes leave little doubt as to the redshift identification. There are no high-ionisation lines detected (e.g., N V 1240 Å, or C IV 1549 Å, which would indicate the presence of an AGN) with 1-σ upper limits of $\sim 10^{-18}$ erg cm^{-2} s^{-1} .

Subsequent infrared observations were obtained at the Keck and the Kitt Peak 4-m telescope. Our measurements are consistent with the estimate[17] of $K \approx 22 \pm 0.3$ mag. We have an upper limit to the [O III] 5007 Å line flux of $F_{5007} < 10^{-16}$ erg cm^{-2} s^{-1} , which is consistent from expectations based on our measurement of the Lyα line flux and simple photoionisation models. This suggests that the object is not highly reddened.

In order to estimate the physical properties of the object, we assume a standard Friedman model cosmology with $H_0 = 75$ km s^{-1} Mpc^{-1} and $\Omega_0 = 0.2$ (our principal conclusions are not sensitive to the exact choice of these parameters). This gives the look-back time of 83% of the age of the universe at this redshift. Assuming the onset of galaxy formation at $z \sim 5$, this object is only $\sim 7 \times 10^8$ yr old, which corresponds to only a few free-fall times for a normal galaxy. This, and the very blue continuum implied by our photometry, suggests that DLA 2233+131 must be young. For our assumed cosmology, the distance modulus is $(m - M) = 47.11$, the angular size distance (appropriate for converting observed angular separations into the restframe linear sizes) is 1.96×10^{28} cm, and the luminosity distance (appropriate for converting observed fluxes into the restframe luminosities) is 8.14×10^{28} cm.

At this point we cannot be sure if the observed emission is coming from a young galaxy's disk, or its bulge, or both. Deep Hubble Space Telescope images may help resolve this question. This uncertainty should be borne in mind in the discussion that follows.

The projected separation of the detected galaxy and the quasar (i.e., its absorber portion) is then 17.2 kpc, comparable to the sizes of normal galaxy disks. The velocity field, if indeed due to rotation, is comparable to the rotation curve amplitudes of normal spirals, for reasonable projection angles. Moreover, the Lyα line shows a red wing (Figure 3), as may be expected from lines of sight intersecting differentially rotating galaxy disks[18,19]. The implied dynamical mass is

$$ M_{dyn} \geq \frac{V^2 R}{G} = 1.86 \times 10^{11} \ M_\odot \ \left(\frac{V}{200 \text{ km s}^{-1}} \right)^2 \left(\frac{R}{20 \text{ kpc}} \right) $$

(a lower limit due to the unknown projection effects). From the observed column density of the neutral hydrogen, $N_{HI} = 1.0 \times 10^{20}$ cm^{-2} [ref. 4], we can estimate the gas mass of

$$ M_{HI} \sim \pi \langle R \rangle^2 \ N_{HI} \ m_p \approx 1.0 \times 10^9 \ M_\odot \ \left(\frac{R}{20 \text{ kpc}} \right)^2 $$

These values are typical of normal galaxy disks today. They are only meant to be indicative, given the uncertainties about the morphology of the object and the projection effects.

The implied Lyα line luminosity is $L_{1216} = 5.3 \times 10^{42}$ erg/s. Estimates of conversion of the Lyα line luminosity to the implied unobscured star formation rate (SFR) are in the range $L_{1216} = (7 \pm 4) \times 10^{41}$ erg/s for $SFR = 1 M_\odot$ yr^{-1}, depending on the stellar initial mass function (IMF)[20,21]. We thus estimate the unobscured SFR in DLA 2233+131 to be $SFR = 7.5^{+10}_{-3} \ M_\odot$ yr^{-1}. An independent estimate of the SFR can be obtained from the restframe continuum luminosity at 1500Å. For our assumed cosmology, $P_{1500} = 9.4 \times 10^{40}$erg s^{-1} Å^{-1} . Population synthesis models[22] for a constant $SFR = 1 M_\odot$ yr^{-1}, assuming a Salpeter IMF, predict $P_{1500} \approx 1.5 \times 10^{40}$erg s^{-1} Å^{-1} , but plausible variations in the IMF slope can change

that number by a factor of 3. With this conversion, we derive $SFR \approx 6.4\ M_\odot\ \mathrm{yr}^{-1}$, in a good agreement with our estimate from the Lyα line.

