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OBSERVING $z > 7$ SOURCES WITH THE GTC

R. Pelló,[1] D. Schaerer,[2,1] J. Richard,[1] J.-F. Le Borgne,[1] and J.-P. Kneib[3,1]

RESUMEN

Presentamos los primeros resultados obtenidos de nuestra exploración piloto ultra profunda en el IR cercano con ISAAC7VLT, enfocada a la detección de fuentes con z > 7 utilizando cúmulos que producen efecto de lentes como Telescopios Gravitacionales naturales. Los modelos de síntesis evolutiva de población III y de brotes de formación estelar extremadamente pobres en metales fueron utilizados para derivar las propiedades observacionales esperadas para estas galaxias de altos z, tales como magnitudes y colores esperados, flujos de las principales líneas de emisión, etc. Estos modelos nos han permitido definir criterios de selección bastante robustos para encontrar galaxias con $z \sim 7 - 10$, basados en fotometría en el IR cercano de banda ancha, en combinación con la técnica tradicional de la caída de Lyman. La amplificación en el núcleo de los cúmulos que actúan como lentes mejora la eficiencia de la búsqueda y el consiguiente seguimiento espectroscópico. La eficacia de la investigación mejorará significativamente gracias a las futuras instalaciones en el IR cercano para objetos múltiples, tales como EMIR/GTC y KMOS/VLT-2, y más adelante, el JWST.

ABSTRACT

We present the first results obtained from our pilot ultra-deep near-IR survey with ISAAC/VLT, aimed at the detection of $z > 7$ sources using lensing clusters as natural Gravitational Telescopes. Evolutionary synthesis models of PopIII and extremely metal-poor starbursts have been used to derive 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 us 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 magnification in the core of lensing clusters improves the search efficiency and subsequent spectroscopic follow up. The research efficiency will be significantly improved by the future near-IR multi-object facilities such as EMIR/GTC and KMOS/VLT-2, and later the JWST.

Key Words: **COSMOLOGY: EARLY UNIVERSE — GALAXIES: EVOLUTION — GALAXIES: HIGH REDSHIFT — INFRARED: GALAXIES**

1. MOTIVATION

The detection of the very first stars and galaxies forming from pristine matter in the early Universe remains one of the major challenges of observational cosmology (cf. review of Loeb & Barkana 2001; Weiss et al. 2000; Umemura & Susa 2001). These sources constitute the building blocks of galaxies, forming at redshifts $z \sim$ 6–30. Indeed, the recent WMAP results seem to place the very first generation of stars at $z \sim$ 10–30 (Kogut et al. 2003). Important progress during the last years has permitted direct observations of galaxies and quasars out to redshifts $z \sim 6.6$ (Hu et al. 2002, Fan et al. 2003, Kodaira et al. 2003). At $z > 7$, the most relevant signatures are expected in the near-IR $\lambda \gtrsim 1\mu$m window. Modeling efforts during the last years have been motivated by JWST, which should be able to observe these objects at redshifts up to $z \sim 30$. However, the delay of JWST and the availability of well suited near-IR facilities in ground-based 8-10m class telescopes hasten the development of observational projects targetting $z \gtrsim 7$ sources. The first studies on the physical properties of these sources can be presently started with instruments such as ISAAC/VLT, and continued with the future multi-object spectrographs such as EMIR at GTC ($\sim$ 2006), or KMOS for the second generation of VLT instruments ($\sim$ 2009).

In this paper we present the first results from our ongoing pilot project with ISAAC/VLT, aiming at looking for the first stars/galaxies through lensing clusters used as Gravitational Telescopes (GTs). The plan of the paper is the following. We summarize in section 2 the observational properties expected for galaxies at $7 \lesssim z \lesssim 10$. In section 3 we present the main characteristics of our ISAAC/VLT project. The method used to identify sources and the first results obtained are also presented in this

[1]Laboratoire d'Astrophysique de l'Observatoire Midi-Pyrénées, France.
[2]Observatoire de Genève, Switzerland.
[3]Caltech Astronomy, USA.

section, in particular the first spectroscopic confirmation of a z=10 candidate. The implications of these results for EMIR/GTC are briefly discussed in section 4.

