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Constraints to the evolution of Ly-α bright galaxies between $z = 3$ and $z = 6$★

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Abstract. Galaxies at high redshift with a strong Ly-α emission line trace massive star formation in the absence of dust, and can therefore be regarded as a prime signature of the first major starburst in galaxies. We report results of the Ly-α search within the Calar Alto Deep Imaging Survey (CADIS). With the imaging Fabry-Perot interferometer, CADIS can detect emission lines in three waveband windows free of night-sky emission lines at 700 nm, 820 nm, and 920 nm. The typical flux detection limit for Ly-α emission redshifted into these windows, $F_{\rm lim} \gtrsim 3 \times 10^{-20}$ W m^{-2}, corresponds to (unobscured) star formation rates of $\gtrsim$10 $M_\odot$/yr at $z = 6$. Candidate Ly-α-emitting galaxies are selected from the total emission line sample, which contains more than 97% of objects at $z < 1.2$, by the absence of flux below the Lyman limit (B-band "dropouts"), and the non-detection of secondary emission lines in narrow band filters. We have detected 5 bright Ly-α-emitting galaxy candidates at $z \simeq 4.8$, and 11 candidates at $z \simeq 5.7$. For two of four observed Ly-α candidates, one candidate at $z \simeq 4.8$, and the other at $z \simeq 5.7$, the emission line detected with the Fabry-Perot interferometer has been verified spectroscopically at the VLT. When compared to Ly-α surveys at $z \leq 3.5$, even the upper limits set by our list of candidates show that bright Ly-α galaxies are significantly rarer at $z \gtrsim 5$ than the assumption of a non-evolving population would predict. Therefore we conclude that the Ly-α bright phase of primeval star formation episodes reached its peak at redshifts $3 < z < 6$.

Key words. galaxies: evolution – galaxies: formation – galaxies: high-redshift

1. Introduction

Important observational information about the epoch of galaxy formation can only be gained from the existence, number counts and properties of galaxies at very high redshift. In the past few years substantial progress has been made in discovering galaxies at redshifts $z > 4$. Several dozen Lyman break galaxies have been detected at $z \sim 4$ (e.g. Steidel et al. 1999). In addition, a substantial number of galaxies at $z > 5$ have been detected and verified spectroscopically (e.g. Dey et al. 1998; Weyman et al. 1998; van Breughel et al. 1998; Hu et al. 1999; Hu et al. 2002; Ellis et al. 2001; Dawson et al. 2002; Ajiki et al. 2002; Rhoads et al. 2003); one of these (van Breughel et al. 1998) is a radio galaxy at $z = 5.2$. Quasars have been identified out to $z = 6.3$ (e.g. Pentericci et al. 2002; Fan et al. 2001). However, there is a lack of *systematic* surveys for high redshift primeval galaxies. Many of the galaxies at $z > 5$ have been detected serendipitously.

Moreover, as it has been pointed out, e.g. by Steidel et al. (1996), the strong metal absorption lines in the spectra of Lyman break galaxies indicate that they have already formed at least one generation of stars that have chemically enriched the systems and lead to dust formation, making Ly-α emission weak or undetectable. Therefore, the Lyman break galaxies do not show the properties expected for primeval galaxies. In contrast to the Lyman break galaxies, all but one of the galaxies found at $z > 5$ exhibit a very strong Ly-α emission line, in agreement with the population synthesis models for primeval galaxies of Charlot & Fall (1993), which predict that a young, dust-free, star-forming galaxy should show strong Ly-α emission with (intrinsic) equivalent widths in the range of 5–25 nm.

A direct probe of galaxy formation is to determine the number counts and redshift evolution of those nascent galaxies. Several systematic surveys aimed at discovering a significant number of $z > 4.5$ galaxies have now been proposed and are being carried out, e.g. Cowie & Hu (1998), Rhoads et al. (2000) and our survey, the **C**alar **A**lto **D**eep **I**maging **S**urvey (CADIS, Meisenheimer et al. 1998, 2003). At $z = 4.5$, a universe with standard parameters $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ is only 1.2 Gyr old, corresponding to a

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look-back time of >90% of the age of the universe. Any object observed at this or an earlier epoch should mark the early stages of galaxy formation.

Unlike the Lyman break technique (e.g. Steidel & Hamilton 1992, 1993), which selects galaxies by the presence of young stars and intervening HI absorption, CADIS selects galaxies by the extreme equivalent widths of their Lyman-α-emission ($W_{\lambda_{\rm rest}} > 10$ nm). It has been demonstrated by Kudritzki et al. (2000) that the high Ly-α equivalent width of these galaxies can only arise in regions nearly free of dust, and therefore the Ly-α emission line is a good tracer of star formation from primordial material. Unlike similar programmes at 8–10 m telescopes, CADIS aims to find *the most luminous* starbursts, with SFR $\geq 10\,M_\odot$/year, which most likely led to the formation of the galactic bulge. Even in the age of 10-m telescopes, only these luminous starbursts are accessible for detailed spectroscopic follow-up.

