Characterizing Faint Galaxies in the Reionization Epoch: LBT Confirms Two $L < 0.2L$ Sources at $Z = 6.4$ Behind The Clash/Frontier Fields Cluster MACS0717.5+3745

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ABSTRACT

We report the LBT/MODS1 spectroscopic confirmation of two images of faint Lyman alpha emitters at $z = 6.4$ behind the Frontier Fields galaxy cluster MACSJ0717.5+3745. A wide range of lens models suggests that the two images are highly magnified, with a strong lower limit of $\mu > 5$. These are the faintest $z > 6$ candidates spectroscopically confirmed to date. These may be also multiple images of the same $z = 6.4$ source as supported by their similar intrinsic properties, but the lens models are inconclusive regarding this interpretation. To be cautious, we derive the physical properties of each image individually. Thanks to the high magnification, the observed near-infrared (restframe ultraviolet) part of the spectral energy distributions and Ly$\alpha$ lines are well detected with $S/N(\lambda_{1500}) > 10$ and $S/N(\text{Ly}\alpha) - 10 - 15$. Adopting $\mu > 5$, the absolute magnitudes, $M_{1500}$, and Ly$\alpha$ fluxes, are fainter than $-18.7$ and $2.8 \times 10^{-18}$ ergs$^{-1}$cm$^{-2}$, respectively. We find a very steep ultraviolet spectral slope $-\beta = -3.0 \pm 0.5 (F_\lambda = \lambda^{\beta})$, implying that these are very young, dust-free and low metallicity objects, made of standard stellar populations or even extremely metal poor stars (age $\lesssim 30$Myr, E(B-V)=0 and metallicity $0.0 - 0.2Z/Z_\odot$). The objects are compact ($< 1$ kpc$^2$), and with a stellar mass $M_* < 10^8 M_\odot$. The very steep $\beta$, the presence of the Ly$\alpha$ line and the intrinsic FWHM ($< 300$ kms$^{-1}$) of these newborn objects do not exclude a possible leakage of ionizing radiation. We discuss the possibility that such faint galaxies may resemble those responsible for cosmic reionization.

Subject headings: dark ages, reionization, first stars — cosmology: observations — galaxies: formation

1. INTRODUCTION

The investigation of the distant Universe and the processes that led to the reionization of the intergalactic medium, are amongst the major goals of observational cosmology (Robertson et al. 2010). While there are tens (a few) spectroscopic confirmations of galaxies at redshift 6(7) (e.g., Vanzella et al. 2009, 2011), accessing the faint-luminosity regime down to $\lesssim 0.2L^*$ remains challenging even with 8-10m class telescopes, especially for $z > 6$. Before the advent of next generation observatories like JWST and the extreme large telescopes, the only viable way to pursue extremely faint distant objects, and investigate the nature of their stellar populations (even PopIII), is to exploit strong lensing magnification (e.g., Zackrisson et al. 2012, 2013). To this aim, Bradley et al. (2013) (B13, hereafter) selected magnified candidate galaxies at redshift 6 – 8 fully exploiting the 16-bands photometry of the CLASH survey (Postman et al. 2011), and found agreement down to $\sim 27$ mag with the UV luminosity functions of blank fields. After the completion of the CLASH program, the investigation of the high-z universe is now continuing with the ultradepth HST Frontier Fields campaign (FF hereafter), that includes four CLASH galaxy clusters.

Accessing the faint luminosity regime ($L \lesssim 0.2L^*$) at $z > 6$ is crucial in the context of cosmic reionization (e.g., Fontanot et al. 2013): faint galaxies dominate the global ultraviolet luminosity density (Bouwens et al. 2007) and possibly have an escape fraction of ionizing radiation larger than the brighter counterparts (e.g., Ferrara & Loeb 2013; Yajima et al. 2011).

Here we report on the LBT/MODS1 spectroscopic confirmation of two faint $z = 6.4$ sources, significantly magnified by the FF galaxy cluster MACSJ0717.5+3745 (Ebeling et al. 2007), study their physical properties, and discuss the contributions of such objects to the reionization of the IGM.
Throughout this paper a concordance ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ is adopted, and magnitudes are in AB scale.

