Part 6

Lensing the High Redshift Universe

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Very High-Redshift Lensed Galaxies

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Abstract. We review in this paper the main results recently obtained on the identification and study of very high-z galaxies using lensing clusters as natural gravitational telescopes. We present in detail our pilot survey with ISAAC/VLT, aimed at the detection of z> 7 sources. Evolutionary synthesis models for extremely metal-poor and PopIII starbursts have been used to derive the observational properties expected for these high-z galaxies, such as expected magnitudes and colors, line fluxes for the main emission lines, etc. These models have allowed to define fairly robust selection criteria to find z$\sim 7-10$ galaxies based on broad-band near-IR photometry in combination with the traditional Lyman drop-out technique. The first results issued from our photometric and spectroscopic survey are discussed, in particular the preliminary confirmation rate, and the global properties of our high-z candidates, including the latest results on the possible z=10.0 candidate A1835-1916. The search efficiency should be significantly improved by the future near-IR multi-object ground-based and space facilities. However, strong lensing clusters remain a factor of $\sim 5-10$ more efficient than blank fields in the z $\sim 7-11$ domain, within the FOV of a few arcminutes around the cluster core, for the typical depth required for this survey project.

1. Introduction

Considerable advances have been made in the exploration of the high-z Universe during the last decade, starting with the discovery and detailed studies of redshift $z \sim 3$ galaxies (Lyman break galaxies, LBGs), mostly from the pioneering work of Steidel and collaborators (cf. Steidel *et al.* 2003, Shapley *et al.* 2003), the $z \sim$ 4–5 galaxies found from different deep multi-wavelength surveys, to galaxies at $z \sim$ 6–7, close to the end of the reionisation epoch of the Universe (e.g. Kodaira *et al.* 2002, Hu *et al.* 2002, Cuby *et al.* 2003, Kneib *et al.* 2004, Stanway et al. 2004, Bouwens *et al.* 2004). To extend the present searches beyond $z \geqslant 6.5$ and back to ages where the Universe was being re-ionized (cf. Fan *et al.* 2002), it is mandatory to move into the near-IR bands. According to WMAP results, the first generation of stars may exist at $z \sim$ 14–20 (Bennet *et al.* 2003; Spergel *et al.* 2003).

At z> 7, the most relevant signatures are expected in the near-IR $\lambda \gtrsim 1\mu$m window. Most feasibility studies during the last years have been motivated by JWST, which should be able to observe galaxies up to redshifts of the order of $z \sim$ 20-30. However, the delay of JWST and the availability of well suited near-IR facilities in ground-based 8-10m telescopes hasten the development of observational projects targeting $z \gtrsim 7$ sources. The first studies on the physical properties of these sources can be started nowadays with instruments such as ISAAC/VLT, and pursued with improved efficiency using the future multi-object spectrographs to come, such as EMIR at GTC ($\sim$ 2006), or KMOS for the second generation of VLT instruments ($\sim$ 2009). In other words, the efficiency of this research is closely related to the instrumental developments in the near-IR domain.

We present here the first results from our ongoing pilot project with ISAAC/VLT, aimed at the detection of $z > 7$ sources through lensing clusters used as Gravitational Telescopes (GTs). Our goal is to build up the first spectroscopic sample of galaxies at $z > 7$ starting with GTs, in preparation of future massive surveys in the field. Such sample should allow to start a detailed study on the physical properties of these objects (SFR, extinction, metallicity, IMF, ...), and also start constraining their global properties (number counts, luminosity function, clustering properties, ...).

The plan of the paper is as follows. We review in section 2 the techniques and main results recently obtained on the identification of high-z galaxies in the optical bands, both in the field and using lensing clusters. In Sect. 3 we summarize the observational properties expected for galaxies at $7 \lesssim z \lesssim 11$. Our pilot survey with ISAAC/VLT, aimed at the detection of z> 7 sources, is presented in details in Sect. 4. The first results issued from our photometric and spectroscopic survey are discussed in this section, in particular the preliminary confirmation rate, and the global properties of our high-z candidates, including the latest results on the possible $z = 10.0$ candidate A1835-1916. A discussion on the preliminary results and constraints derived from the $7 \leqslant z \leqslant 10$ photometric candidates is given in Sect. 5, together with future prospects. Throughout this paper, we adopt the cosmological parameters: $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$ and $H_0 = 70$ km s^{-1} Mpc^{-1}.

2. Looking for $z \sim 5 - 7$ galaxies in the optical bands

Different field surveys in the optical bands have been successful in the systematic search for galaxies close to the reionisation epoch. These surveys are mainly based on 2 different techniques, which can easily be exploited in the near-IR bands: narrowband (NB) imaging surveys aimed at detecting Lyman-α emission, and broad-band multi-color surveys using photometric redshifts at some level (see a review by Spinrad, 2003).

The pioneering Large Area Lyman Alpha Survey (LALA, Rhoads & Malhotra 2001, Rhoads *et al.* 2003) used NB imaging together with BVR broad-band photometry to target strong Lyman-α emission at $z \sim 5.7$ in a KPNO + CTIO $36' \times 36'$ field of view. The spectroscopic follow up at LRIS/Keck confirmed 3/4 candidates, with important line fluxes (a few $\times 10^{-17}$ erg cm^{-2} s^{-1}) and $\sigma_v \geqslant 200$ km/s. Rhoads *et al.* (2004) have recently published new results at higher redshifts: a z=6.535 galaxy, representing 1/3 of candidates confirmed, with restframe $\sigma_v \geqslant 40$ km/s and Lyman-α flux 2×10^{-17} erg cm^{-2} s^{-1}. Other NB surveys in the field have also provided interesting galaxy samples in the z$\sim 5 - 7$ interval: the z=6.17 galaxy found by Cuby *et al.* (2003) in the CFHT-VIRMOS Deep Survey; the two $z \sim 6.6$ galaxies detected by Kodaira *et al.* (2003), and the large sample of Lyman-α emitters at $z \sim 5.7$ by Hu et al. (2004). In the later case, the authors used a combination of NB imaging at 8150Å (SuprimeCam) and broad-band photometry in the optical bands to select candidates for a subsequent spectroscopic follow up with DEIMOS/Keck. Their confirmation rate is very high: 18 sources out of 26 candidates are confirmed at high-z in a $34' \times 27'$ field of view, thus leading to 0.03 sources/arcmin^2 and redshift bin $\delta z = 0.1$. All these sources have important Lyman-α fluxes (a few $\times 10^{-17}$ erg cm^{-2} s^{-1}), and display broad Lyman-α lines ($\sigma_v \sim 200$ km/s).