2. PROPERTIES OF $7 \lesssim Z \lesssim 10$ GALAXIES

We have used the evolutionary synthesis models by Schaerer (2002, 2003) for Population III and extremely metal deficient stars to derive the expected magnitudes and colors of galaxies at $7 \lesssim z \lesssim 10$. The dependence of their properties on the IMF and upper mass limits for star formation were studied in previous papers (e.g. Schaerer & Pelló 2001; Pelló & Schaerer 2002). We have also computed the expected S/N ratios for the main emission lines using telescope and instrumental parameters in the near-IR corresponding to ISAAC/VLT, and the future multi-object facilities EMIR/GTC and KMOS/VLT.

According to our simulations, the predicted magnitude in the K'(Vega) band is typically $\sim$ 24 to 25 for the reference stellar halo mass of 10^7 $M_{\odot}$. Nebular continuous emission and strong emission lines have important effects on the integrated fluxes and colors of such galaxies. Figure **??** displays the J-H versus H-Ks color-color diagram for different models with $5 \leq z \leq 11$, compared to the location of stars and normal galaxies at $0 \leq z \leq 8$, including the starbursts templates SB1 and SB2, from Kinney et al. 1996, and the low metallicity galaxy SBS0335-052. Broad-band colors do not allow to constrain the physical properties of these galaxies, such as the IMF, star-formation mass range, ages, etc., but they are useful to identify sources on ultra-deep photometric surveys (cf. below).

The main emission lines expected are Lyman α and HeII λ1640, the strongest HeII line. In principle, 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. A measure of the hardness of the ionising flux, which constrains the upper end of the IMF and the age of the system, could be obtained through the detection of both HeII λ1640 and Lyman α. A rough measurement of the continuum using the photometric spectral energy distribution (SED) provides additional information on the stellar populations, extinction, etc.

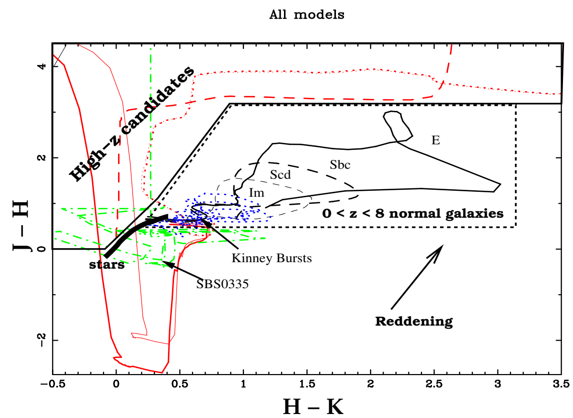

Fig. 1. J-H versus H-Ks color-color diagram (Vega system) for young starbursts (metal-poor and metal-free) objects, showing the position for the different redshifts over the interval of $z \sim 5$ to 12. The position of stars and normal galaxies up to $z \leq 8$ including also starbursts templates (SB1 and SB2, from Kinney et al. 1996, and the low metallicity galaxy SBS0335-052) are also shown, as well as the shift direction induced by reddening. Various line styles (solid, dashed, dotted) illustrate young starburst models with Lyman-α contributions of 100, 50, and 0 %. Because of the limiting magnitudes in the different filters, most $z \sim 7$–10 candidates are expected within the "High-z candidates" region. This diagram illustrates that such galaxies can well be separated from "normal" objects on the basis of JHK photometry.

3. A PILOT PROJECT WITH ISAAC/VLT

Lensing clusters acting as GTs are useful tools to investigate the properties of distant galaxies. Successful systematic searches for $z \gtrsim 5$ galaxies with GTs have appeared during the last three years (e.g. Ellis et al. 2001; Hu et al. 2002; Kneib et al. 2004).

We were granted ISAAC/VLT time to develop a project aimed at searching for $z \gtrsim 7$ galaxies using GTs. This prototype observational program is presently going on. The method used and the first results obtained are summarized below.