1.1. Target selection and magnification

B13 selected 15 magnified $z \approx 6$ galaxy candidates behind the FF galaxy cluster MACSJ0717.5+3745, by using their drop-out features and corresponding photometric redshift estimate. We report here the spectroscopic observations of two candidates from their sample, macs0717.0859 and macs0717.1730 (859 and 1730 for short, hereafter), with photometric redshifts of $6.1 \pm 0.2$ and $6.0^{+0.2}_{-0.3}$, respectively. The magnifications reported in B13 were $\mu = 15.6$ (859) and $\mu > 100$ (1730) (i.e. the latter unconstrained since the object is too close to the critical curves). The magnification estimates were based on the revised lens model by Zitrin et al. (2009; see also Medezinski et al. 2013) who first performed the strong-lensing analysis for this cluster, uncovering that is the largest magnifying lens known to date (see Figure 1). Here we have also estimated the magnifications from several other lens models made for the Frontier Fields program (including a refurbished version of the Zitrin et al. model used in B13), by running the Magnification Calculator available online. The estimate from different groups, methods and assumptions span the range between 5 and 70, with some solutions even higher than 100 within the 68% confidence interval. The medians among the different models are: $\mu = 17.4^{+25}_{-15} (^{+50}_{-12})$ for 1730 and $\mu = 6.9^{+1}_{-1} (^{+30}_{-2})$ for 859, where statistical and systematic errors (in parentheses) are quoted. The models for this lens are still not fully constrained in the regions where the two $z = 6.4$ are detected, both due to proximity to the critical curves, and, lack of multiple-images constraints nearby. We also acknowledge the possibility that the two sources presented here are actually counter images of a single background galaxy, as some of the models provided by the different groups predict counter images within few, to dozen arcseconds, from the location of the other $z = 6.4$ object. We did not detect, however, any additional counter images where the models predict them (although possibly, due to lesser magnification where other images are predicted).

As not all models predict counter images, and predicted counter images were not identified in the data, it cannot be unambiguously determined if indeed the two objects are images of the same source. What is relevant

3 http://archive.stsci.edu/prepds/frontier/lensmodels/
here, though, is the agreement among the different models that the sources are strongly magnified ($\mu > 5$), and the single or double nature does not alter our findings on the derived physical properties. In the following, to be more conservative, we derive rest-frame quantities by adopting $\mu = 5$ for both sources, and express the results in terms of $\mu_5 = \mu/5$.

2. DATA AND SAMPLE SELECTION

2.1. Spectroscopic observations with LBT/MODS1

The spectroscopic observations have been performed in dual mode with the MODS1 instrument at the LBT, that exploits the two red (5800-10300Å) and blue (3200-6000Å) channels, yielding a total spectra coverage from 3200 to $\sim$10300Å on source. The red G670L and blue G400L grisms with a slit width of 1″ have been adopted, providing a spectral resolution of $R \approx 1500$ for both. Science frames of 1200s have been acquired with a dithering pattern of 1.5″ shift along the slit for a total integration time of 16800s for 859, and 11200s for 1730. The average seeing conditions were $\approx 1.0″$. Data reduction has been performed with the MODS1 spectroscopic reduction pipeline based on VIPGI tasks (Scodeggio et al. 2005).

In the two slits located on 859 and 1730, two emission lines are clearly detected at 8980Å and 9300Å, respectively, with observed fluxes of $1.4 \times 10^{-17}$ergs$^{-1}$cm$^{-2}$ (with $S/N = 15$) and $\approx 1.0 \times 10^{-15}$ergs$^{-1}$cm$^{-2}$ (with $S/N = 9$), respectively (see Figures 2 and 3).

3. RESULTS

- **Nature of the lines**: The large spectral coverage (3200 − 10300Å) allows us to exclude low redshift solutions like $H\alpha$ at $z = 0.37$ or [O ii]λ5007 at $z = 0.79$, that would be in contrast with the single line detection. The only possible degeneracy is among [O ii]λ3727 and Ly$\alpha$. However, [O ii]λ3727 can be reliably excluded because of the following reasons: (1) the doublet [O ii]λ3726 − 3729 is resolved in the present observations (see an example in Figure 2 panel C) and (2) the observed equivalent width (see below) of the lines is not compatible with the typical values observed at $z < 1.5$, i.e., they are too large (e.g., Vanzella et al. 2009 and their Fig. 12). Moreover, source 859 shows an asymmetric line profile toward the red wavelengths (Figure 3), that is typical of this transition at high redshift. The spectrum of 1730 is slightly shallower (11200s) and noisier than 859 (close to the edge of the slit), and prevents us from detecting the asymmetric shape, but the line width and the equivalent width are not consistent with the [O ii]λ3727 doublet.