The broad-band photometric selection of high-z sources is usually an extrapolation of the drop-out LBGs technique to higher redshifts, with subsequent spectroscopic identification of the selected candidates. When the photometric spectral coverage is wide

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enough, standard photometric redshifts can be derived through SED fitting procedures. An excellent example of this technique is the sample at $z \sim 4.5 - 6.6$ selected by Lehnert & Bremer (2003) in a 44 arcmin^2 field, using an Riz color criterium. 6 out of 12 "good" candidates were spectroscopically confirmed with FORS/VLT, thus leading to a number density for these sources which is close to LBGs at lower redshifts. Also Bouwens *et al.* (2003) and Stanway *et al.* (2004) have recently derived the $z \sim 6$ star formation density from I-dropouts candidates at this redshift selected on ACS/GTO HST fields.

Gravitational magnification by lensing clusters has proven highly successful in identifying a large fraction of the most distant galaxies known today. The systematic search for high-z targets around the critical lines allowed Ellis *et al.* (2001) to find a lensed galaxy at z=5.58 behind A2218, spectroscopically confirmed at Keck. This source is a faint compact galaxy, dominated by its Lyman-α emission, the stellar continuum beeing negligible in this case. Another interesting object recently discovered by Hu *et al.* (2002) is a lensed galaxy at z=6.56 behind the cluster A370. The authors used NB imaging at 9152 Å obtained with LRIS on the Keck telescope, to identify the image by the equivalent width of the line emission and the absence of flux at lower wavelengths. As it happens with sources identified from NB imaging, the flux measured in the line is relatively high:2.7×10^{-17} erg cm^{-2} s^{-1}. The magnification factor is moderate, only 4.5, the source beeing located more than 1' from the cluster center.

A deep and "blind" spectroscopic survey for high-z Lyman-α emitting sources was performed by Santos *et al.* (2004), around the critical lines in 9 intermediate-z lensing clusters. They targeted candidates at $4.5 \leqslant z \leqslant 6.7$, magnified by a factor of at least 10. Eleven of such candidates were later confirmed at $2.2 \leqslant z \leqslant 5.6$ with LRIS long-slit and ESI spectra at Keck, taking advantage from the higher resolution to resolve the [OII]λ3727 doublet or Lyman-α asymmetric profiles to discriminate between low and high-z sources. Thanks to the lensing magnification, these authors derived the Lyman-α Luminosity Function to unprecedented depths (see also J. Richard's poster, this conference).

In a recent paper, Kneib *et al.* (2004) discuss the identification of a possible $z \sim 7$ compact galaxy behind A2218. This is a faint triply imaged galaxy identified from deep z-band imaging with ACS/HST. Although there is no emission line detected in this object, both photometric and lensing modelling considerations provide a fair determination of its redshift. Regardless of the precise redshift, the multi-wavelength data available for this object already provide an interesting information on its nature (see also D. Schaerer's talk and J. Richard's poster, this conference). The important point here is that GTs allow to define different samples of high-z sources, using the same criteria as for field surveys (NB or broad-band imaging), but also some specific criteria based on lens-modelling considerations (systematic searches around the critical lines). All of them have a common point: the final samples will consist of sources intrinsically fainter than the field ones. The search efficiency as compared to blank fiends depends on two opposite trends: gravitational magnification (allowing to increase the number of faint sources, and thus the total number of sources at the end), and dilution due to the reduction of the effective area surveyed. As shown below, strong lensing clusters remain a useful tool for $z \geqslant 7$ studies.

3. Expected properties of galaxies at z$\geqslant 7$

Our project is to start looking for $z \sim$ 7–11 galaxies. At such redshifts, the most relevant signatures are expected in the $\lambda \gtrsim 1\mu$m domain. We have used the evolutionary synthesis models by Schaerer (2002, 2003) for Population III and extremely metal

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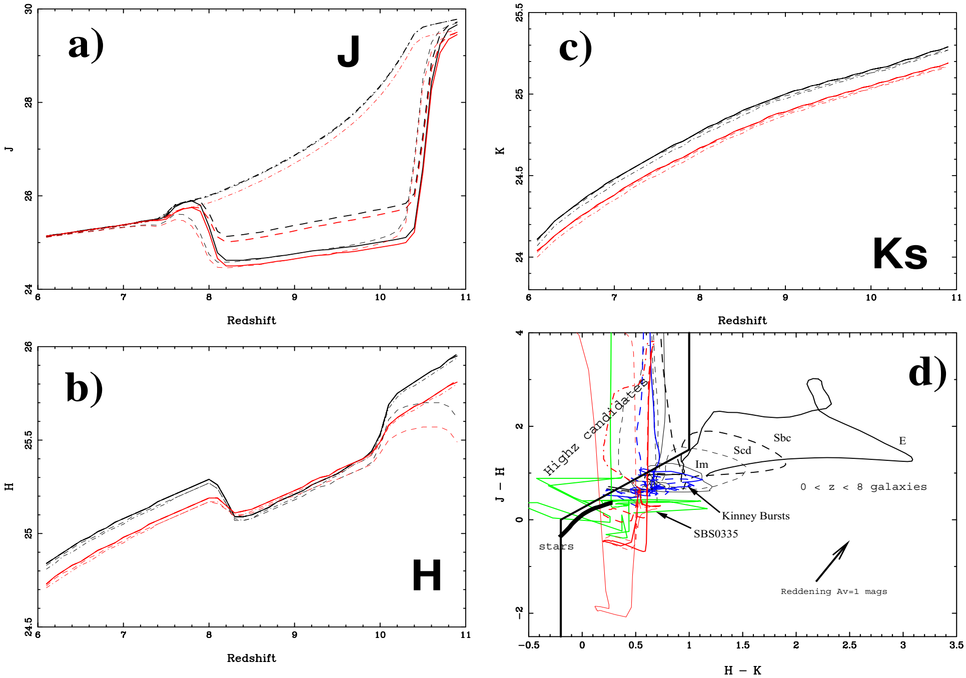

