CHARACTERIZING FAINT GALAXIES IN THE REIONIZATION EPOCH: LBT CONFIRMS TWO $L < 0.2 L^*$ SOURCES AT $z = 6.4$ BEHIND THE CLASH/FRONTIER FIELDS CLUSTER MACSJ0717.5+3745

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Abstract

We report the LBT/MODS1 spectroscopic confirmation of two images of faint Ly$\alpha$ 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 also be 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 $S/N(\lambda_{1500}) \gtrsim 10$ and $S/N(Ly\alpha) \approx 10-15$. Adopting $\mu > 5$, the absolute magnitudes, $M_{1500}$, and Ly$\alpha$ fluxes are fainter than $-18.7$ and $2.8 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ respectively. We find a very steep ultraviolet spectral slope $\beta = -3.0 \pm 0.5$ ($F_\nu \propto \lambda^\beta$), implying that these are very young, dust-free, and low metallicity objects, made of standard stellar populations or among institutions in the United States, Italy, and Germany. LBT Corporation partners are: The University of Arizona on behalf of the Arizona university system; Istituto Nazionale di Astrofisica, Italy; LBT Beteiligungsgesellschaft, Germany, representing the Max-Planck Society, the Astrophysical Institute Potsdam, and Heidelberg University; The Ohio State University; and The Research Corporation, on behalf of The University of Notre Dame, University of Minnesota, and University of Virginia. 12 Hubble Fellow.

Key words: cosmology: observations – dark ages, reionization, first stars – galaxies: formation

Online-only material: color figures

1. INTRODUCTION

The investigation of the distant universe and the processes that led to the reionization of the intergalactic medium (IGM) are among the major goals of observational cosmology (Robertson et al. 2010). While there are tens (a few) of spectroscopic confirmations of galaxies at redshift 6 (7) (e.g., Vanzella et al. 2009, 2011), accessing the faint-luminosity regime down to $\lesssim 0.2 L^*$ remains challenging even with the 8–10 m class telescopes, especially for $z > 6$. Before the advent of next generation observatories like James Webb Space Telescope (JWST) and the extremely 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 redshifts 68, fully exploiting the 16-band photometry of the CLASH survey (Postman et al. 2012) 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 ultradeep Hubble Space Telescope (HST) Frontier Fields campaign (FF hereafter), which includes four CLASH galaxy clusters.

Accessing the faint luminosity regime ($L \lesssim 0.2 L^*$) 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, which are 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 Letter, a concordance $\Lambda$CDM cosmology with $\Omega_m = 0.3$, $\Omega_L = 0.7$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ is adopted, and magnitudes are in AB scale.
Figure 1. Sixteen-band CLASH RGB false-color image of MACS0717.5+3745, with the two $z = 6.4$ spectroscopically confirmed images marked with red circles (the insets show the J215 zoom). The critical curves ($\mu > 100$ here) for a source at $z_s = 6.4$ from the revised Zitrin et al. model are overlaid in white. The green circles mark the multiple images used as constraints (see Zitrin et al. 2009; Limousin et al. 2012; Medezinski et al. 2013). As can be seen, 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 a few to a dozen arcseconds from the location of the other $z = 6.4$ object. We did not, however, detect 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 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 most conservative, we derive rest-frame quantities by adopting $\mu = 5$ for both sources and express the results in terms of $\mu_S = \mu/5$.

2. DATA AND SAMPLE SELECTION

2.1. Spectroscopic Observations with LBT/MODSI

The spectroscopic observations have been performed in dual mode with the MODSI instrument at the Large Binocular Telescope (LBT), which exploits the two red (5800–10300 Å) and blue (3200–6000 Å) channels, yielding a total spectra coverage from 3200 to ~10300 Å on source. The red G670L and blue G400L grisms with a slit width of 1″ were adopted, providing a spectral resolution of $R \simeq 1500$ for both. Science frames of 1200 s have been acquired with a dithering pattern of 1.5″ shift along the slit for a total integration time of 16,800 s for 859, and 11,200 s for 1730. The average seeing conditions were $\simeq 1″$. Data reduction has been performed with the MODSI spectroscopic reduction pipeline based on VIPGI tasks (Scodellino et al. 2005). In the two slits located on 859 and 1730, two emission lines are clearly detected at 8980 Å and 8981 Å, respectively, with observed fluxes of $1.4 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ (with S/N = 15) and $\approx 1.0 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ (with S/N = 9), respectively (see Figures 2 and 3).

