News from $z \sim 6–10$ galaxy candidates found behind gravitational lensing clusters

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Abstract. We summarise the current status of our project to identify and study $z \sim 6–10$ galaxies thanks to strong gravitational lensing. Building on the detailed work from Richard et al. (2006), we present results from new follow-up observations (imaging) undertaken with ACS/HST and the Spitzer Space Telescope and compare our results with findings from the Hubble Ultra-Deep Field (UDF). These new observations are in agreement with the high-$z$ nature for the vast majority of the candidates presented in Richard et al. (2006). We also discuss the properties of other optical dropout sources found in our searches and related objects (EROs, sub-mm galaxies, ...) from other surveys.

1. Introduction

Combining the power of strong gravitational lensing to detect faint distant objects and the availability of near-IR instruments on large ground-based telescopes we have started a few years ago a pilot-project with the aim of finding star-forming galaxies at redshifts beyond 6-6.5. This project, initially based on VLT data plus observations obtained at CFHT and HST, has produced $\sim 13$ galaxy candidates at redshifts between $\sim 6$ and 10 (Richard et al. 2006).

Here we summarise the current status of the project and present results from new follow-up observations (imaging) undertaken with ACS/HST and the Spitzer Space Telescope and compare our results with findings from the Hubble Ultra-Deep Field (UDF). Spectroscopic follow-ups have been summarised elsewhere (see e.g. Pelló et al. 2005). A recent overview of the project is given in Schaerer et al. (2006a).

2. Observations

Focussing on two well known gravitational lensing clusters, Abell 1835 and AC114, we obtained deep near-IR images in the $SZ$, $J$, $H$, and $Ks$ bands with ISAAC and an additional $z$-band image with FORS2 (see Richard et al. 2006).
These deep images, reaching e.g. a $1\sigma$ depth of 26.1 in $H_{AB}$, were then used to search for objects which are detected at least in two near-IR bands, which show a blue near-IR colour, and which are undetected (i.e. “dropped out”) in all optical bands. These criteria are optimised to select high redshift ($z > 6$) objects with intrinsically blue UV-restframe spectra, i.e. very distant starburst galaxies, and to avoid contamination from intrinsically faint and red cool stars. Different combinations of colour-colour plots allow a crude classification into several redshift bins. An example of such a diagram, showing the expected location of $z \sim 8-11$ galaxies and of candidates found behind Abell 1835 is shown in Fig. 1. A complete report is given in Richard et al. (2006).

3. High-z galaxy candidates and the cosmic star formation density during reionisation

Applying the above selection criteria to the observations of the two lensing clusters has yielded 13 candidates whose spectral energy distribution (SED) is compatible with that of star forming galaxies at $z \gtrsim 6$ (Richard et al. 2006). The typical lensing magnification reaches from 1.5 to 10, with an average of $\sim 6$, i.e. nearly 2 magnitudes. Their star formation rate, as estimated from the UV restframe luminosity, is typically between $\sim 4$ and 20 $M_\odot$ yr$^{-1}$ after correcting for lensing.

We have used this data to attempt to constrain for the first time with lensing clusters the density of star-forming galaxies present at $6 \lesssim z \lesssim 10$. After taking into account the detailed lensing geometry, sample incompleteness, and correcting for false-positive detections we have constructed a luminosity function (LF) of these candidates assuming a fixed slope taken from observations at $z \sim 3$. Within the errors the resulting LF is compatible with that of $z \sim 3$ Lyman break galaxies. At low luminosities it is also compatible with the LF derived by
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Figure 2. Evolution of the comoving SFR density as a function of $z$ including a compilation of results at $z \lesssim 6$, our estimates obtained from both clusters for the redshift ranges $[6-10]$ and $[8-10]$ and the values derived from the HST UDF (labeled “UDF”, Bouwens et al. 2004, 2005b). Red solid lines: SFR density obtained from integrating the LF of our first category candidates down to $L_{1500} = 0.3 L^z_{z=3}$. From Richard et al. (2006).

Bouwens et al. (2005a) for their sample of $z \sim 6$ candidates in the Hubble Ultra Deep Field (UDF) and related fields. However, the turnover observed by these authors towards the bright end relative to the $z \sim 3$ LF is not observed in our sample.

Finally, from the LF we determine the UV star formation rate (SFR) density at $z \sim 6-10$, shown in Fig. 2. Our values indicate a similar SFR density as between $z \sim 3$ to 6, in contrast to the drop found from the deep NICMOS fields. (Bouwens et al. 2005b). As also discussed at this conference by Bouwens and Hopkins, the latter SFR values have been revised upwards, reducing the differences with our study (see Hopkins 2007). Further observations are required to fully understand these differences. Taken at face value, our relatively high SFR density is in good agreement e.g. with the recent hydrodynamical models of Nagamine et al. (2005), with the reionisation models of Choudhury & Ferrara (2005), and also with the SFR density inferred from the past star formation history of observed $z \sim 6$ galaxies (e.g. Eyles et al. 2006).

4. Follow-up observations of the high-z candidates with HST and Spitzer

New additional observations, including ACS/HST and Spitzer imaging, have recently been secured on these clusters. The ACS/HST $z_{850LP}$ observations confirm that the vast majority (all except one of the above 13) of our high-z candidates are optical dropouts as expected, remaining undetected down to a $1\sigma$ limiting magnitude of $28.-28.3 \text{ mag}_{AB}$ (Hempel et al. 2007).