Figure 1. (a) J(Vega) magnitude as a function of redshift for a top-heavy IMF, for a fiducial stellar halo of 10^7 $M_\odot$. The values corresponding to a normal Salpeter IMF are about 2 magnitudes fainter over all the redshift interval. Black and red (grey) lines correspond respectively to burst ages 10^4 and 10^6 yrs. Various models for Pop III objects are presented, for different fractions of the Lyman α emission entering the integration aperture: 0% (thick dot-dashed line), 50% (thick dashed line), and 100% (thick solid line). Thin dot-dashed lines correspond to a self-consistent extended Lymanα halo emission (Loeb & Rybicki 1999), whereas thin dashed lines display the same model with 10% of Lymanα emission entering the integration aperture. (b) Same as a) for H(Vega) magnitude versus redshift. (c Same as a) for Ks(Vega) magnitude versus redshift. (d) $J-H$ versus $H-Ks$ color-color diagram (Vega system) showing the position expected for different objects over the interval of $z \sim 0$ to 11. The position of stars and normal galaxies up to z $\leqslant$ 8 are shown, as well as the shift direction induced by reddening $A_V = 1$ magnitude. Various models for Pop III objects are presented, with different fractions of Lyman α emission entering the integration aperture: 100% (thick dot-dashed line), 50% (thick dashed line), and 0% (thick solid line). Thin solid and dashed lines correspond to a core (non-resolved) source, whith extended Lyman α halo, for 50% and 10% of Lyman α emission entering the integration aperture. The location of starbursts templates (SB1 and SB2, from Kinney *et al.* 1996), and the low metallicity galaxy SBS0335-052 are also given for comparison. All star-forming models enter the high-z candidate region at zge 8.

deficient starbursts to derive the expected magnitudes and colors of galaxies in this redshift domain. For genuine PopIII sources, nebular continuous emission dominates the ZAMS spectra at $\lambda \geqslant 1400$ Å and strong emission lines are present (Lyman α, HeIIλ1640, HeIIλ3203, ...). The IMF could be dominated by very massive stars, up to $\sim 1000 M_\odot$, with a possible lack of low-mass stars (top-heavy IMF, Abel *et al.* 1998, Bromm *et al.* 1999). An important issue for our project is the photometric selection of candidates allowing a subsequent successful spectroscopic follow up.

Simulations have been done to define the observing strategy to target $z > 7$ sources. We consider a fiducial stellar mass halo of 10^7 $M_\odot$, corresponding to a collapsing DM halo of $2 \times 10^8 M_\odot$, thus typically to $\sim$ 1.5 to 2 σ fluctuations between z=5 and 10 (e.g. Loeb & Barkana 2001). Magnitudes are to be rescaled according to this value for other mass halos. These sources are espected to be unresolved on 0.3" scales. The reionization redshift is assumed to be $z \sim 6$. Lyman series troughs (Haiman & Loeb 1999), and Lyman forest following the prescription of Madau (1995) are included. Simulations accounting for an extended Lyman-α halo (cf. Loeb & Rybicki 1999) have also been computed, together with simple assumptions for the Lyman α emission line with arbitrary different fractions of the emission flux entering the integration aperture. Two extreme assumptions are considered here for the IMF, either a standard Salpeter IMF, with stars forming between 1 and 100 $M_{\odot}$, or a top-heavy Salpeter IMF, with stellar masses ranging between 50 and 500 $M_{\odot}$. Early versions of these simulations were presented in Schaerer & Pelló (2001) and Pelló & Schaerer (2002), as feasibility studies for EMIR/GTC and ISAAC-KMOS/VLT.

Genuine $z > 7$ sources are optical dropouts. Fig. 1 displays the $J - H$ versus $H - Ks$ diagram for different models compared to the location of stars and normal galaxies at $0 \leqslant z \leqslant 8$. We used the set of empirical SEDs compiled by Coleman, Wu and Weedman (1980) to represent the local population of galaxies, with spectra extended to wavelengths $\lambda \leqslant 1400$ Å and $\lambda \geqslant 10000$ Å using the equivalent spectra from the GISSEL library for solar metallicity (the Bruzual & Charlot 1993). We also included the starbursts templates SB1 and SB2, from Kinney et al. (1996), and the low metallicity galaxy SBS0335-052. The shift in this diagram corresponding to an intrinsic reddening of A_V=1, with the reddening law by Calzetti *et al.* (2000), is shown by an arrow. As shown in Fig. 1, the $J - H$ versus $H - Ks$ color-color diagram of optical dropouts is particularly well suited to identify galaxy candidates at $8 \leqslant z \leqslant 11$. At redshifts above $z \sim 10$, galaxies are expected to be non-detected in the J-band. At $6 \leqslant z \leqslant 9$, the same photometric selection can be performed including the Z (0.9 μm) and SZ (1.1 μm) filters.