3. RESULTS

1. Nature of the lines. The large spectral coverage (3200–10300 Å) allows us to exclude low redshift solutions like H$\alpha$ at $z = 0.37$ or [O III] $\lambda 5007$ at $z = 0.79$, which would be in contrast with the single line detection. The only possible degeneracy is between [O III] $\lambda 3727$ and Ly$\alpha$. However, [O III] $\lambda 3727$ can be reliably excluded because of the following reasons: (1) the doublet [O III] $\lambda 3726$–3729 is resolved in the present observations (see 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 Figure 12). Moreover, source 859 shows an asymmetric line profile toward the red wavelengths (Figure 3), which is typical of this transition at high redshift. The spectrum of 1730 is slightly shallower (11,200 s) 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 III] $\lambda 3727$ doublet.

14 http://archive.stsci.edu/prepds/frontier/lensmodels/

15 http://lbt-spectro.iasf-milano.inaf.it/pipelinesInfo/
Therefore, we conclude that the two emission lines are Lyα at the same redshift $6.387 \pm 0.002$. The striking concordance 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 remodelling, which is out of the scope of the present work. In the following we assume that these two objects are multiple images. While source 1730 is likely to be a single object, the similarity to source 859 is intriguing, this similarity is again consistent with the option that these two objects are multiple images. While source 1730 is close to a bright galaxy and its photometry has to be taken with caution, source 859 is isolated and with reliable colors (Figure 2). As noted by Zackrisson et al. (2013, hereafter Z13), the possible presence of the 2175 Å dust feature may interfere with the estimate of the UV slope. However, we tend to exclude this possibility on the basis of the redshift and the Lyα emission lines that favor low dust attenuation.

1. Ultraviolet spectral slope $\beta$ ($F_\nu \propto \lambda^\beta$). Following Castellano et al. (2012) and Bouwens et al. (2013), ultraviolet spectral slopes were estimated by fitting the near-infrared WFC3 magnitudes redward of the Lyα line using the Y105, J125, F140W, and H160 bands (for 859 the F110W band was also available and has been included in the fit). Being achromatic, strong lensing does not affect the colors of the sources. The measured slopes for 859 and 1730 are very steep, $\beta = -3.02 \pm 0.37$ and $\beta = -3.01 \pm 0.56$. Interestingly, this similarity is again consistent with the option that these two objects are multiple images. While source 1730 is close to a bright galaxy and its photometry has to be taken with caution, source 859 is isolated and with reliable colors (Figure 2).

2. Rest frame UV continuum luminosity at 1500Å. As mentioned above the wide spread of the magnifications allows us to identify an interval of possible luminosities. Given the observed Y105 magnitudes ($\approx 1500$ Å) of 26.42 ± 0.11 for 859 and 26.34 ± 0.16 for 1730, the two sources have un lensed luminosities of $L_{1500} \approx 2.0 \mu_{\odot} L_{\odot}$, adopting $L_{\odot}$ from Bouwens et al. (2007). Even in the more conservative case ($\mu > 5$), these are the faintest spectrophotically confirmed sources at these redshifts with such a high signal to noise (Balestra et al. 2013; Bradac et al. 2012; Schenker et al. 2012).

3. Equivalent widths and FWHM of the lines. The continuum is not detected in the spectra. Therefore, we derive the continuum level under the Lyα transition by using the closest $HST$ band not including the line (Y105) and correcting for the UV slope $\beta$ (see below). The rest-frame EWs of 859 and 1730 are 45 ± 7 Å and 32 ± 10 Å, respectively. These are typical values if compared with those observed at similar redshifts among Lyman break galaxies or Lyα emitters (Stark et al. 2011). The observed FWHM of the lines is also modest; after correcting for the instrumental profile they are $\lesssim 150$ km s$^{-1}$.

