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**Author:** Matthee, J.J.A.  
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Chapter 4
On the evidence for PopIII-like stellar populations in the most luminous Lyman-α emitters at the epoch of reionization

Here we present follow-up observations with X-SHOOTER and FORS2 on the VLT, and DEIMOS on Keck of the two most luminous Ly$\alpha$ candidates in the COSMOS field: ‘MASOSA’ and ‘CR7’. We confirm very strong Ly$\alpha$ emission with S/N > 10 at $z = 6.541$ and $z = 6.604$, respectively. MASOSA has a strong detection in Ly$\alpha$ with FWHM=386 ± 30 km s$^{-1}$ and a very high EW$_0$ (> 200Å), but undetected in the continuum, implying low stellar mass and a likely young stellar population. ‘CR7’, with an observed Ly$\alpha$ luminosity of $10^{43.92±0.05}$ erg s$^{-1}$ is the most luminous Ly$\alpha$ emitter ever found at $z > 6$ and is spatially extended (∼ 16 kpc). ‘CR7’ reveals a narrow Lyα line with FWHM=266 ± 15 km s$^{-1}$ and is detected in the NIR ($M_{1500} = -22.2 ± 0.1$, $\beta = -2.2 ± 0.4$) and in Spitzer/IRAC (implying strong H$\beta$/[OIII] emission). We tentatively detect a narrow He$\text{II}$1640Å emission line ($\approx 3\sigma$, FWHM = 180 ± 30 km s$^{-1}$, EW$_0 = 25 ± 15$Å), but no other emission-line in the rest-UV. We conclude that CR7 is best explained by a combination of an extremely metal poor and highly ionising population which dominates the rest-frame UV and the nebular emission and a more normal stellar population. HST/WFC3 observations show that the light is indeed spatially separated between a very blue component, coincident with the peak Ly$\alpha$, and two fainter components (∼ 5 kpc away). Our findings are consistent with theoretical predictions of a star-formation occurring in waves, with metal poor star formation migrating away from the original sites of star formation.

Based on
Sobral, Matthee, Darvish, Schaerer, Mobasher, Röttgering, Santos and Hemmati
&
Sobral, Matthee, Brammer, Ferrara, Alegre, Röttgering, Schaerer, Mobasher and Darvish
Proclaimer

Finding and observing the first generation of stars (PopIII stars) in the early Universe is one of the key goals of extragalactic astrophysics. So far, no PopIII stars have been observed directly, likely because they are only observable for a short time at very high redshift. In 2015, I contributed significantly to an article that presented a luminous galaxy at $z = 6.6$ with promising evidence that hot, low metallicity stellar populations, with properties resembling PopIII stars, resided within it (Sobral et al., 2015b). I identified this galaxy, that we named COSMOS Redshift 7, or CR7 (Matthee et al. 2015; Chapter 2). For the Sobral et al. (2015b) article, I particularly contributed to the photometric measurements, the writing of telescope proposals that lead to the observations, the interpretation of the data and I contributed to the writing of the manuscript.

The Sobral et al. (2015b) article had significant impact in the scientific community. Several research groups theoretically investigated the nature of CR7, leading to a number of articles whose results are summarised in Appendix A of this Chapter. In addition, independent observational investigations by Bowler et al. (2017b) and Shibuya et al. (2018) revisited some of the results from Sobral et al. (2015b), most importantly the strength and significance of the He\text{II} emission line detection. The He\text{II} line, combined with the non-detection of metal lines, has been fundamental for the interpretation that ‘PopIII-like’ stars reside in CR7. While detailed comparisons to Bowler et al. (2017b) and Shibuya et al. (2018) are presented in Appendices B and C of this Chapter, I note that the interpretation of ‘PopIII-like’ stars in CR7 is most reliably refuted by our [CII] detection with ALMA (Matthee et al. 2017e; Chapter 5).