This paper is structured in the following way: in Sect. 2 we describe how we select Ly-α galaxy candidates at $z > 4.7$ with CADIS. In Sect. 3 we present the spectroscopic follow-up of some Ly-α candidates. Finally, in Sect. 4 we discuss the comparison between observed and theoretical number counts of Ly-α-emitting galaxies up to $z \approx 6$.

2. Lyman-α candidates from the CADIS survey

CADIS combines a moderately deep multi-band survey (10 σ limit, $R_{\rm lim} = 24$) with a deep emission line survey employing an imaging Fabry-Perot-Interferometer ($F_{\rm lim} = 3 \times 10^{-20}$ W m^{-2}), which covers three waveband windows essentially free of atmospheric OH emission lines: A ($\lambda = 702 \pm 6$ nm), B ($\lambda = 819 \pm 5$ nm), and C ($\lambda = 920 \pm 8$ nm). The classification and analysis of emission line galaxies from CADIS are outlined in Hippelein et al. (2003), and Meisenheimer et al. (2003). Therefore, in this section we will present only those aspects which are relevant to the search for Ly-α galaxies using the CADIS (emission line) survey.

The optimal detection of a weak emission line galaxy superimposed on the bright night sky is reached when the instrumental resolution $\delta\lambda$ is adapted to the expected line width. Assuming $\Delta v \approx 300$ km s^{-1}, a typical virial velocity of a Milky Way-like galaxy, $\delta\lambda \cong (1+z)(\Delta v/c)\lambda_0 \cong 0.9$ nm for a Lyman-α emission line at $z \sim 6$. On the other hand, the detection probability increases with the observed volume $\Delta V \sim \Delta z \Delta\Omega \sim \Delta\lambda\Delta\Omega$, where $\Delta\Omega$ denotes the solid angle surveyed. Using a Fabry-Perot (FP) Etalon with $\Delta\lambda \cong 2$ nm, tuned in 9 steps and covering an interval of 12–15 nm, CADIS provides an optimal compromise of both sensitivity and search volume. The three wavelength intervals (A, B, and C, see Fig. 1) which are scanned by CADIS correspond to Lyman-α redshifts of $z \cong 4.8$, 5.7, and 6.6, respectively. The field size is $\Delta\Omega \approx 100$ arcmin^2. Model predictions (Thommes & Meisenheimer 1995) of the galaxy abundance down to a line flux limit $F_{\rm line} \geq 3.0 \times 10^{-20}$ W m^{-2} (which can be reached with the Calar Alto 2.2- and 3.5-m telescopes within a few hours of observing time) made clear, before the project had even started, that at most a handful of Lyman-α galaxies would be expected per field and wavelength interval in the case of an open universe, which is commonly assumed today ($\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$). Accordingly we decided to search every wavelength interval in five fields. After six years of observations at Calar Alto, 90% of the planned Fabry-Perot data have been obtained. The Fabry-Perot wavelength intervals that have been almost completely analysed are given in Table 1. The analysis of interval C has been postponed for the moment because of technical problems (strong "fringing" in the CCD images), and low expectations of success on the basis of the results at $z < 6$, which will be presented in this paper.

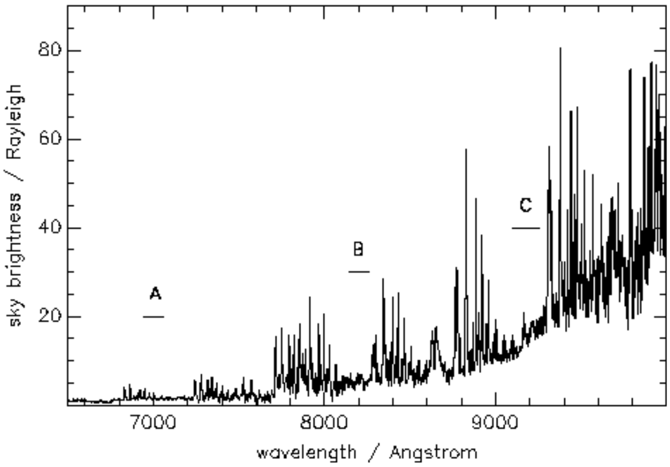

Fig. 1. Night-sky emission spectra. The windows A, B, and C which are searched by CADIS are essentially free from atmospheric OH emission lines.

Table 1. The analysed FP-windows in four CADIS fields.

Field	FP-window	Center coordinates		$\Delta\Omega$	Δz
name	observed	α(2000)	δ(2000)	arcmin^2	analysed
		(h m s)	(° ′ ″)		
01h	B	01 47 33.3	02 19 55	105	0.095
09h	A	09 13 47.5	46 14 20	98	0.082
	B				0.070
16h	B	16 24 32.3	55 44 32	107	0.095
23h	A	23 15 46.9	11 27 00	103	0.057
	B				0.082

The following results are based on the data in the FP-windows in four CADIS fields presented in Table 1. It should be noted that the analysis of 69% of window B, and *only* 27% of window A has been finished (see Table 1), in terms of the final $\Delta\Omega \times \Delta z$: $\Delta\Omega_{\rm final}$ will be ≈ 500 arcmin^2, corresponding to five CADIS fields, $\Delta z_{\rm final}$ for each Fabry-Perot window will be $\Delta z_{\rm final} \approx 0.1$.