Therefore we conclude that the two emission lines are Ly$\alpha$ at the same redshift $6.387 \pm 0.002$. The striking accordance of the two redshifts may add support to the hypothesis that these two objects are multiple images of the same background source. If confirmed, this could provide further constraints to the lens model and therefore deserves future investigation and lens remodeling, which is out of the scope of the present work. In the following we assume that these are two individual objects and look at the properties of each of them separately.

- **Rest frame UV continuum luminosity at 1500Å**: As mentioned above the wide spread on the magnifications allow us to identify an interval of possible luminosities. Given the observed Y105 magnitudes (≈1500Å) of 26.42 ± 0.11 for 859 and 26.34 ± 0.16 for 1730, the two sources have unlensed luminosities of $L_{1500} \approx 0.2 \mu_5^{-1} L_{1500}^{*} = \mu_5$, adopting $L_{1500}^{*}$ from Bouwens et al. (2007). Even in the more conservative case ($\mu > 5$), these are the faintest spectroscopically confirmed sources at these redshifts with such a high signal to noise (Balestra et al. 2009 and their Fig. 12).

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two distinct objects, we estimate a proper separation of isophotal areas (provided by SExtractor) converted into sources are resolved in the HST/WFC3 images. Their slopes for 859 and 1730 are very steep, again consistent with the option that these two objects are multiple images. While the source 1730 is close to a 2175˚ line, using the Y105, J125, F140W and H160 bands (for Castellano et al. (2012) and Bouwens et al. (2013), ultraviolet spectral slope $\beta$ of models described in Malhotra et al. 2003), and that they are spatially resolved, their emission is due to star formation activity.

As described above, the two discovered sources (or a single one in the case of multiple images) are the faintest galaxies at $z > 6$ ever observed with a spectroscopic redshift confirmation and well detected $Ly\alpha$ lines and SEDs. The investigation of new luminosity regimes through the strong-lensing magnification gives the opportunity to explore possible new physical conditions.

4.1. Nature of the stellar populations

We examine their rest–frame properties through a SED analysis. We first derive physical parameters assuming ordinary stellar populations, i.e., by comparing the observed SED with a set of Bruzual & Charlot (2003) templates (BC03), assuming Salpeter IMF, metallicity of 0.02, 0.2, 1.0 $Z/Z_\odot$, and E(B-V) spanning the range $[0.0 - 1.0]$. The current 1-$\sigma$ lower limits from IRAC (3.6µm and 4.5µm channels) for 859 are $\approx 26.1AB$, too shallow to provide solid constraints on $[O III]5007+H\beta$ and $H\alpha$ nebular emissions. The other source 1730 is contaminated by close brighter galaxies. The SED fitting with BC03 includes nebular line and continuum emission following Schaefer & de Barros (2009) (see Castellano et al. 2014 for further details). The output of this exercise is listed in Table 1. Regardless of the adopted $\mu$, the two sources turn out to be very small ($\lesssim 1$ sq.kpc), with low SFRs ($\sim 1-2 M_\odot/yr$) and low stellar masses of $< 10^5 M_\odot$. The properties related to colors (i.e., independent from the magnification $\mu$), such as dust attenuation, age, and metallicity, are consistent with newborn objects. Adopting the standard Kennicutt conversions (Kennicutt 1998) and correcting for the IGM attenuation of $Ly\alpha$ photons (e.g., $> 50\%$, Dijkstra & Jeeson-Daniel 2013), we obtain $SFR(Ly\alpha) \gtrsim SFR(UV)$, where $SFR(UV)$ is derived from the SED fit. This is indicative of ages $< 100$Myr, E(B-V)$\approx 0$ (Verhamme et al. 2008) and

![Figure 4](image)

**FIG. 4.**—SED fits with BC03 templates are shown. Nebular emission lines are included in the fit. The two arrows for 859 are 1-sigma lower limits of IRAC 3.6µm and 4.5µm channels.