4. Size of the sources. As reported in B13, the two sources are resolved in the $HST$/WFC3 images. Their isophotal areas (provided by SExtractor) converted into physical units are $5 \pm 3$ kpc$^2$ and $7 \pm 4$ kpc$^2$. If they are two distinct objects, we estimate a proper separation of $\sim 30$ kpc in the source plane at $z = 6.387$, for the range of models described in Section 1.

5. Active galactic nucleus (AGN) activity. At $z = 6.387$ the expected N v $\lambda 1240$ line is not detected (see Figure 3).
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| Table 1 | Observed and Physical Parameters for 859 and 1730 |
|---------|-----------------------------------------------|
| Quantity | macs0717_0859 | macs0717_1730 |
| R.A. (J2000) | 07:17:38.18 | 07:17:37.85 |
| Decl. (J2000) | +37:45:16.9 | +37:44:33.7 |
| Redshift | 6.387(±0.002) | 6.387(±0.003) |
| Y1(05,observed) | 26.42(±0.11) | 26.34(±0.16) |
| H160(,observed) | 26.88(±0.15) | 26.78(±0.18) |
| H160(unresolved) | 28.63±2.5log10(μs) | 28.53±2.5log10(μs) |

Notes. Lyα fluxes are in units of erg s^{-1} cm^{-2}. Physical properties refer to the BC03 models with nebular emission and the associated 68% intervals (in parentheses) correspond to models with χ^2 probabilities higher than 0.68.

The SFR(Lyα) has been derived adopting the Kennicutt (1998) conversion. Quantities related to Lyα do not include possible IGM absorption. μ = 1 corresponds to μ = 5.

3. DISCUSSION AND CONCLUSIONS

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 Lyα lines and spectral energy distributions (SEDs). The investigation of new luminosity regimes through 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 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 initial mass function; metallicities of 0.02, 0.2, and 1.0 Z⊙; and E(B - V) ranging the range [0.0–1.0]. The current 1σ lower limits from IRAC (3.6 μm and 4.5 μm channels) for 859 are ≃26.1AB, too shallow to provide solid constraints on [O III] λ5007/Hβ and Hα nebular emissions. The other source, 1730, is contaminated by close brighter galaxies. The SED fitting with BC03 is shown in Figure 4 and includes nebular line and continuum emission following Schaerer & de Barros (2009); see M. Castellano et al. (2014, in preparation for further details). The output of this exercise is listed in Table 1. Regardless of the adopted μ, the two sources turn out to be very small (≤1 kpc^2), with low star formation rates (SFRs ~ 1–2 M⊙ yr^{-1}) and low stellar masses of <10^8 M⊙. The properties related to colors (i.e., independent of the magnification μ), such as dust attenuation, age, and metallicity, are consistent with newborn objects. Adopting the standard Kennicutt (1998) and correcting for the IGM attenuation of Lyα photons (e.g., >50%; Dijkstra & Jeong-Daniel 2013), we obtain SFR(Lyα) ≃ SFR(UV), where SFR(UV) is derived from the SED fit. This is indicative of ages <100 Myr, E(B – V) ≃ 0 (Verhamme et al. 2008), and f esc(Lyα) close to unity (Atek et al. 2008, 2014).

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⊙, the resulting ages are forced to the minimum value, 10 Myr. For this reason it is interesting to extend the investigation toward a possible presence of younger and/or extremely metal poor (EMP; Z ≈ 1/2000 Z⊙) and Pop III stars (Z = 0). For this purpose we consider the SED fitting and the predicted HST/WFC3 colors provided by R10 (hereafter R10), Inoue (2011, hereafter I11), and Z13, which also include nebular contribution. The observed UV slope is compatible with either very young, but still standard (Pop II) stellar populations (BC03), or with EMP/Pop III stars. In particular, 859 (with the most reliable photometry) has a β = –3.02 ± 0.37 that is consistent with an age ≲ 1 Myr if Log_{10}(Z/Z⊙) = 0 or an age ≳ 1–100 Myr if Log_{10}(Z/Z⊙) < -4 (in both I11, Figure 11). Similarly, compared with the models of Z13, the UV slope is compatible with metal poor stars if ages are >10 Myr, and even Pop III if compared with R10 (assuming we are observing the stellar component). Conversely, the observed Lyα EWs would suggest that we are dealing with standard stellar populations, given that Pop III stars are often associated with Lyα EW ~ 500–1500 Å rest-frame (Schaerer 2003; R10; I11). A large IGM attenuation of the Lyα line (>90%) could hide an intrinsic EW > 500 Å, making it still compatible with the Pop III interpretation. However, the influence of the IGM is highly uncertain here (see also Laursen et al. 2011; Dayal et al. 2011; Dijkstra & Jeong-Daniel 2013). Another possibility is that the Lyα EW could be lowered for extremely metal poor (Z/Z⊙ < 10^{-4}) and even Pop III (Z/Z⊙ = 0) galaxies if f esc > 0 (Z13). For example, I11 found a Lyα EW of ~65 Å 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 ~ 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 Pop III stars, although we certainly cannot exclude their presence in 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 ($M_* < 10^9 M_{\odot}$) could significantly contribute to, or even be the dominant populations in, providing the ionizing radiation (e.g., Fontanot et al. 2013; Ferrara & Loeb 2013; Yazima et al. 2011; Razoumov & Sommer-Larsen 2010; but see Gnedin et al. 2008).