The current classification of emission line galaxies shows that more than 97% of the emission line galaxies are foreground galaxies ($z < 1.2$), in which we mainly detect the lines Hα, Hβ, [O III] λ 5007, and [O II] λ 3727. Therefore, the main challenge is to separate those foreground objects from the Ly-α

candidates. We identify Lyman-α-galaxy candidates among the emission line galaxies by the following exclusion criteria:

(1) There should be no flux below the Lyman limit of a Lyman-α galaxy, because of an intrinsic drop in the spectra of hot O and B stars at the Ly-limit (Charlot & Fall 1993), and absorption by the neutral interstellar medium either in the galaxy itself (Leitherer et al. 1995a, 1995b) or in Lyman-limit foreground systems close to the primeval galaxy. For $z > 4.7$ the Lyman limit lies at $\lambda > 520$ nm. Therefore, no flux should be detected in the CADIS B filter ($\lambda_{\rm cent} = 461$ nm, $FWHM = 113$ nm). Accordingly, we require that $F_B < 2 \cdot \hat{\sigma}_B$ ("blue dropouts"), where F_B is the flux measured in the B filter, and $\hat{\sigma}_B$ its true overall error which takes into account both calibration errors and the scatter of the flux between the individual images. From 614 emission line galaxies selected in four fields in the FP-windows given in Table 1 this criterion yields $N_{\rm Noblue} = 85$ galaxies, i.e. 13.8% of the 614 emission line galaxies.

(2) Every remaining Ly-α candidate has to be carefully checked on the FP, pre-filter and R images because of the possible contamination by nearby bright objects. Candidates that are closer than about 3″ to a bright object are most likely spurious, since the changing atmospheric conditions change the tails of bright objects affecting the photometry of close-by galaxies. Therefore, such spurious objects are removed from the list of candidates. After this step, 5.7% of the emission line galaxies remain.

(3) Foreground galaxies, for which we detect one of the prominent emission lines Hα, Hβ, [O III] λ 5007, or [O II] λ 3727 in the Fabry-Perot images, can be excluded as soon a secondary line is detected in one of the veto filters, leaving 4.7% of the galaxies.

(4) The distinction between a (rare) galaxy with bright [O II] λ 3727 emission but weak restframe UV continuum, i.e., undetectable in the CADIS B filter, and a Lyman-α-galaxy is ambiguous based on the CADIS veto filters, because no line bluewards of [O II] λ 3727 can be detected. Instead, we have to use the entire spectrum for this decision. Lyman-α galaxies at high redshift should distinguish themselves by a continuum step across the Lyman-α line, due to absorption from neutral hydrogen in the Ly-α clouds and Ly-limit systems along the line of sight (Madau 1995). Therefore, the candidates that remain after step (3) are classified in two categories: likely Ly-α, if they show almost no continuum on the blue side of the Ly-α emission line, e.g. no significant flux in the R filter, and likely [O II] λ 3727 objects otherwise. However, we need spectroscopic follow-up observations of candidates belonging to *both* categories, since it cannot be excluded for sure that some Ly-α galaxies fall between the likely [O II] λ 3727 objects. After this step, 16 Lyman-α-candidates (classified as most likely Ly-α) remain (see Table 2), i.e., 2.6% of the emission line galaxies we found in four CADIS fields. In addition we are left with 13 likely [O II] λ 3727 candidates.

Table 2. The current list of 16 CADIS Lyman-α-candidates.
^{v} The line of the Ly-α candidate has been verified by spectroscopic follow-up.
^{n} The line of the Ly-α candidate has *not* been verified by spectroscopic follow-up.
^{q} Probable quasar.

FPI	Field	Nr	z	$F_{\rm line}$(W m^{-2})
A	09h	21556	4.734	5.7×10^{-20}
	23h	34751	4.772	5.0×10^{-20}
	23h	34105	4.793	4.2×10^{-20}
	23h	50707^v	4.801	4.0×10^{-20}
	09h	38114	4.741	3.7×10^{-20}
B	23h	40663	5.732	6.4×10^{-20}
	23h	23836	5.705	5.7×10^{-20}
	23h	28548	5.694	5.6×10^{-20}
	23h	45745	5.733	5.1×10^{-20}
	23h	9324	5.730	4.8×10^{-20}
	16h	3171	5.746	4.3×10^{-20}
	01h	3238^v	5.732	4.1×10^{-20}
	23h	45065	5.735	4.1×10^{-20}
	16h	2314^q	5.694	3.4×10^{-20}
	01h	27927^n	5.677	3.1×10^{-20}
	01h	28090^n	5.681	2.9×10^{-20}

3. Spectroscopic observations

Due to the low abundance of Ly-α galaxies (see Sect. 4), spectroscopic follow-up at large telescopes constitutes an important part of the survey: first, we have to search close to the detection limit, which makes contamination by noise non-negilible, and second, even very rare and unlikely contaminants, like distant supernovae or other transient objects, reach surface densities comparable to that of the Ly-α candidates, and can be mistaken for emission line galaxies in our observations of the FPI scans which are spread over years in some fields.