**Table 1.** Observed and physical parameters for 859 and 1730.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>macs0717_0859</th>
<th>macs0717_1730</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decl. (J2000)</td>
<td>07:17:37.85</td>
<td>+37:44:33.7</td>
</tr>
<tr>
<td>Redshift</td>
<td>6.387(±0.002)</td>
<td>6.387(±0.003)</td>
</tr>
<tr>
<td>Y105(observed)</td>
<td>26.42(±0.11)</td>
<td>26.34(±0.16)</td>
</tr>
<tr>
<td>H160(observed)</td>
<td>26.88(±0.15)</td>
<td>26.78(±0.18)</td>
</tr>
<tr>
<td>H160(unlensed)</td>
<td>28.63±2.5 Log10(µ5)</td>
<td>28.53±2.5 Log10(µ5)</td>
</tr>
</tbody>
</table>

**NOTE.** — $Ly\alpha$ fluxes are in units of ergs$^{-1}$cm$^{-2}$. Physical properties refer to BC03 models with nebular emission and the associated 68% intervals in parentheses correspond to models with $\chi^2$ probabilities higher than 0.68. The $SFR(Ly\alpha)$ has been derived adopting the Kennicutt (1998) conversion. Quantities related to $Ly\alpha$ do not include possible IGM absorption. $µ_5 = 1$ corresponds to $µ = 5$.
The SEDs can be reproduced with ordinary stellar populations, albeit the best solutions typically lie close to the edge of the parameter space (e.g., $Z$, age and E(B-V)). Fixing $Z = Z_\odot$, the resulting ages are forced to the minimum value, 10Myr. For this reason it is interesting to extend the investigation toward a possible presence of younger and/or extremely metal poor (EMP, $Z \simeq 1/2000Z_\odot$) and PopIII stars ($Z = 0$). For this purpose we consider the SED fitting and the predicted HST/WFC3 colors provided by Raiter et al. (2010), Inoue et al. (2011) and Zackrisson et al. (2013), (R10, I11 and Z13, respectively), that also include nebular contribution. The observed UV slope is compatible either with very young, but still standard (PopII) stellar populations (BC03), or with EMP/PopIII stars. In particular, 859 (with the most reliable photometry) has lar populations (BC03), or with EMP/PopIII stars. In

The observed Lyα EWs would suggest that we are dealing with standard stellar populations, given that PopIII stars are often associated with Lyα EW $\sim 500 – 1500\AA$ rest-frame (Schaerer et al. 2003; R10; I11). A large IGM attenuation of the Lyα line (90%) could hide a intrinsic EW> 500Å, making it still compatible with the PopIII interpretation. However the influence of the IGM is highly uncertain here (see also Laursen et al. 2011; Dayal et al. 2011; Dijkstra & Jeeson-Daniel 2013). Another possibility is that the Lyα EW could be lowered for extremely metal poor ($Z/Z_\odot < 10^{-4}$) and even PopIII ($Z/Z_\odot = 0$) galaxies if $f_{esc} > 0$ (Z13). For example, I11 found a Lyα EW of $\simeq 65\AA$ for $Z = 0$ and 10Myr constant star formation, when $f_{esc} = 0.9$.

While it is hard to make definitive statements about the populations content of these $z \sim 6.5$ sub-luminous galaxies given the current information we have about them, we observe that they are overall less evolved than their more massive counterparts and their very blue UV colors could be explained even without having to invoke PopIII stars, although we certainly cannot exclude their presence in the stellar populations (e.g., Finkelstein et al. 2010). These kind of galaxies could be examples of very low chemical enrichment, dust-free systems, barely higher than the pristine gas that is probably still feeding their activity of star formation.

4.2. Cosmic reionization

Regardless of the nature of the stellar populations, the potential role these sources have in the framework of cosmic reionization is intriguing. It is believed that the abundant, fainter galaxies ($M_* < 10^6M_\odot$) could significantly contribute to, or even be the dominant populations in, providing the ionizing radiation (e.g., Fontanot et al. 2013; Ferrara & Loeb 2013; Yajima et al. 2011; Razoumov & Sommer-Larsen 2010; but see Gnedin et al. 2008).

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5 We note that the probability to observe a galaxy of a few Myr old is generally small, because of its short time.
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REFERENCES


Robertson, B. E., Ellis, R. S., Dunlop, J. S., McLure, R. J., Stark, D. P., 2010, Nature, 468, 49