3.1. *Method*

Galaxy candidates at $z \gtrsim 7$ are selected from ultra-deep $JHKs$ images 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 $J-H$ color (due to the discontinuity trough the J band), and a blue $H-Ks$ colour corresponding to an intrinsically blue UV restframe spectrum. The detection in at least

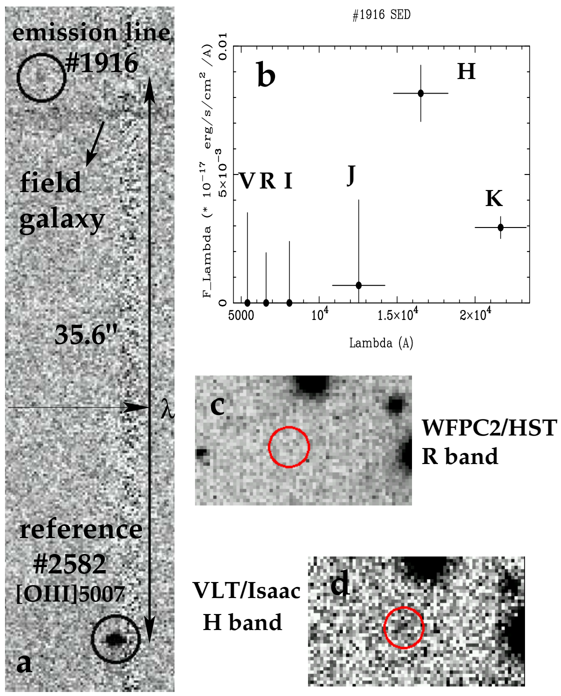

Fig. 2. The object #1916 in A1835: **a)** 2D spectrum showing the detected emission line at 1.33745 μm(leading to $z = 10.00$ when identified as Lyman-α, as well the nearby field galaxy and the [O III] λ5007 line of the galaxy #2582 ($z = 1.68$, Richard et al. 2003) used as a reference to stack the data sets. The line is seen on 2 independent overlapping bands. **b)** Photometric optical to near-IR SED in F_λ units. **c) and d)** Thumbnail images in the HST-WFPC2 R band, where the object is not detected, and in the H band.

two bands longward of Lyman α and the combination with the above $H - Ks$ colour criterion allows us to avoid contamination by cool stars.

Ultradeep JHKs imaging of 2 lensing clusters were obtained: A1835 ($z = 0.25$) and AC114 ($z = 0.31$), under excellent seeing conditions ($\sim 0.4''$ to $0.6''$). A complete report and analysis of these observations will be given elsewhere (Richard et al. in preparation). The best candidates are retained for follow-up spectroscopy with ISAAC/VLT. The broad band SED of each source is used to constrain the redshift using a modified version of the public photometric redshift code *Hyperz* (Bolzonella et al. 2000), including numerous empirical and theoretical spectral templates for both galaxies and AGNs, and keeping internal extinction as a free parameter. The J band domain, where Lyman-α should be located for objects in this redshift interval, is systematically explored with ISAAC according to the priorities set by the photometric redshift probability distribution.

3.1.1. *First Results on $7 \lesssim z \lesssim 10$ Photometric Candidates*

Applying the above broad-band search criteria has provided 5-10 $z > 7$ galaxy candidates per lensing cluster in the observed fields. About half of them have photometric SEDs accurate enough to allow a robust identification within this redshift interval, and thus to be included in the spectroscopic follow up sample. Lensing effects are taken into account to determine the intrinsic properties of these sources and the effective areas surveyed on 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. From the observed magnitudes and magnification factors derived from the lens model their star formation rates are estimated to be a few M$_\odot$yr^{-1} (lensing corrected, assuming a "standard" Salpeter IMF from 1–100 M$_\odot$). Adopting typically $SFR \sim 2$ M$_\odot$yr^{-1} we obtain an estimate of the star formation rate density shown in Fig. 3, and compared to previous estimates between $z = 0 - 7$. Obviously for now the SFR density at $z > 7$ remains highly uncertain. Ricotti et al. (2004) recently derived a fairly high SFR density at $z = 10$ based on our galaxy detection with spectroscopic redshift (A1835 IR1916, cf. below). However, their study suffers mostly from a highly uncertain survey volume area and an overestimated *mean* magnification factor. In short, a more detailed analysis and additional observations are required to draw more firm conclusions on the behaviour of the SFR density at $z > 7$.