The first goal of the spectroscopic follow-up of likely Ly-α galaxies with 8-m class telescopes is therefore to verify the emission line. Furthermore, the line shape and the continuum blue- and red-wards of the emission line could allow us to decide between Ly-α and [O II] λ 3727: if the line has been verified, but the resolution is not good enough to identify the emission line, a second step is the clear confirmation of the line using higher resolution grisms, in order to see if the line shows the asymmetric profile expected for Ly-α, or the double [O II] $\lambda\lambda$3726, 3729 line with separation $\Delta\lambda \cdot (1+z)$, where $\Delta\lambda = 2.75$ Å. If galaxies with bright Ly-α line at $z > 4.7$ are confirmed, we plan a detailed study of the corresponding galaxy as third step.

Thus, confirming Ly-α candidates by spectroscopy is a slow process. Nevertheless, the verification or non-verification of a line for every single Ly-α candidate is very important in order to set more robust upper limits to the number counts of galaxies at high redshift, which can set stringent constraints on theoretical models (see Sect. 4).

Spectroscopic follow-up observations of Ly-α candidates in the 01h- and 23h-fields were obtained in the summer and autumn of 2001, using FORS 2 at the VLT. The slitmasks contained 1.0″ wide slits of length between 10″ and 20″. The position angle of each mask was chosen such that the number of Ly-α candidates in the $6.8' \times 6.8'$ FORS field of view is maximized. Regions of the slitmasks not devoted to primary targets were used to obtain spectra of low metallicity emission line galaxies. The results of the observations of these low metallicity emission line galaxies will be presented and discussed in another paper (Maier et al. 2003, in preparation).

Depending on the distribution of candidates, we used two different grisms, the lower resolution 300 I grism, which gives a spectral resolution of about 1.2 nm, at 800 nm, for slitlets 1″ wide, and the 600 RI grism, which gives a higher spectral resolution of about 0.8 nm, at 800 nm, for slitlets 1″ wide. Three $z \approx 5.7$ Ly-α candidates, 01h-3238, 01h-28090, and 01h-27927, were observed for 215 min using the 300 I grism with FORS2, and one $z \approx 4.8$ Ly-α candidate, 23h-50707, was observed for a total of 150 min using the 600 RI grism with FORS2. Fluxes were calibrated using multiple observations of the spectrophotometric standard stars LTT 7379, EG 274 and LTT 7987 (Hamuy et al. 1992, 1994). Seeing varied between 0.″5 and 1.″2.

For two of the four observed Lyman-α candidates we verified the emission line, for 01h-3238 at 819.0 ± 0.3 nm, and for 23h-50707 at 705.7 ± 0.3 nm (see Figs. 2 and 3). No continuum and no additional emission lines are seen on the VLT spectra, and, according to the CADIS measurements, these two objects satisfy the criteria (1)–(4) for Ly-α candidates. Therefore, we conclude that the two emission lines are very likely Ly-α lines of high redshift galaxies, 01h-3238 at $z = 5.735 \pm 0.003$ and 23h-50707 at $z = 4.803 \pm 0.003$, respectively.

The line of the other two observed Ly-α candidates, 01h-28090 and 01h-27927, is not seen on the VLT spectra. These are the Ly-α candidates with the faintest fluxes of our Ly-α candidates list. One explanation for the non-detection could be that the slit possibly missed (part of) the line emitting region of these two galaxies. This is indicated by some emission line objects on the same masks as the Ly-α candidates which show a spectroscopic determined flux smaller than the CADIS flux. Thus, the slit width of 1.″0 used for the VLT observations was possibly too narrow, and we may have thus measured only a fraction of the emission line flux of the Ly-α candidates. The reason for this is that our astrometry delivers rather accurate coordinates (better than 0.″2) for objects with multiple detections (FP and continuum), but can be off by more than 0.″5 for objects detected only in the Fabry-Perot images (Ly-α candidates). On the other hand, the two Ly-α candidates could be indeed spurious, since we expect a residual contamination of about 50% in our list of Ly-α candidates. The reason for the non-verification of the lines has to be established by extending the statistics of spectroscopic follow-up observations.

It should be noted that we could verify an emission line (at 820.9 ± 0.3 nm) also for the galaxy 01h-4616. This object, which shows no flux in the B filter and in the veto filters, passed the criteria (1)–(3), but was classified as a probable [O II] λ 3727 galaxy at $z \approx 1.2$ according to criterion (4). No other lines are seen on the VLT spectrum, and a continuum on both sides of the line is detected. Therefore, the emission line is indeed likely to be [O II] λ 3727 at $z = 1.202 \pm 0.001$.