An important issue is the photometric depth needed to detect typical stellar haloes up to a given mass. According to our simulations, the predicted (Vega) magnitudes for the reference stellar halo, assuming a top-heavy Salpeter IMF, range between ~ 24.5 and 26.5 in J, ~ 24.5 and 25.5 in H, and ~ 24 to 25 in Ks, depending on models, within the $z \sim 7$–10 interval (Fig. 1). These values are about 2 magnitudes fainter for a standard Salpeter IMF. If we intend to detect typical stellar haloes up to a few 10^7 $M_{\odot}$, and a significant fraction of them above 10^8 $M_{\odot}$ (depending on IMF assumptions), with a gravitational magnification ranging between 1 and 3 magnitudes, the depth needed is of the order of $J \sim 25.5$, $H \sim 24.5$ and $K \sim 24.0$.

The main emission lines expected in the near-IR domain, which should allow an accurate redshift determination, are HeII λ1640 and Lyman-α. Lyman-α can be detected on near-IR spectroscopic surveys with 8-10 m class telescopes, with a reasonable S/N over the redshift intervals z $\sim$ 7 to 18, with some gaps depending on the spectral resolution (OH subtraction), the atmospheric transmission, the intrinsic properties of sources and the intergalactic medium (IGM) transmission. A joint detection with HeII λ1640 should be possible for $z \sim 5.5$-7.0 (Lyman-α in the optical domain), $z \sim 7$–14 with both lines in the near-IR. The typical expected fluxes for these lines in our models range between 10^{-17} and a few 10^{-18} erg/s/cm2. Thus, a reasonable S/N$\sim 3-5$ could be obtained with a mid-resolution near-IR spectrograph such as ISAAC/VLT, with exposure times of the order of a few hours (see also simulations by Barton *et al.* 2003). The detection of both HeII λ1640 and Lyman-α should allow to constrain the upper end of the IMF and the age of these systems.

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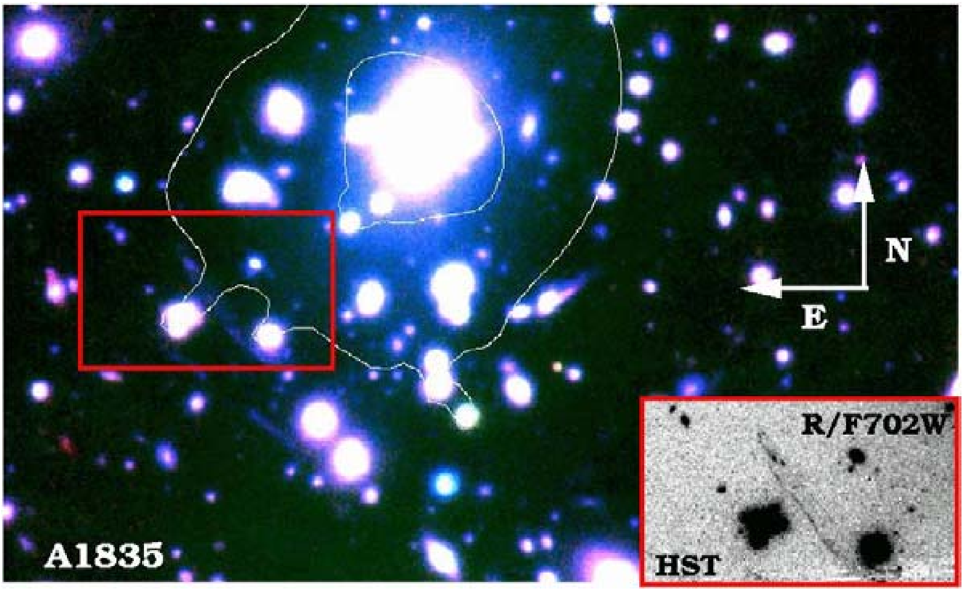

Figure 2. Composite RzH image of the core of the lensing cluster A1835, showing the critical lines at $z = 1.55$, and a close view of the main arc structure as seen on the R/F702W HST image.

4. Feasibility studies with GTs: A pilot project with VLT/ISAAC

4.1. *Survey Definition*

We were granted ISAAC/VLT time to develop a pilot survey aimed at searching for $z \gtrsim 7$ galaxies using GTs. Galaxy candidates are selected from ultra-deep $JHKs$ images (+ FORS/z and ISAAC/SZ when available) in the core of gravitational lensing clusters for which deep optical imaging is also available, including HST data. We apply the Lyman drop-out technique to deep optical images. The main spectral discontinuity at $z \gtrsim 6$ shortward of Lyman-α is due to the large neutral H column density in the IGM. In addition, galaxies are selected according to Fig. 1: we require a fairly red $J - H$ or $z/SZ - J$ color (due to the discontinuity trough the z, SZ or J bands), and a blue $H - Ks$ colour corresponding to an intrinsically blue UV restframe spectrum. The detection in at least two bands longward of Lyman α and the combination with the above $H - Ks$ colour criterion allows us to avoid contamination by cool stars. After the photometric selection of candidates, a spectroscopic follow up was carried out with ISAAC/VLT. Our survey will be presented in details in a forthcoming paper (Richard *et al.* 2004, in preparation).

Two lensing clusters were selected for this pilot survey. Table 1 summarizes the main properties of the near-IR photometric data.

• AC114 (α=22:58:48.26 δ=-34:48:08.3 J2000, $z = 0.312$) is very well known lensing cluster showing many multiple images with redshifts ranging between $z \sim 1$ and 4 (Smail *et al.* 1995; Natarajan et al. 1998; Campusano *et al.* 2001; Lemoine-Busserolle *et al.* 2003). In addition to the near-IR data summarized in Tab. 1, we have used optical photometry as reported in Campusano et al. (2001), including deep HST/WFPC2-F702W(R) images.