This SFR, only a few times higher than in most spiral galaxies today, is an order of magnitude less than the observed star formation rates in ultraluminous IRAS galaxies, or expected rates in proto-ellipticals, but it is comparable to what may be expected from a gradually forming, young disk. This may be a lower limit, if some line emission is absorbed by the gas or dust. We derive the restframe equivalent width of 37Å, less than what most models would predict[20,21] for our estimated SFR, which can be explained by a very modest amount of absorption, or the effect of superposed stellar Lyα absorption.

Some of the observed Lyα emission may be due to the ionization of the H I cloud by the metagalactic UV flux, which at this redshift is estimated to be in the range $J_\nu \approx (1.5 \pm 0.5) \times 10^{-21}$ erg cm^{-2} s^{-1} Hz^{-1} sr^{-1} [ref. 23]. Following Wolfe $et\ al.$ [6], at $z = 3.153$ this implies the observed Lyα surface brightness of $(1.8 \pm 0.6) \times 10^{-19}$ erg cm^{-2} s^{-1} arcsec^{-2} , which is a negligible fraction of the observed line flux.

We can also extrapolate the observed continuum flux to the restframe B band. Assuming a flat spectrum, we obtain for the observed flux $F_\nu(B_{rest}) = 0.36\ \mu$Jy, and for a power law spectrum $F_\nu \sim \nu^\alpha$, with $\alpha = -0.4$, the reddest spectrum compatible with our data, $F_\nu(B_{rest}) = 0.53\ \mu$Jy. In the assumed cosmology, these correspond to the absolute magnitudes $M_B = -20.33$ and -20.75, respectively. For comparison, an L_* galaxy today has an $M_B = -20.4$ for the same cosmology. Thus, the optical luminosity of DLA 2233+131 corresponds to that of normal, evolved disk galaxies today, and is at least two orders of magnitude lower than that of typical quasars at that redshift. Given its higher star formation rate, we conclude that it yet has to make most of its stars.

This discovery should then be considered in the context of searches for protogalaxies. Despite considerable efforts, no obvious population of progenitors of normal galaxies has been found in the past[24,25,26,27]. One promising technique is to select high-redshift galaxies through their continuum colors, using the Lyman discontinuity at 912Å[16,17]. Most searches to date have concentrated on emission-line objects, primarily the Lyα line redshifted in the optical window, or the hydrogen Balmer lines or nebular oxygen lines redshifted into the near-infrared[20,24,25,26,27,28,29]. Many interesting high-redshift galaxies have been found in this way, but essentially all of them either contain active nuclei (AGN), or are located in a close proximity of one, and thus may be powered by reprocessed AGN radiation, rather than star formation. It is still possible that many or all of the known high-redshift AGN are situated in young galaxies.

DLA systems represent an already well-established, *large population* of high-redshift objects for which the confusion with AGN does not arise. They have been proposed as likely progenitors of normal disk galaxies[1], on the basis of their properties as inferred from the absorption signatures alone. In support of this idea, the properties of DLA 2233+131, a field galaxy now clearly identified with a DLA system, are exactly what may be expected of a young, still forming disk galaxy at a high redshift. This object may eventually evolve into a normal spiral galaxy not very different from our own. This is also fully consistent with the interpretation of Lyman break objects at comparable redshifts as a population of proto-bulges[17]. The populations of DLA systems, of which DLA 2233+131 may be representative,

and of Lyman break objects may overlap considerably, and they may be tentatively identified as progenitors of typical normal galaxies today.

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Figure Captions:

Figure 1: Finding charts for the field. The top image is a 3 arcmin square, from V and R band images obtained at the Palomar 60-inch telescope. The quasar is marked with the arrow; its coordinates are: $\alpha = 22^h33^m51.1^s$, $\delta = +13°10'46''$ (B1950 equinox). The bottom image is a 40 arcsec square, from R band images obtained at the Keck telescope. The DLA galaxy is indicated with the arrow. In both images north is up and east to the left, and the intensity contours are spaced logarithmically.