We calculate the absolute Ly-α luminosity of 01h-3238 and 23h-50707 from the observed fluxes measured in the FP scan (since the spectroscopic observations are subject to slit losses, see above). The Lyα flux is $f(\mathrm{Ly}\alpha) = (4.1 \pm 0.8) \times 10^{-20}$ W m^{-2} for 01h-3238, and $f(\mathrm{Ly}\alpha) = (4.0 \pm 0.8) \times 10^{-20}$ W m^{-2} for 23h-50707. Using a $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ cosmology, we obtain an absolute Lyα luminosity of $L(\mathrm{Ly}\alpha) \simeq (14.5 \pm 3.0) \times 10^{35}$ W for 01h-3238, and $L(\mathrm{Ly}\alpha) \simeq (9.5 \pm 1.9) \times 10^{35}$ W for 23h-50707. Note that these Lyα luminosities are the highest found in any $z \gtrsim 5$ galaxy (luminosities are estimated by using the same cosmology): e.g. 3.3×10^{35} W for the lensed galaxy HCM 6A at $z = 6.56$ (Hu et al. 2002); 6.1×10^{35} W for SSA22-HCM1 at $z = 5.74$ (Hu et al. 1999); 3.4×10^{35} W for HDF 4-473.0 at $z = 5.60$ (Weymann et al. 1998). Taking the Ly-α to Hα ratio for Case B recombination and no dust (Brocklehurst 1971), together with the Kennicutt (1983) conversion between Hα luminosity and star formation rate, the derived star formation rates for the two Ly-α galaxies are: (14.5 ± 3.0) $M_\odot$ yr^{-1} for 01h-3238, and (9.5 ± 1.9) $M_\odot$ yr^{-1} for 23h-50707. Kudritzki et al. (2000) found that the derived star formation rates depend very strongly on whether we witness a burst or continuous star formation, the SFR being higher in the case of a starburst. Therefore, the derived SFRs using the Kennicutt (1983) empirical formula for the case of continuous star formation represent only lower limits for the SFRs. The true values of the SFRs in the case of a starburst may be a factor of five higher.

4. Comparison between observed and theoretical abundances of Ly-α emitting primeval galaxies

The CADIS selection suppresses the contamination in the list of Ly-α candidates to less than 50% (see Sect. 2). As a consequence, the list of CADIS Ly-α candidates allows us to set *stringent* upper limits for the density of Ly-α-emitting galaxies at $z > 4.7$. We can therefore discuss the evolution of the population of Ly-α emitting galaxies from $z = 3$ to $z = 6$ by comparing the maximum abundance derived from the list of CADIS Ly-α candidates with the results of other systematic surveys at $3 < z < 6$.

Figure 4 shows the cumulative number counts of Lyman-α-galaxies at $z = 4.8$ (left panel) and at $z = 5.7$ (right panel), presented as the total number of galaxies, N per deg^2 per $\Delta z = 0.1$, that are brighter than a certain observed flux, F_{lim}. In the cumulative histogram of CADIS Ly-α galaxy candidates, the upper edge represents the total number of CADIS candidates per deg^2 and per $\Delta z = 0.1$, brighter than the respective F_{lim}, based on the list of Ly-α candidates from Table 2: e.g. at $z = 5.7$, in four fields with a total $\Delta\Omega_{\mathrm{total}} = 413\,\mathrm{arcmin}^2 \approx 1/9\,\Box^\circ$, we find one candidate brighter than $F_{\mathrm{lim}} = 6.4 \times 10^{-20}$ W m^{-2}, two candidates brighter than $F_{\mathrm{lim}} = 5.7 \times 10^{-20}$ W m^{-2}, etc. The filled squares additionally take into account the likely residual contamination by noise plus unidentified [O II] λ 3727-emitting galaxies, and therefore represent our best-guess upper limit to the abundance of Ly-α galaxies.

Additional abundance measurements, showed as filled triangles, are from Hu et al. (1998) at $z = 4.5$, and from Hu et al. (1999) at $z = 5.7$. Hu et al. detected two Ly-α galaxies at $z = 4.52$ in a 24 arcmin^2 field, and one Ly-α galaxy at $z = 5.74$ using narrowband observations in a 30 arcmin^2 field.