• A1835 (α=14:01:02.08 δ=+02:52:42.9 J2000, $z = 0.252$) is the most X-ray luminous cluster in the X-ray-Brightest Abell-type Clusters of Galaxies ($XBACS$) and the ROSAT Brightest Cluster samples (Ebeling *et al.* 1998). A velocity dispersion of 1500 km/s has been obtained by Czoske et l. (2004) for this massive cluster from a spectroscopic survey

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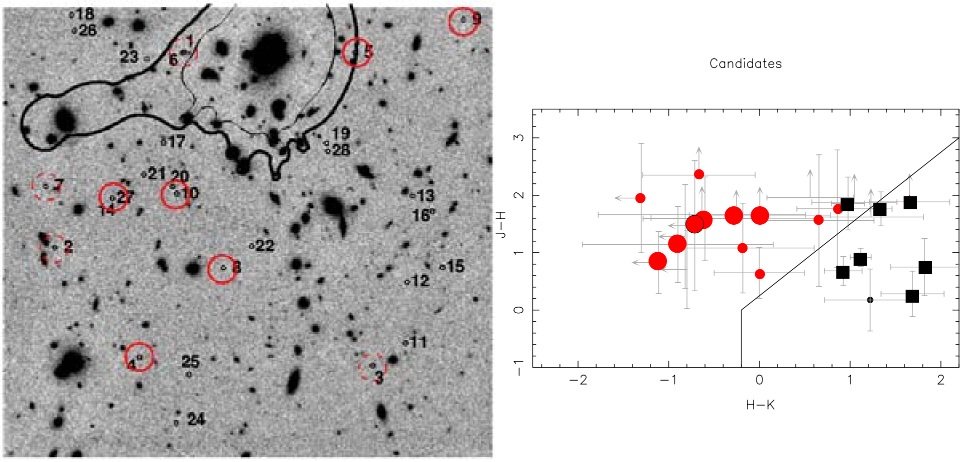

Figure 3. Left. *H*-band image for A1835 showing the location of the critical lines at z=1.5 (dashed curve) and z=10 (solid curve). The final candidates are circled. Large (red) solid circles display the first priority candidates, whereas dashed circles correspond to the secondary targets with a degenerate low-z solution in their redshift probability distribution. The other points are faint secondary targets selected only through their location on the color-color diagrams. **Right.** Color-color diagram showing the location of all optical-dropouts detected in A1835. The region selected corresponds to very high redshift candidates at $z \sim$ 8–11. Optical dropouts fulfilling the EROs definition are shown by black squares. Large and small red dots display respectively the first priority candidates for spectroscopy and the secondary targets for which a degenerate low-z solution exists according to their redshift probability distribution.

Table 1. Summary of Near-IR photometry obtained for our 2 lensing clusters in this project: filter, filter effective wavelength, AB correction ($m_{AB} = m_{Vega} + C_{AB}$) and, for each cluster, total exposure time, average seeing measured on the original images, limiting (Vega) magnitudes (1σ within a 1.5" diameter aperture).

			AC114			A1835		
Filter	λ_{eff} (nm)	C_{AB} (mag)	texp (ksec)	seeing (")	m_{lim} (mag)	texp (ksec)	seeing (")	m_{lim} (mag)
z	919	0.554	-	-	-	6.36	0.70	26.7
SZ	1063	0.691	-	-	-	21.96	0.54	26.8
J	1259	0.945	6.48	0.52	26.0	6.48	0.65	25.6
H	1656	1.412	13.86	0.40	24.9	13.86	0.50	24.7
Ks	2167	1.873	18.99	0.34	24.8	18.99	0.38	24.7

with VIMOS/VLT of $\sim$ 600 cluster members up to $R \leqslant 23$. Strong and weak lensing were reported in this cluster (Smail *et al.* 99, Limousin *et al.*, in preparation). In addition to the near-IR data summarized in Tab. 1, we have obtained deep VRI images at CFHT, and HST/WFPC2-F702W(R) data (limitig mag. R_{702W} =28.9). A mass model is available mainly based on a set of multiple images at z=1.56 (see Fig. 2).

4.2. *Photometric selection of candidates*

To look for high-z galaxy candidates we have applied the traditional Lyman break or drop-out technique. Optical/possibly J-band drop-out and a blue UV rest-frame SED (i.e. peculiar $J - H$ and/or $H - K$ colors, as shown in Fig. 1), allow us to select galaxy candidates with redshifts $z \sim$ 7–10 with intense ongoing star-formation. For the brightest candidates, we have computed photometric redshifts based on the SED fitting of the

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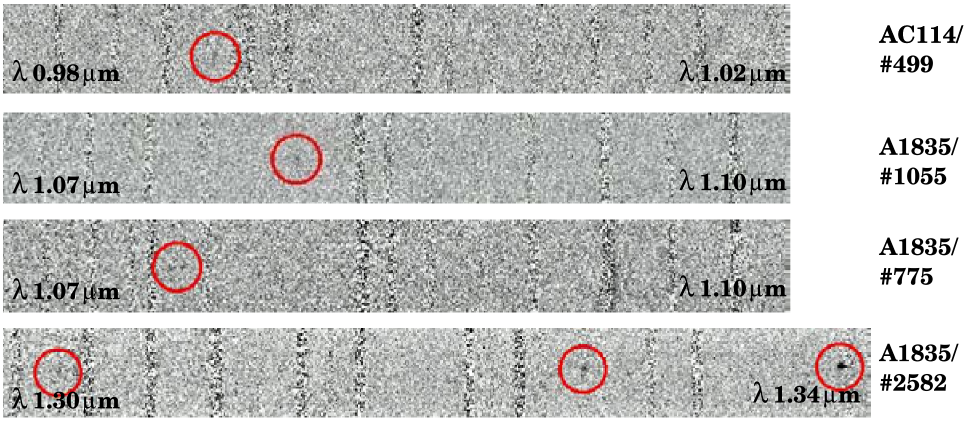

Figure 4. Sky-subtracted 2D spectra showing some of the emission lines detected in our sample of high-z candidates in A1835 and AC114. From top to bottom: AC114-499 (z=7.17 candidate, Lyα); A1835-1055 (z=7.89 candidate, Lyα); A1835-775 (low-z contamination at z=1.89, double line [OII]3727) and A1835-2582 (low-z contamination at z=1.67; Hβ, [OIII]4959,5007; Richard *et al.* 2003)

available photometric data using an adapted version of the code *Hyperz* (Bolzonella *et al.* 2000).