Since 2015, new data, analysis methods and interactions with the community drove us to update parts of the Sobral et al. (2015b) article. These updates are presented in an article that Sobral, Matthee et al. submitted to MNRAS, but which is not yet accepted for publication. To simultaneously reflect the initial results and the natural advancement of science, the following Chapter is a version of the Sobral et al. (2015b) article rewritten slightly in the light of lessons learned over the past three years, while maintaining its structure, main result, discussion and conclusions that have motivated the interest in the community. I re-analysed and re-reduced the X-SHOOTER spectrum independently (§4.3.3; similar to the analysis in Chapter 6) and do not include SINFONI observations. A subsection is added that discusses differences with respect to the Sobral et al. (2015b) reduction, in particular focusing on the updated significance of the He\text{II} line (§4.3.4). The main text uses the photometric data available at the time of writing the Sobral et al. (2015b) article for its relevance to the impact of the article and its influence on literature articles. However, a subsection is added with revised UltraVISTA DR3 photometry and their implications (§4.5.5).

4.1 Introduction

The study of the most distant sources such as galaxies, quasars and gamma ray bursts offers unique constraints on early galaxy and structure formation. Such
observations are particularly important to test and refine models of galaxy formation and evolution (e.g. Vogelsberger et al., 2014; Schaye et al., 2015) and to study the epoch of re-ionisation (e.g. Furlanetto et al., 2004; McQuinn et al., 2006; Iliev et al., 2006). Over the last two decades, considerable effort has been dedicated towards finding the most distant sources. More recently, and particularly due to the upgraded capabilities of HST, multiple candidate galaxies up to \( z \sim 8 - 11 \) (e.g. Bouwens et al., 2011; Ellis et al., 2013) have been found with deep broad-band photometry. However, spectroscopic confirmation is still limited to a handful of galaxies and quasars at \( z > 6.5 \) (e.g. Mortlock et al., 2011; Ono et al., 2012; Schenker et al., 2014; Finkelstein et al., 2013; Pentericci et al., 2014; Oesch et al., 2015), for both physical (galaxies becoming increasingly fainter) and observational reasons (the need for deep near-infrared exposures).

At these redshifts (\( z > 6.5 \)), the Ly\( \alpha \) line is virtually the only line available to confirm sources with current instruments. However, Ly\( \alpha \) is easily attenuated by dust and neutral hydrogen in the interstellar and inter-galactic medium. Indeed, spectroscopic follow-up of UV-selected galaxies indicate that Ly\( \alpha \) is suppressed at \( z > 7 \) (e.g. Caruana et al., 2014; Tilvi et al., 2014) and not a single \( z > 8 \) Ly\( \alpha \) emitter candidate has been confirmed yet (e.g. Sobral et al., 2009b; Faisst et al., 2014; Matthee et al., 2014). If the suppression of Ly\( \alpha \) is mostly caused by the increase of neutral hydrogen fraction towards higher redshifts, it is clear that \( z \sim 6.5 \) (just over 0.8 Gyrs after the Big Bang) is a crucial period, because re-ionisation should be close to complete at that redshift (e.g. Fan et al., 2006).

Narrow-band searches have been successful in detecting and confirming Ly\( \alpha \) emitters at \( z \sim 3 - 7 \) (e.g. Cowie & Hu, 1998; Malhotra & Rhoads, 2004; Iye et al., 2006; Murayama et al., 2007; Hu et al., 2010; Ouchi et al., 2010). The results show that the Ly\( \alpha \) luminosity function is constant from \( z \sim 3 \) to \( z \sim 6 \), but there are claims that the number density drops from \( z \sim 6 \) to \( z \sim 6.6 \) (e.g. Ouchi et al., 2010; Kashikawa et al., 2011) and that it drops at an even faster rate up to \( z \sim 7 \) (e.g. Shibuya et al., 2012; Konno et al., 2014). Moreover, the fact that the rest-frame UV luminosity function declines from \( z \sim 3 - 6 \) (e.g. Bouwens et al., 2015a) while the Ly\( \alpha \) luminosity function (LF) is roughly constant over the same redshift range (e.g. Ouchi et al., 2008) implies that the cosmic average Ly\( \alpha \) escape fraction is likely increasing, from \( \sim 5\% \) at \( z \sim 2 \) (e.g. Hayes et al., 2010; Ciardullo et al., 2014), to likely \( \sim 20 - 30\% \) around \( z \sim 6 \) (e.g. Cassata et al., 2015). Surprisingly, it then seems to fall sharply with increasing redshift beyond \( z \sim 6.5 \). Current results could be a consequence of re-ionisation not being completed at \( z \sim 6 - 7 \), particularly when taken together with the decline in the fraction of Lyman break selected galaxies with high EW Ly\( \alpha \) emission (e.g. Tilvi et al., 2014; Caruana et al., 2014; Pentericci et al., 2014). However, it is becoming clear that re-ionisation by itself is not enough to explain the rapid decline of the fraction of strong Ly\( \alpha \) emitters towards \( z \sim 7 \) (e.g. Dijkstra, 2014; Mesinger et al., 2015).