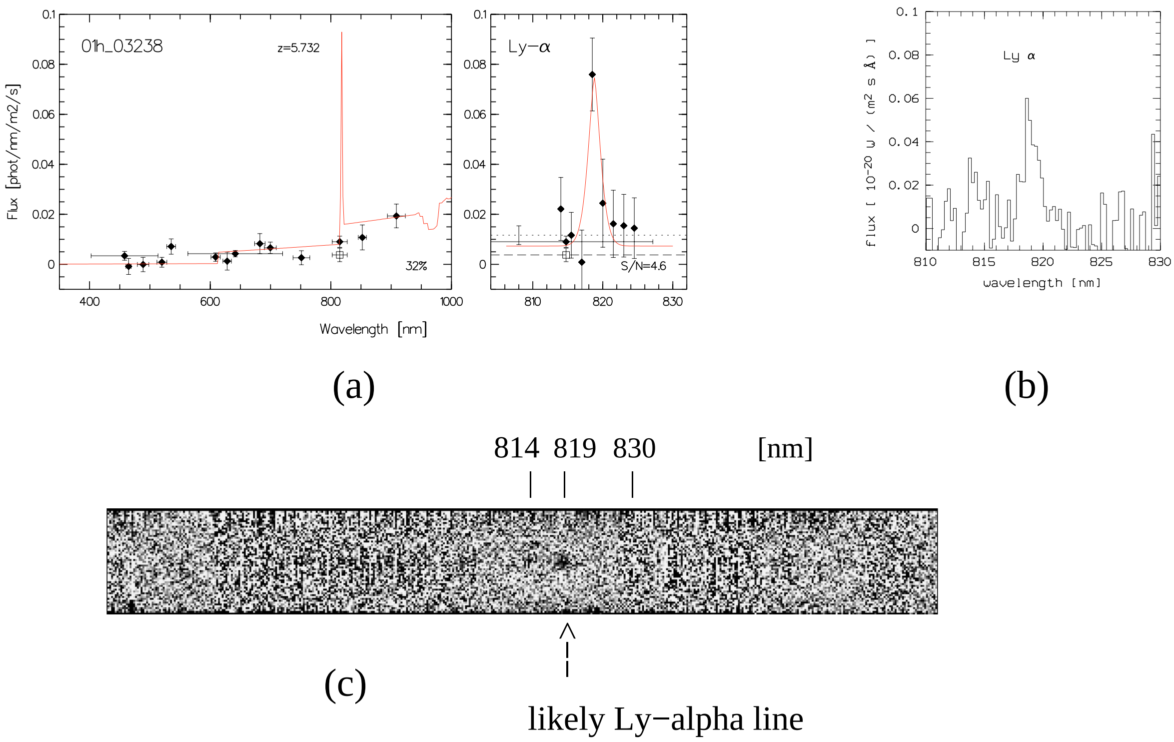

Fig. 2. 01h-3238, a likely Ly-α galaxy at $z = 5.732$. **a)** Photometry in all 14 optical CADIS filters fitted by a continuum-model (left panel), and the Fabry-Perot measurements with an emission line fit to the observed flux data (right panel). **b)** The single emission line, verified with FORS2 at the VLT, using the 300I grism. **c)** The two dimensional VLT spectrum.

Stars indicate preliminary results from the Large Area Lyman Alpha Survey (LALA) at $z = 4.6$ (Malhotra & Rhoads 2002) and at $z = 5.7$ (Rhoads et al. 2003). Malhotra & Rhoads (2002) found 157 Ly-α *candidates* at $4.37 < z < 4.57$ in one field of 0.36 deg^2. The arrow in Fig. 4 (left panel) indicates the upper limit of the number density of Ly-α-emitters based on the list of these candidates. Rhoads et al. (2003) reported 18 Ly-α *candidates* at $z \approx 5.7$ in one field of ~0.2 deg^2, of which three (out of four observed) candidates have been verified spectroscopically. Rhoads et al. infer a number density $39 < N < 54$ of Ly-α-emitters per deg^2 per $\Delta z = 0.1$ down to their detection limit (see Fig. 4, right panel). For comparison, we show in Fig. 4 the measured abundance of Lyman-α-emitting galaxies at $z = 3.5$ through emission-line-surveys from Hu et al. (1998, small circles), and Kudritzki et al. (2000, large circles; converted from $z = 3.1$).

In order to parametrize the observed number counts at $z = 3.5$, we use the model by Thommes & Meisenheimer (2003). It basically assumes (i) that Ly-α-galaxies mark the onset of star-formation in present-day spheroids, (ii) a rather short-lived Ly-α-bright phase due to rapid dust formation (~10^8 yrs), and (iii) a mass dependent formation history as given by the peak formalism. In order to fit the abundance at $z = 3.5$ we used model parameters that set the peak of Ly-α-emission for the bulge of the Milky Way around $z \simeq 6$. The normalization at $z = 3.5$ is set by the abundance of present day spheroids together with a free parameter – the duration of the Ly-α-bright phase. For the present work, we decided not to fine-tune the model in a way that a consistent description of the abundances at all redshifts $3.5 \leq z \leq 5.7$ is obtained. This will be presented in a forthcoming paper. Here we rather would like to demonstrate a robust qualitative statement – namely that Ly-α-galaxies are less common at $z = 5.7$ than at $z = 3.5$. To this end we simply *shift* the model function for $z = 3.5$ to higher redshift by taking into account both the higher luminosity distance (shift to the right), and the smaller comoving volume $\Delta V/\Delta z$ (shift to bottom). This "no-evolution model" is shown by the dotted line in Fig. 4.

It is obvious from Fig. 4 that the CADIS upper limits both at $z = 4.8$ and $z = 5.7$ fall short of such a non-evolution model, while at the faint end, $F_{\rm line} \leq 10^{-20}$ W m^{-2}, the present results could still be compatible with no evolution.

Since our statistics at $z \simeq 4.8$ are extremely limited, we will focus any further discussion on redshifts around $z = 5.7$.