Our present photometric survey in AC114 and A1835 with ISAAC/ESO reaches an **effective** depth after magnification correction by 1 magnitude of 26.4, 26.0, and 26.5 (3 σ, AB mags, 1.5" aperture) in J, H, and Ks respectively, and sufficient accuracy (typically $\lesssim \pm 0.5$ mag in $J - H$ and $H - K$) to apply our photometric selection criteria. This is also illustrated in Fig. 3. With a magnification $\mu > 1$ mag over the entire field of view, the depth of our current observations is actually quite comparable to or even deeper, close to the critical lines, than the NICMOS-UDF. However, as the UDF, the **effective** field of view surveyed in the two clusters, after correction for lensing, remains relatively small, ~ 80 % of the UDF.

4.3. *VLT/ISAAC spectroscopic follow-up*

To look for faint emission lines, we have systematically explored the 0.9-1.40 μ m domain (SZ and J bands of ISAAC), where Lyman-α should be located for objects within the $7 < z < 10.5$ redshift interval. Priorities are set according to the photometric redshift probability distribution. First priority objects determine the observation sequence. Each band has $\sim$ 600 Å width. With a spectral resolution for the sky lines of $R = 3100$, corresponding to the instrumental 1 arcsec slit width, the fraction of spectral band lost because of strong OH sky emission lines, is of the order of 30%. Spectroscopic data were reduced using IRAF procedures and conforming to the ISAAC Data Reduction Guide 1.5†, using the same procedure described in Richard *et al.* (2003). Figure 4 displays 2D sky-subtracted spectra showing some of the emission lines detected in our sample of high-z candidates in A1835 and AC114. Typical line intensities range between 10^{-17} and a few 10^{-18} erg/s/cm2.

4.3.1. *AC114*

Two first priority candidates were observed in this cluster during a single run, both of them very close to the z$\geqslant$7 critical lines, with photometric redshifts ranging between 6.8 and 8.5. One of them, AC114-499, displays a faint emission line at 9935 Å compatible

† `http://www.hq.eso.org/instruments/isaac/index.html`

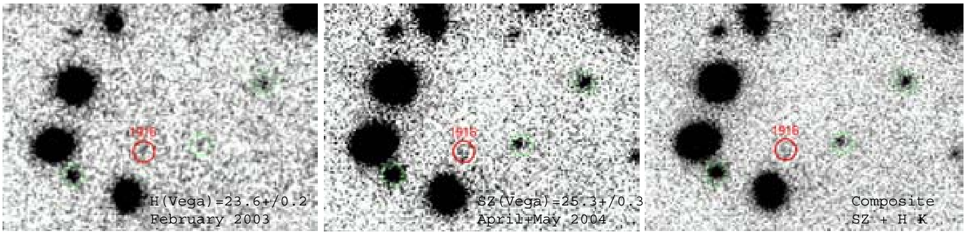

Figure 5. Thumbnail images of $16'' \times 22''$ around the source #1916 in A1835, obtained with ISAAC/VLT. From left to right: original H-band image obtained in February 2003 (t_{exp} =3.9h); SZ-band image (1.06μm, t_{exp} =6.1h), where the source was re-detected in May 2004; and composite image in $SZ + H + Ks$, i.e. all the images where the source was detected with S/N $\geqslant$ 3. Error bars correspond to mock simulations, and magnitudes are computed within 1.5" diameter aperture (the size of the circle in these images). Given the time scale and the detection levels, a TNO or a spurious detection seems highly unlikely.

with $z = 7.17$ (if Lyman-α, see Fig. 4). A solution at $z = 0.98$ (if this line corresponds to [OIII]λ5007) cannot be excluded. This source has to be confirmed.

4.3.2. *A1835*

Two observing runs were conducted in this cluster, with the following results, in addition to the first source likely to be at $z = 10.0$ (A1835-1916), which is discussed in the next section:

- A1835-1055: This source exhibits a unique emission line within the wavelength interval explored, which could be $z = 7.89$ (if Lyman-α, see Fig. 4). Given the spectral resolution of our observations, it is unlikely [OII]λ3727 at $z = 1.9$, because the doublet would easily be resolved. It is difficult to reconcile with [OIII]λ5007 at $z = 1.16$, because [OIII]λ4959 is not detected, or with Hβ at $z = 1.22$, because in this case [OIII]λ5007 should be present.
- A1835-2582: This is a rather unusual emission line galaxy at $z = 1.68$, already studied in details by our group using these data (see Richard *et al.* 2003). This galaxy is extremely faint ($M_B \sim -16.4$), with a gravitational magnification of ~ 2 magnitudes. Three lines, [OIII]$\lambda\lambda$4959,5007 and Hβ, were detected in our spectra.
- A1835-775: A double emission line is detected at the position of this source. It is likely the [OII]λ3727 doublet at z=1.888.
- A1835-1143: A faint line is detected at $\sim 3\sigma$, to be confirmed.

In addition to these sources, two other candidates observed in this cluster did not show emission lines within the J band. Of high priority, confirmation observations of A1835-1055 and A1835-1143 are scheduled.