3.1.2. *Spectroscopic confirmation of a z=10 candidate*

We report in a recent paper the first likely spectroscopic confirmation of a $z = 10.0$ galaxy in our sample (see Pelló et al. 2004). This galaxy (called #1916) was the best candidate found in the field of the lensing cluster A1835, and a good example of the research procedure. In this case, the photometric redshift probability distribution shows a clear maximum at redshift $z_{\rm phot} \sim$ 9–11. This estimate is 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 (see Fig. 2).

The spectroscopic redshift determination was obtained with ISAAC/VLT between 29 June and 3 July

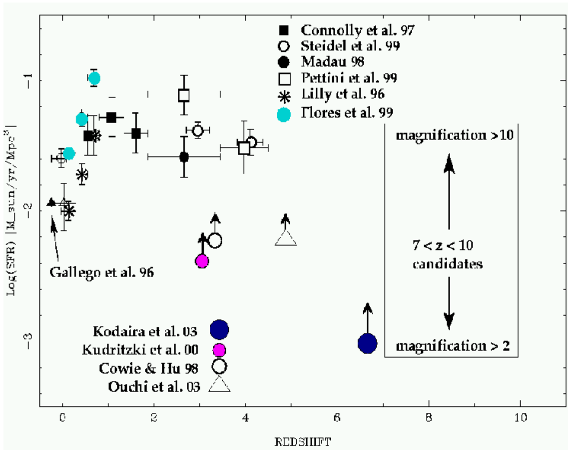

Fig. 3. SFR density derived from our 5 best candidates at $7 \lesssim z \lesssim 10$ in the lensing cluster A1835, compared to previous estimates up to $z \lesssim 7$. Upper and lower limits correspond to extreme assumptions for the typical magnification factors ranging between $\gtrsim 2$ and $\gtrsim 10$.

2003, under excellent seeing conditions, using a 1 arcsec slit width. The observed spectral interval covers the range from 1.162 to 1.399 μm(redshifts $z \sim 8.5$–10.5 for Lyman-α). The observations 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 (see Fig. 2), which appears on 2 different overlapping wavelength settings. When identified as Lyman-α in good agreement with the photometric SED, the observed line gives a redshift of $z = 10.00175 \pm 0.00045$, the most likely one given the data set (see a detailed discussion in Pelló et 2004).

Given the location of the image on the lensing plane, the source is highly magnified by a factor of 25. Its intrinsic AB magnitude is 28.5 and 29 in the H and Ks bands respectively. The star formation rate obtained from a direct scaling of its UV restframe flux ranges between 1.8 and 3 M$_\odot$ yr^{-1} after lensing correction, assuming a "standard" Salpeter IMF from 1–100 M$_\odot$. The UV restframe spectrum is very blue, compatible with a small extinction in this galaxy. Only a relatively small fraction of the Lyman-α flux emitted from the source is observed. Scaling young burst models with metallicities $Z \gtrsim 1/50 Z_\odot$ to the observed SED we obtain $M_\star \sim 2 \times 10^8$ M$_\odot$ (or lensing corrected values of $M_\star \sim 8 \times 10^6$ M$_\odot$) and luminosities of $L \sim 4 \times 10^{11}$ L$_\odot$ (2×10^{10} L$_\odot$ lensing corrected) for the standard Salpeter IMF. The observed and derived properties of this object are in good agreement with expectations for a young protogalaxy experiencing a burst of star formation at $z = 10$.