Figure 2: Intermediate-resolution spectra of the quasar (QSO, top) and the damped Lyα galaxy (DLA, bottom), obtained at the Keck telescope. Absorption features due to the DLA galaxy are marked in the spectrum of the quasar; in addition, Si II 1260 line is present in absorption at $\lambda = 5231$Å, but it may be confused with the associated Lyα absorption in the quasar spectrum itself. Strong Lyα emission is seen in the spectrum of the DLA galaxy. Note the complete absence of high-ionisation lines of N V 1240 and C IV 1549 (marked at the appropriate locations), suggesting that there is no detectable active nucleus in this object. The glitch at 5577Å is due to the poor night sky line subtraction. The continuum, but not the Lyα line, is oversubtracted in this spectrum, due to the presence of a much brighter QSO nearby; the true continuum level should be around 0.35 μJy.

Figure 3: The top panel shows a zoom-in on the spectroscopic frame, showing the Lyα line emission from the DLA galaxy, and the associated absorption in the quasar spectrum. Their central redshifts are indicated, and the corresponding restframe velocity difference is only 209 km s^{-1} , comparable to rotation curve amplitudes of normal disk galaxies. The projected angular and velocity scales are indicated. Note the red wing in the Lyα line, which is better seen in the bottom panel, showing a zoom-in on the extracted spectrum. This is a characteristic line shape expected from differentially rotating galaxy disks.
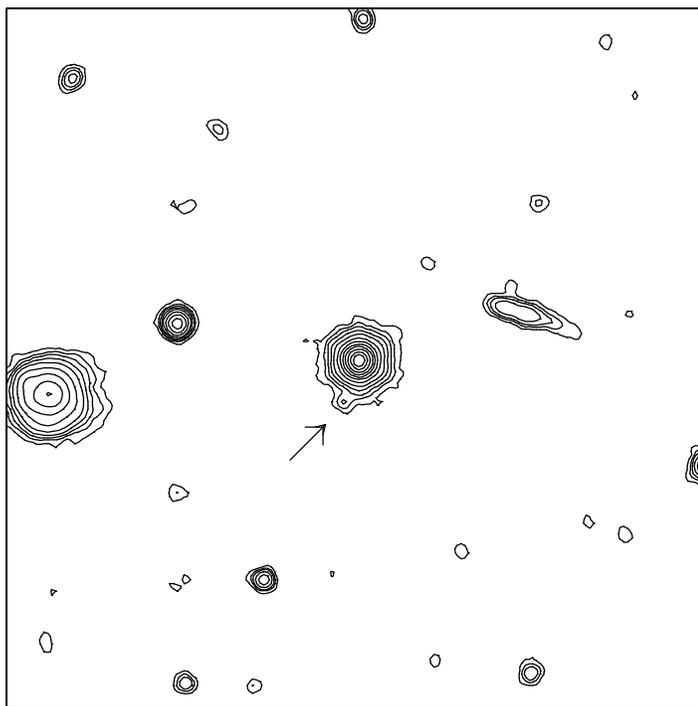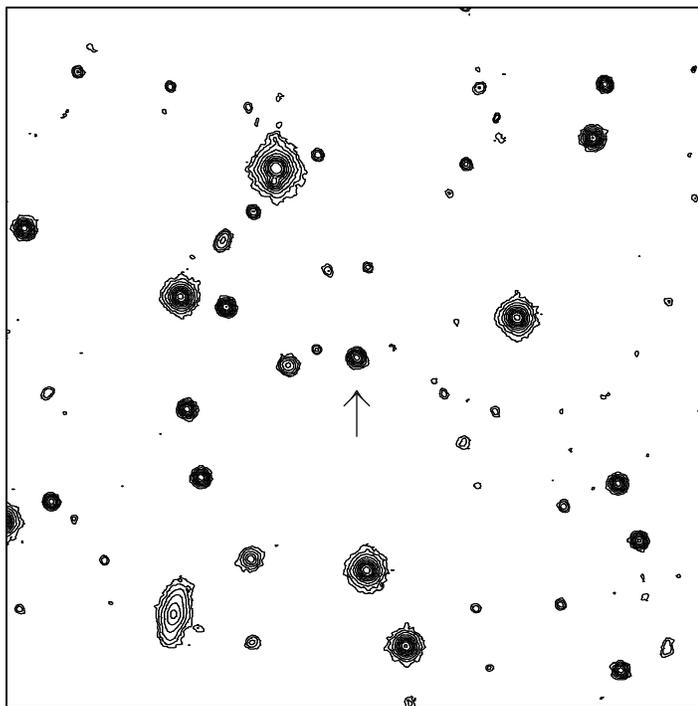
Figure 1 —— Djorgovski et al.