4.3.3. *Results: A1835-1916*

We recently obtained the first likely spectroscopic confirmation of a $z = 10.0$ galaxy in our sample (Pelló *et al.* 2004). This galaxy (called A1835-1916) was one of the best candidates in the A1835 field, and a good example of the search procedure. With our original data the photometric redshift probability distribution showed a clear maximum at redshift $z_{\rm phot} \sim$ 9–11. This estimate was mainly corroborated by a strong break of $\gtrsim$ 3.1 to 3.7 AB mags between VRI and H, which has a high significance independently of the definition used for the limiting magnitudes. Our ISAAC/VLT spectroscopic observations (29 June to 3 July 2003), under excellent seeing conditions, resulted in the detection of one weak emission line at the 4-5 σ level with an integrated flux of $(4.1 \pm 0.5) \times 10^{-18}$ erg cm^{-2} s^{-1} at a wavelength of 1.33745 μm, which appears on 2 different overlapping

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wavelength settings. When identified as Lyman-α in good agreement with the photometric SED, we obtained $z = 10.0$ for this source, the most likely one given the data set available at this epoch. Its properties have been widely discussed in different papers (see also D. Schaerer's talk, this conference). Also, our recent spectroscopic observations in the H band (1.6915 to 1.8196 μm, 2 overlapping bands), display no other emission lines. In particular, neither HeIIλ1640 nor CIVλ1550 have been detected. We also exclude all the likely solutions at $z \sim 2-2.6$, as well as most of the $z \leqslant 2$ possibilities.

The field around A1835-1916 has been reobserved between 30 May and 6 June 2004 by Bremer *et al.* (2004) with NIRI/GEMINI in the H band. Surprisingly, the object is not seen anymore in these images, which are at least ~ 0.5 mag deeper than the ISAAC images taken approx. 15 months earlier. The reality of our initial photometric detections is not questioned (Bremer *et al.* reconfirm it using our data), and the detection cannot be spurious, as jointly detected in 2 filters HKs with S/N$\gtrsim$4 and 3 respectively — according to our mock simulations in a 1.5" aperture. Bremer *et al.* conclude on the possible low-z nature for this object. However, the analysis of new SZ (1.06μm) images obtained 19 April ($\sim 4h$ exposure, 77 images) and 15 May ($\sim 2h$ exposure, 45 images) 2004, has provided some new puzzling results. Although the two series of images have identical seeing and photometric zeropoint, A1835-1916 is virtually non-detected or very faint in the 19 April combination (S/N$\lesssim$1.5-2), whereas it is clearly detected in the final composition (see Fig. 5). The difference between the 2 series of images is about 0.5 magnitudes, but this value is still to be taken with care. However, when we consider this result together with our previous findings (the source was virtually non-detected in our J images), and the recent non-detection by Bremer *et al.* in the H band, it seems quite clear that this source could be intrinsically variable. Its nature (and hence also its redshift) presents quite a puzzle.

Possible explanations for faint transient/variable objects include TNO, but the typical motions of $\sim 1''/h$ are difficult to reconcile with the time scales and rejection schemes. Alternatively this could be a distant lensed SN (e.g. Marri & Ferrara 1998; Marri *et al.* 2000) or a tidal disruption of a star by a BH (cf. Stern et al. 2004), but such events are thought to be very rare, and the source show up at least twice in a 15 months period. The UV variability of a distant quasar (e.g. Czerny, 2004; Rengstorf *et al.*, 2004) is a more likely explanation, given the amplitude and time scale of the variability. In this case, the emission line previously detected could correspond to the UV line of a high-z AGN. The observed SED of the source is likely to be contaminated by intrinsic variability.

4.3.4. *Results: Confirmation Rate*

Our spectroscopic survey with ISAAC has targeted 2 out of ∼5 good candidates in AC114, and 7 in A1835 (4 "first priority" targets and 3 secondary ones). From this sample of 9 targets, 2/3 of the objects observed display emission lines. Actually 5 sources have clear emission lines detected, and another one is still to be confirmed. These emission-line sources can be classified as follows:

• **High-z $z \geqslant 7$ candidates**. This sample includes A1835-1916, AC114-499, A1835-1055 and A1835-1143 (faint line still to be confirmed).

• **Low-z sources**. This sample includes extremely faint sources at z∼1.5-2, such as A1835-2582 (z=1.68, Richard et al. 2003) and A1835-775 (z=1.89).

In summary, from 6 first priority targets observed in 2 clusters, we have clearly confirmed 1 candidate (A1835-1916), which is found to be a puzzling source, 2 are still to be confirmed at $z \geqslant 7$, 1 is found to be a low-z contamination, and 2 of them do not show emission lines. From the 3 secondary targets observed, only one is a possible $z \geqslant 7$ source, whereas the other one showing emission lines is a faint low-z galaxy. According

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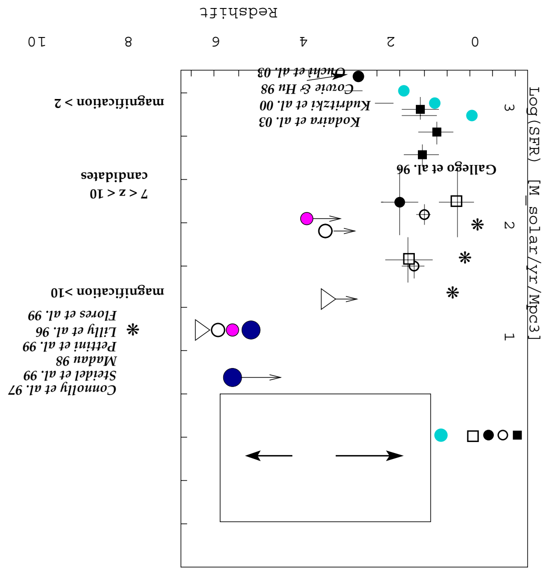

Figure 6. SFR density estimated from our 5 best candidates at $7 \leqslant z \leqslant 10$ in the lensing cluster A1835, compared to previous values up to $z \leqslant 7$. This is a rough estimate, with upper and lower limits corresponding to extreme assumptions for the typical magnification factors ranging between $\geqslant 2$ and $\geqslant 10$. This figure illustrates the inherent uncertainties associated to such small-numbers statistics.

to these numbers, the efficiency of our survey nowadays could range between ~ 30 and 50%, with interesting low-z by-products. The final confirmation rate will depend on the results obtained from our last observing run, which is still uncomplete when writing this paper. Improving the candidate confirmation, and possibly finding other emission lines such as HeIIλ1640 or CIVλ1550 is of great interest to quantify the nature/metallicity of these objects.