In collaboration with Eiichi Egami we have also access to IRAC/Spitzer GTO images at 3.6, 4.5, 5.8 and 8.0 $\mu$m of large sample of lensing clusters
Figure 3. Best fit SED to the ACS, ISAAC, and Spitzer observations (non-detections) of two high-

\( \text{z} \) candidates from Richard et al. (2006) (top panels) and \( \chi^2 \) as a function of redshift (bottom panels). The two objects show a photometric redshift estimate of \( z \sim 8.4 \) (left) and 8.5 (right) respectively. The current IRAC/Spitzer limits are compatible with the high-

\( \text{z} \) nature of these objects. Deeper observations might be able to detect some of the candidates at \( > 3 \) \( \mu \)m.

including Abell 1835 and AC114. 11 of 18 high-

\( \text{z} \) candidates are in “uncontaminated” regions so that IRAC photometry is feasible. These 11 objects remain undetected at 3.6 and 4.5 micron in median stacked images at a 2\( \sigma \) upper limit per source of 0.16 to 0.2 microJansky at 3.6-4.5 micron. Except for one object, these upper limits are compatible with the expectations from extrapolating their SED to longer wavelengths! This is easily understood, since extrapolation of their intrinsically blue SED to IRAC wavelengths shows that their expected fluxes fall below the Spitzer sensitivity of the available observations. This is illustrated in Fig. 3, showing best fit SEDs of two candidates at \( z \sim 8.4–8.5 \) obtained using a modified version of the photometric redshift code \textit{Hyperz} of Bolzonella et al. (2000). In other words, the IRAC non-detection can be understood if the objects are young star forming (blue) galaxies at high-

\( \text{z} \). It implies that these objects do not host “old” stellar populations with strong Balmer breaks, and that they are not affected by significant extinction. In conclusion, the Spitzer non-detection is compatible with the high-

\( \text{z} \) interpretation for the majority of our high-

\( \text{z} \) candidates. A more detailed account of these observations will be presented elsewhere.

Labbé et al. (2006) have recently announced the detection of 2 to 4 \( z \sim 7 \) candidates with IRAC/Spitzer at 3.6 and 4.5 \( \mu \)m in the GOODS UDF field. We have analysed their objects using the same SED fitting methods as mentioned above (cf. Schaerer et al. 2006b for more details). Overall we confirm their findings in terms of stellar ages, extinction etc. Our best fit redshifts are found between \( \sim 6.4 \) and 7.7, with a mean of 7.1. For illustration the fits for two objects — # 964 providing the best fit (lowest \( \chi^2 \)) and # 1125 of lower quality — are shown in Fig. 4. The comparison with Fig. 3 shows that our constraints
Figure 4. Same as Fig. 3 for two high-z galaxies from Labbé et al. (2006), # 964 on the left, and # 1125 on the right. Their estimated photometric redshift is ∼7.4 and 7.0 respectively.

on the photometric redshift are comparable to that of 1125. However, it must be reminded that our IRAC exposures are much shallower (the upper limits are a factor 4 to 5 times higher). Given that the GOODS/UDF Spitzer observations correspond to a total integration time of ∼46 hours (!) the gain in accuracy is not surprising. In fact, given the relatively high number of high-z candidates found in our fields and their brighter magnitude compared to the UDF sources, additional deeper IRAC/Spitzer imaging of our cluster fields could potentially allow the detection of these objects.

For completeness, remember that two other z ∼ 6.5–7 galaxies, both found thanks to gravitational lensing, have been detected earlier by Spitzer (Egami et al. 2005, Chary et al. 2005). Their stellar populations and dust properties have been discussed in these papers and in detail by Schaerer & Pelló (2005).

5. Follow-up observations of other optical dropout sources

Our search for optical dropout galaxies behind lensing clusters yields also other interesting objects, such as extremely red objects (EROs; see Richard et al. 2006). In contrast to the high-z candidates most of them are detected by IRAC/Spitzer. These objects turn out to have similar properties as e.g. faint IRAC selected EROs in the Hubble UDF (cf. Yan et al. 2004), other related objects such as the putative post-starburst z ∼ 6.5 galaxy of Mobasher et al. (2005), and some sub-mm galaxies. Similar objects, although possibly more extreme have been discussed by Rodighiero at this conference.

For most of the lensed EROs we find photometric redshifts showing a strong degeneracy between “low-z” (z ∼ 1–3) and high-z (z ∼ 6–7). Although formally best fits are often found at high-z, their resulting bright absolute magnitudes, the number density of these objects, and in some cases Spitzer photometry or longer wavelength observations, suggest strongly that all of these objects are at
“low-z”. The majority of these objects are best fitted with relatively young (< 0.5–0.7 Gyr) and dusty starbursts. Several of our objects show indications for very strong extinction, with $A_V \sim 2.4–4$. We also derive stellar masses, SFR and related quantities. For more details see Schaerer et al. (2006b).

6. Future

With our pilot program it has been possible to find several very high redshift candidate galaxies by combining the power of strong gravitational lensing with the large collecting area of the VLT. However, differences with other studies based on deep blank fields are found, and already differences between our two clusters indicate that these could at least partly be due to field-to-field variance. Given the relatively low S/N ratio of the high-z candidates and the large correction factors applied to this sample, it is of great interest to increase the number of lensing clusters observed with this technique.

Furthermore, rapidly upcoming new spectrographs (e.g. EMIR on GRANTECAN, KMOS/VLT) will provide a huge efficiency gain for spectroscopic follow-up of faint candidate sources, thanks to their increased spectral coverage and multi-object capabilities. Observations at longer wavelengths, e.g. with HERSCHEL, APEX and later ALMA, are also planned to search for possible dust emission in such high-z galaxies and to characterise more completely other populations of faint optical dropout galaxies. Finally the JWST and ELTs will obviously be powerful machines to study the first galaxies. Large territories remain unexplored in the early universe!

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