While the number counts of Hu et al. at $z = 5.7$ (a single galaxy found by Hu et al. 1999) still seem compatible with the no-evolution model, the abundance of Ly-α-galaxies from LALA and the limits given by the CADIS candidates fall significantly short of the no-evolution prediction. The under-abundance of Ly-α emitting galaxies at $z = 5.7$ compared to $z = 3.5$ becomes even more obvious if one considers that the noise distribution of our survey predicts residual contamination of about 50%. Nevertheless, before drawing definite conclusions, one should consider whether selection effects could lead to an under-estimation of the number of Ly-α-emitting galaxies. Potential influences on the upper limits include: objects

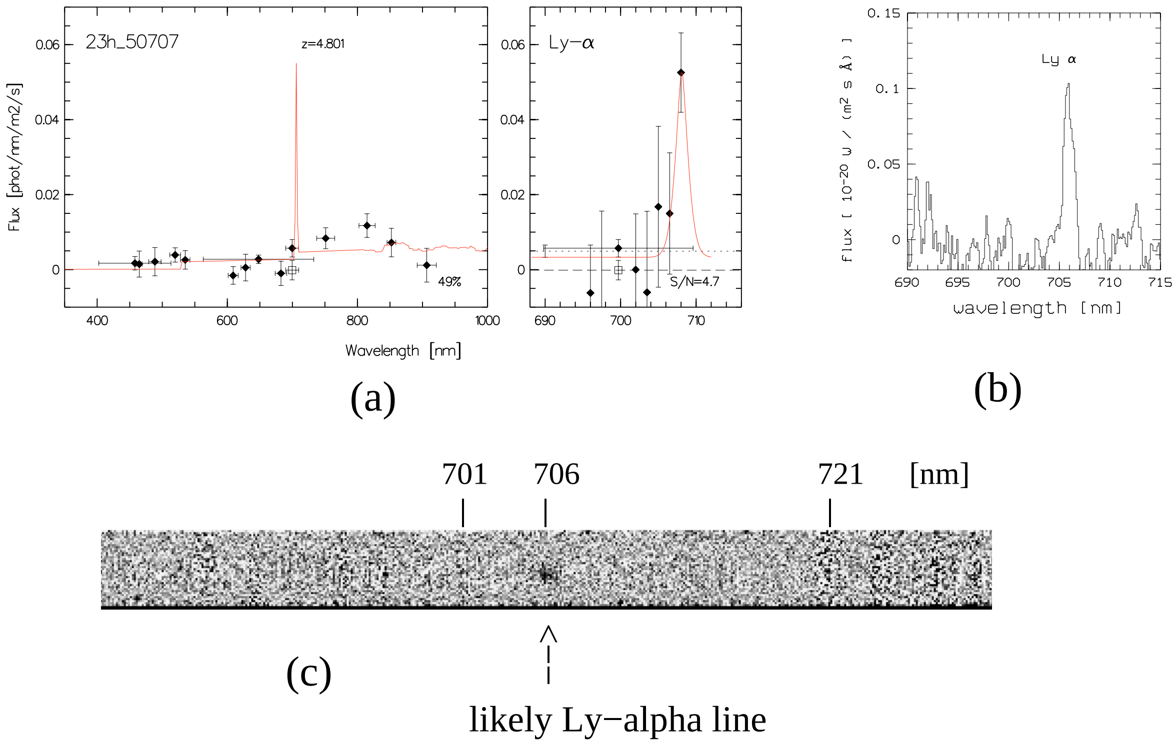

Fig. 3. 23h-50707, a probable Ly-α galaxy at $z = 4.801$. **a)** Photometry in all 14 optical CADIS filters fitted by a continuum-model (left panel), and the Fabry-Perot measurements with an emission line fit to the observed flux data (right panel). **b)** The single emission line, verified with FORS2 at the VLT, using the 600RI grism. **c)** The two dimensional VLT spectrum.