5. Discussion

5.1. *Preliminary results on the 7$\leqslant z \leqslant$ 10 photometric candidates*

Applying the above broad-band selection criteria has provided 5-10 $z > 7$ galaxy candidates per lensing cluster in the observed fields. We have used the lensing models to derive the **effective** areas and corresponding volumes surveyed at the different source planes. Typical magnification factors range between $\gtrsim 2$ and $\gtrsim 10$. The corresponding number density of objects within $7 \lesssim z \lesssim 10$ ranges between 2×10^{-2} and 4×10^{-4} per Mpc^{-3}, i.e. typically a few 10^3 objects deg^{-2}. The main uncertainties are due to simplifying assumptions, incompleteness corrections, and the values adopted for the typical magnification factors of our sample. These quantities have been evaluated with care and will be presented in a forthcoming paper (Richard *et al.* 2004, in preparation).

From the observed H magnitudes and magnification factors derived from the lens model, the typical star formation rates for these candidates are estimated to be a few $M_\odot yr^{-1}$ (lensing corrected, assuming a "standard" Salpeter IMF from 1–100 $M_\odot$). We have used simulations to correct for observational incompleteness in our photometric data. Fig. 6 displays the star formation rate density derived from our 5 best candidates at $7 \leqslant z \leqslant 10$ in the lensing cluster A1835, compared to previous values from the literature. This figure illustrates the inherent uncertainties associated to such small-numbers

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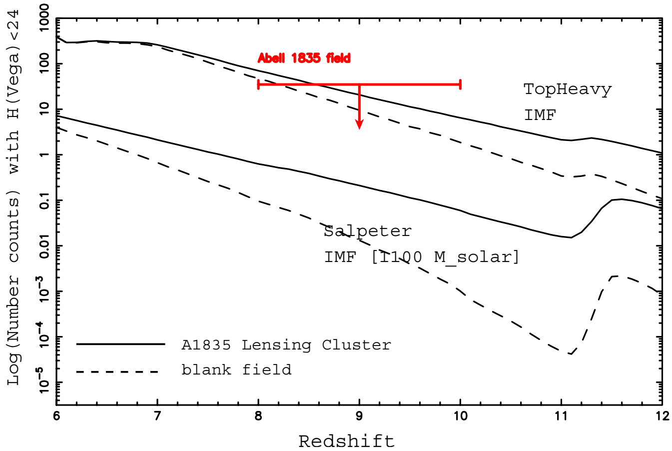

Figure 7. Comparison between the expected number counts of galaxies in the field of ISAAC, up to $H \leqslant 24$, per redshift bin $\Delta z = 1$, in a blank field and in the field of the strong lensing cluster A1835. Two different extreme assumptions for the IMF are used: a Salpeter IMF, and a top-heavy IMF (stars forming between 50 and 500 $M_{\odot}$). We display our own candidates in this field, corrected for photometric completeness.

statistics. In short, a more detailed analysis and additional observations are required to draw more firm conclusions on the behaviour of the SFR density at $z > 7$.

5.2. *Future developments*

An important issue of this project in view of the future facilities (such as EMIR at GTC and the future KMOS for the VLT 2nd generation) is the strategy for target selection, and the efficiency achieved in spectroscopic studies. As shown in Sects. 3 and 4, starbursts could be detected from deep near-IR photometry based on a measurement of two colors with accuracies of the order of 0.3-0.5 mag. As shown in Fig. 7, GTs remain the ideal fields for the first prospective studies. In this figure we compare the expected number counts of high-z galaxies with $H \leqslant 24$, per redshift bin $\Delta z = 1$, in a blank field and in the field of the strong lensing cluster A1835, for 2 different extreme assumptions for the IMF: a standard Salpeter IMF, and a top-heavy IMF (stars forming between 50 and 500 $M_{\odot}$). A simple Press-Schechter formalism for the abundance of halos and standard ΛCDM cosmology were considered in these order of magnitude simulations, as well as a conservative fixed fraction of 10% of the baryonic mass in halos converted into stars. Strong lensing fields are a factor of $\sim 5-10$ more efficient than blank fields of the same size in the z $\sim 7-11$ domain, all the other conditions beeing the same. In addition, the large magnification factors achieved on unresolved sources facilitates the spectroscopic follow up from ground-based telescopes. Additional discussion can be found in Pelló et al. (2004b).

Large Surveys devoted to the identification and study of $z \geqslant 7$ galaxies are already planned. It is crucial to increase the multiplexing capabilities of near-IR spectrographs, as well as the field of view and the typical wavelength interval which can be explored in a single shot. An important project in this area is the GOYA Survey, using the new multi-object near-IR spectrograph EMIR at GTC, starting in 2006 (Garzón *et al.* 2003).

6. Conclusions

The bottom line in the present searches for z $\sim 7-11$ galaxies is efficiency. The different techniques used to identify high-z candidates (narrow-band or broad-band searches) are complementary. They have to be improved and optimized in the near future to enhance the confirmation rates. Both the identification procedures and the individual high-z sources issued from these procedures should be validated, if possible through complementary observations of the same field.

The search efficiency should be significantly improved by the future near-IR multi-object ground-based and space facilities. However, strong lensing clusters remain a factor of $\sim 5-10$ more efficient than blank fields in the z $\sim 7-11$ domain, within the FOV of a few arcminutes around the cluster core, for the typical depth required for these survey projects.

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