QSO 2233+131 z_{em} = 3.295

C IV 1549 abs.

Si II 1304 abs.
O I 1303,

Lyα 1216 abs.

F_ν (μJy)

500

0

DLA 2233+131 z_{em} = 3.153

C IV 1549 ?

n.s.

N V 1240 ?

Lyα

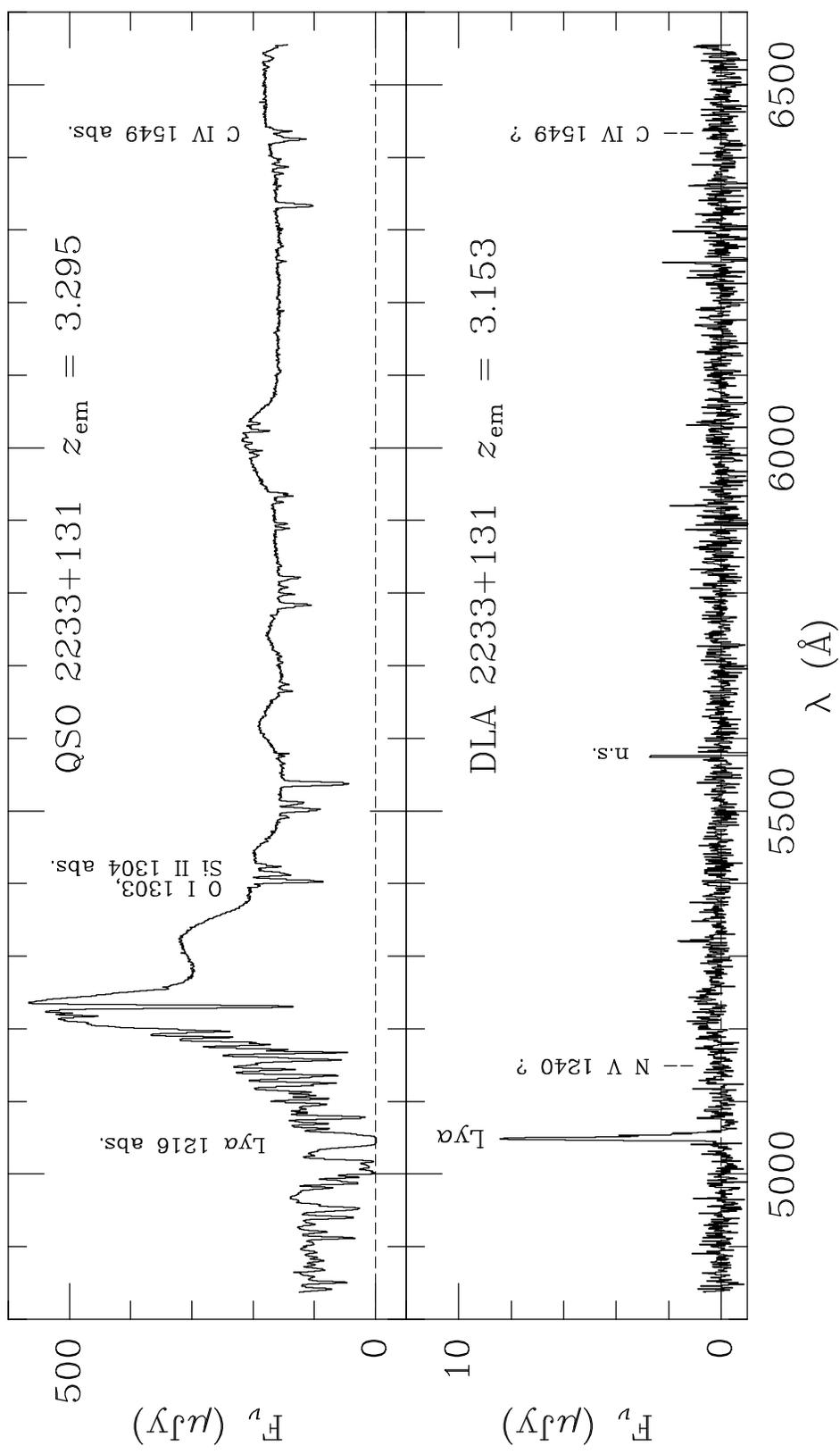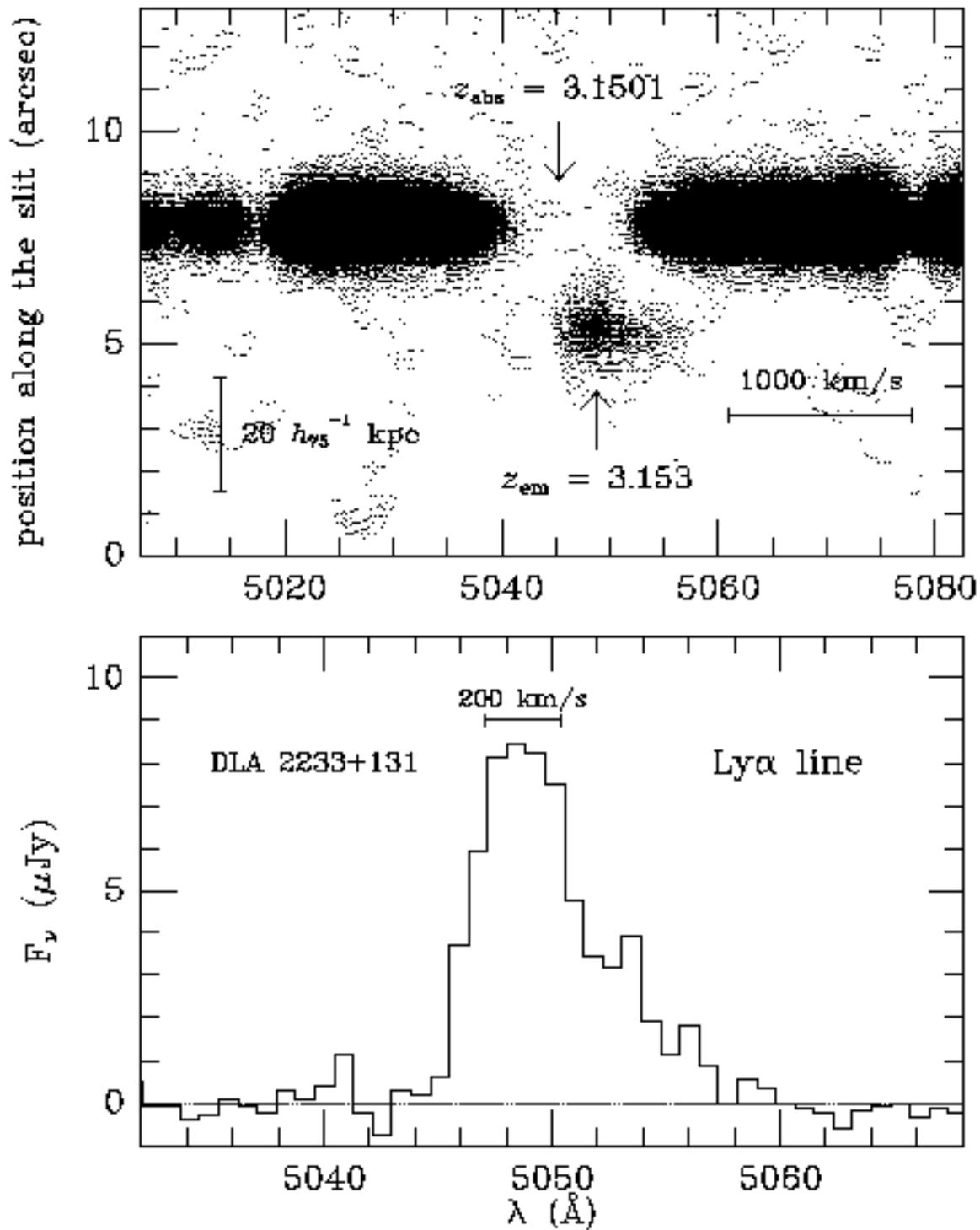F_ν (μJy)

10

0

λ (Å)

5000   5500   6000   6500

Figure 2 -- Djorgovski et al.

Figure 3 -- Djorgovski et al.