4. IMPLICATIONS FOR EMIR/GTC

Simulations and pilot observations conducted by our group on the possible detection of $z \gtrsim 7$ galaxies support this scientific case in view of the future ground-based near-IR facilities such as EMIR at GTC and the future KMOS for the VLT 2nd generation (Schaerer & Pelló 2001; Pelló & Schaerer 2002). An important issue of this project in view of the future facilities is the strategy for target selection, and the efficiency achieved in spectroscopic studies. As shown in sections 2 and 3.1, 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. 4, GTs are the ideal fields for the first prospective studies. We compare in this figure the expected number counts of high-z galaxies with K'< 24 in our GT ongoing survey, for 2 different extreme assumptions for the IMF, leading to intrinsically bright or faint sources. 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 the baryonic mass in halos converted into stars.

As seen in Fig. 4, strong lensing fields are a factor of $\sim 5-10$ more efficient than blank fields of the same size in the z $\sim 8-10$ domain. This is the motivation of all present searches for $z \gtrsim$6-7 galaxies using GTs (and ISAAC in particular). The large field of view of the future instruments (between $\sim 6' - 8'$ for EMIR/GTC and KMOS/VLT) provides the same efficiency than GT fields in "optimistic" models, and even better efficiency up to $z \sim$10, simply because the size of the field compensates the magnification (and dilution) effects. In the most pessimistic models (assuming intrinsically fainter sources), the benefit of the wide field of view versus strong lensing extends only up to $z \sim$7.5, the magnification being a major benefit in this case. As shown in the figure, when this regime is attained, the number of sources expected per redshift bin $\Delta z = 2$ falls below 1 source per arcmin^{-2}, and thus we can still take benefit from the presence of GTs in the surveyed field. The redshift bin considered ($\Delta z = 2$) corresponds to the typical wavelength interval which can be explored in a single shot with EMIR. These numbers are to be considered as orders of magnitude. Using higher redshift GTs could improve the situation for "compact" lensing studies with respect to $\sim 6' - 8'$ blank fields.

Thanks to its multiplexing capabilities, spectral resolution and wide field of view, EMIR at GTC will be the best suited instrument to continue exploring the formation epoch of the first stars in galaxies

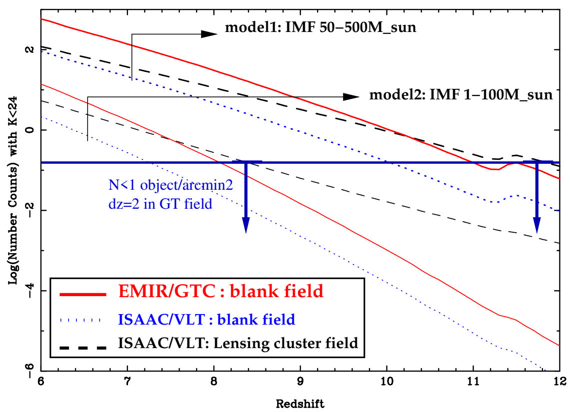

Fig. 4. Comparison between the expected number counts of "primordial galaxies" up to K≤24, per redshift $\Delta z = 0.1$, with and without the presence of a strong lensing cluster, AC114 (z=0.31) in this example, within the field of view of ISAAC/VLT, compared to EMIR/GTC. Two different extreme assumptions for the IMF are used. The solid horizontal line displays the domain corresponding to less than 1 source per arcmin^{-2} within $\Delta z = 2$.

using significant samples of high−z sources. A relatively high spectral resolution (R ∼ 3000-5000) considerably increases the chances of detection between the sky lines. Once this is obtained, the data can be rebinned to increase the S/N. The medium spectral resolution is also favoured to attempt to measure the emission line profiles, in particular to distinguish genuine "primordial" stellar sources from potential very high-z AGN (cf. Tumlinson et al. 2001).

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J.-P. Kneib: Caltech Astronomy, MC105-24, Pasadena, CA 91125, USA (kneib@caltech.edu).
J.-F. Le Borgne, R. Pelló and J. Richard: Laboratoire d'Astrophysique de l'Observatoire Midi-Pyrénées, UMR5572, 14 Av. Edouard-Bélin, F-31400 Toulouse, France (leborgne, roser, jrichard@ast.obs-mip.fr).
D. Schaerer: Observatoire de Genève, 51, Ch. des Maillettes, CH-1290 Sauverny, Switzerland (daniel.schaerer@obs.unige.ch).