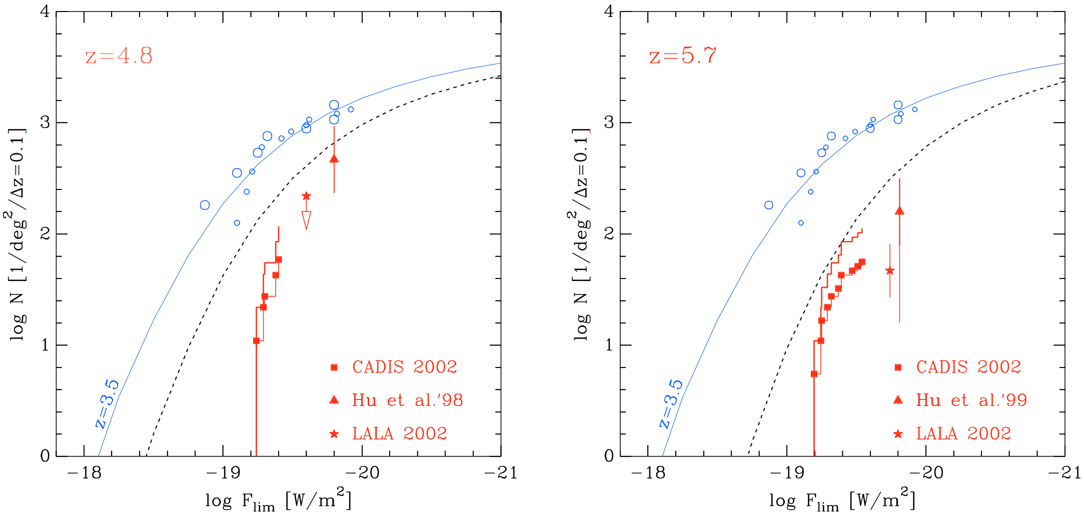

Fig. 4. Cumulative number counts of Lyman-α-galaxies, N deg^{-2} per $\Delta z = 0.1$, which are brighter than a certain observed flux F_{lim}, at $z = 4.8$ (left panel) and $z = 5.7$ (right panel). In the cumulative histogram the upper edge represents the number of candidates, while the squares take into account the likely residual contamination by noise. Additional values of the number density are from Hu et al. (1998) for $z = 4.5$, and from Hu et al. (1999) at $z = 5.7$. Stars show preliminary results from the Large Area Lyman Alpha Survey (LALA) at $z = 4.6$ (Malhotra & Rhoads 2002), and at $z = 5.7$ (Rhoads et al. 2003). Open circles denote the measured abundance of Lyman-α-galaxies at $z = 3.5$ through emission-line-surveys from Hu et al. (1998, small circles), and Kudritzki et al. (2000, large circles). A model luminosity function from Thommes & Meisenheimer (2003), fitted to the values at $z = 3.5$, has been converted to the redshifts searched by CADIS assuming *no* evolution between $z = 5.7$ und $z = 3.5$ (dotted lines).

classified as probable [O II] λ3727 galaxies for which the emission line is actually Ly-α, the fainter surface brightnesses of high redshift objects, and the large-scale structure. The weakly-confined bright end of the luminosity function at $z = 3.5$ may limit the comparison at the bright end. Therefore, we have to discuss how robust the CADIS upper limits are.

The distinction between a galaxy with [O II] λ3727 emission, but no flux in the CADIS B filter, and a Lyman-α-galaxy is ambiguous (see step (4) in Sect. 2). Therefore, some of the probable [O II] λ 3727 objects may turn out to be Ly-α galaxies, and some presumed Ly-α galaxies may turn out to be [O II] λ 3727-emitting galaxies. However, any asymmetry in this mutual contamination has already been accounted for by assuming a conservative estimate of 50% contamination of the Ly-α candidate sample.

Surface brightness depends on the apparent size of an object at redshift z, which does not change much between $z = 3.5$ and $z = 5.7$, and on the luminosity distance. Since the model luminosity function is converted to $z = 5.7$ taking the luminosity distance into consideration, most of the effect of the $(1 + z)^{-4}$ dimming towards higher redshift has already been accounted for.

Large-scale structure can influence galaxy counts even at high redshifts (Steidel et al. 1998). Since we derive the number counts of Ly-α galaxies at $z \approx 5.7$ by combining four CADIS fields (with a total area about 14 times the size of the field searched by Hu et al. 1998), large-scale structure should average out. Nevertheless, it should be kept in mind that results from small fields, like those searched by Hu et al. (1998, 1999), could be affected by large-scale structure.

Two points should be noted about the bright end of the luminosity function at $z \approx 3.5$. First, the *observed* Ly-α line fluxes for the most luminous galaxies at $z \approx 3.5$ found by Hu et al. (1998) and Kudritzki et al. (2000) are of the order of 10^{-19} W m^{-2}. Taking into account the higher luminosity distance at $z = 5.7$ (compared to $z = 3.5$), these galaxies would have apparent line fluxes of $\sim 3 \times 10^{-20}$ W m^{-2} at $z = 5.7$ (using a $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70$ km s^{-1} Mpc^{-1} cosmology); i.e., galaxies with intrinsically bright Ly-α emission, corresponding to observed line fluxes $> 3 \times 10^{-20}$ Wm^{-2} at $z \approx 5.7$ – as searched by CADIS − have not yet been found in the small fields searched at $z \approx 3.5$. Thus, the shape of the bright end of the luminosity function relies mainly on our model. Second, the number counts at the bright end of the luminosity function at $z = 3.5$, resulting from the brightest galaxy detected by Kudritzki et al. (2000, large circles), are higher than the results of Hu et al. (1998, small circles). Since large-scale structure can influence galaxy counts even at high redshifts (Steidel et al. 1998), the Kudritzki et al. number counts could be biased, because Kudritzki et al. searched only one field, whereas the Hu et al. survey goes over two fields. Disregarding the brightest galaxy from Kudritzki et al. would result in a steeper luminosity function at the bright end at $z = 3.5$ and thus lessen the discrepancy at $z = 5.7$.

In summary, we conclude that the luminosity function of Ly-α-bright galaxies declines between $z = 3.5$ and $z = 5.7$. This implies that the peak of the Ly-α-bright phase − i.e., the first formation of massive stars − is reached after $z = 6$. Although, in principle, both luminosity evolution or density evolution could account for this finding, we only can establish the decrease in density around 3×10^{-20} W m^{-2}, as the bright end of the Ly-α luminosity function is still not determined well enough at $z = 3.5$.

The onset of massive star formation should contribute a substantial fraction of the UV photons which reionize the universe. Moreover, both bright starbursts (SFR $\geq 10\, M_\odot$/yr) and the formation of supermassive black holes indicate a strong concentration of baryons within the centers of the most prominent density peaks. Therefore, our result seems to confirm additionally the finding from the analysis of the HI absorption in the spectra of SDSS quasars at $z > 6$ (Fan et al. 2002) that the reionization of the universe does not occur long before $z = 6$.

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