The direct measure of the escape fraction of ionizing radiation ($f_{\text{esc}}$) is in principle possible at $z < 4$. At higher redshifts the measurement is unfeasible due to the complete IGM attenuation of the Lyman continuum. Nonetheless, it is worthwhile to investigate each of the main components that build the $f_{\text{esc}}$ quantity. As discussed in Vanzella et al. (2012), the $f_{\text{esc}}$ parameter is the product of the gas transmission $T_{4900} = \exp(-\tau_{4900})$ and the dust transmission $T_{\text{dust}} = 10^{-0.4 \alpha_{4900}}$. To first order, Lyman continuum emitters should have both low dust content $A_{4900}$ and low optical depth $\tau_{4900}$. Interestingly, the two sources described in this Letter could match such requirements. First, given the very steep UV continuum the term related to dust attenuation is significantly higher than zero ($T_{\text{dust}} = 10^{-0.4 \alpha_{4900}} \sim 1$), as reported in Stiavelli et al. 2007 by extrapolating the Calzetti extinction law down to the Lyman continuum, $A_{5100} = A_{4900} = 0$ if $E(B-V) = 0$. Second, even though addressing the gas attenuation in the interstellar medium with current data is admittedly less reliable, it is worth noting that the presence of Ly$\alpha$ emission would not be in contrast with an $f_{\text{esc}} > 0$. As discussed in Nakajima & Ouchi (2013), the EW(Ly$\alpha$) remains almost unchanged if $f_{\text{esc}}$ is $\approx 0.8$. If the IGM is attenuating $<70\%$ of the line (Dijkstra & Jeeson-Daniel 2013), the resulting intrinsic FWHM ($\lesssim300$ km s$^{-1}$) would be in line with possible low H$_1$ column density in front of the stars (Schaerer et al. 2011). The reason is that Ly$\alpha$ resonance scattering is less effective if $N_{HI}$ is low, and photons escape easily along the shorter path, decreasing the FWHM. Moreover, the observed UV slope $\beta \approx -3$ could also indicate a deficit of nebular continuum, allowing the stellar component to emerge in the observed SED (i.e., $f_{\text{esc}} > 0.5, R_{10}, N_{11}, Z_{13}$). This, could, in turn, be a telltale sign of efficient feedback in those systems, capable of either sweeping away or ionizing a significant fraction of the gas surrounding the stars, a mechanism advocated by theoretical models in low-mass halos to self-regulate star formation. As a consequence, a proportionally higher fraction of ionizing radiation could be leaking out of these systems ($f_{\text{esc}} > 0$) compared to their more massive counterparts and be available to keep the IGM ionized.

Regarding the single or multiple nature of the sources, the similarity in the physical and observed characteristics we derived in this work would support that they are multiple images of a single background $z = 6.4$ galaxy, but the different mass models we examined remain inconclusive regarding this option.

As discussed in Zackrisson et al. (2012) and Z13, such galaxies represent the ideal candidates for future near- and mid-infrared spectroscopic observations, especially in the investigation of the interplay between the UV slopes and the equivalent width of H$\beta$ lines, and its relation to the $f_{\text{esc}}$ parameter. Future facilities such as JWST and extremely large telescopes will address this issue.

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