It is likely that re-ionisation was very heterogeneous/patchy (e.g. Pentericci et al., 2014), with the early high density regions re-ionising first, followed by the rest of the Universe. If that were the case, this process could have a distinguishable effect on the evolution of the Ly\( \alpha \) luminosity function, and it may be that
the luminous end of the luminosity function evolves differently from the fainter end, as luminous Lyα emitters should in principle be capable of ionising their surroundings and thus are easier to observe. This is exactly what is found by Matthee et al. (2015), in agreement with spectroscopic results from Ono et al. (2012).

In addition to using Lyα emitters to study re-ionisation, they are also useful for identifying the most extreme, metal poor and young galaxies. Studies of Lyα emitters at \( z > 2 - 3 \) show that, on average, these sources are indeed very metal poor (Finkelstein et al., 2011; Nakajima et al., 2012; Guaita et al., 2013), presenting high ionisation parameters (high [OIII]/Hβ line ratios; Nakajima et al. 2013) and very low typical dust extinctions (e.g. Ono et al., 2010). Given these observations, Lyα searches should also be able to find metal-free, PopIII stellar populations (since galaxies dominated by PopIII emit large amounts of Lyα photons, e.g. Schaerer 2002, 2003). However, so far, although some candidates for PopIII stellar populations have been found (e.g. Jimenez & Haiman, 2006; Dijkstra et al., 2007; Nagao et al., 2008; Kashikawa et al., 2012; Cassata et al., 2013), and some metal poor galaxies have been confirmed (e.g. Prescott et al., 2009), they are all significantly more metal rich than the expected PopIII stars, and show e.g. Ciii] and Civ emission. For example, when there is no evidence for the presence of an AGN and no metal lines, the short-lived Heii1640Å emission line (the ‘smoking gun’ for PopIII stars in extremely high EW Lyman-α emitters without any metal emission line) was never detected with high enough EW (e.g. Nagao et al., 2008; Kashikawa et al., 2012).

Until recently, Lyα studies at the epoch of re-ionisation have been restricted to the more numerous, relatively faint sources of \( L_{\text{Ly} \alpha} \sim 10^{42.5} \) erg s\(^{-1}\) (with some exceptions, e.g. \( z = 5.7 \) follow-up: Westra et al. 2006; Lidman et al. 2012; and ‘Himiko’: Ouchi et al. 2009). However, with the wide-field capabilities of current instruments (including Hyper Suprime-Cam; Miyazaki et al. 2012), the identification of luminous Lyα emitters will become increasingly easier. Recently, significant progress was made towards finding luminous Lyα emitters at \( z = 6.6 \) (Matthee et al., 2015), through a \( \sim 5 \) deg\(^2\) narrow-band survey, which resulted in the identification of the most luminous Lyα emitters at the epoch of re-ionisation. Matthee et al. (2015) reproduced the Lyα luminosity function of Ouchi et al. (2010) for relatively faint Lyα emitters at \( z = 6.6 \) for the UDS field, who find a decrease in their number density compared to lower redshifts.

However, Matthee et al. (2015) find that the luminous end of the \( z = 6.6 \) LF resembles the \( z = 3 - 5.7 \) luminosity function, and is thus consistent with no evolution at the bright end since \( z \sim 3 \). Extremely luminous Lyα emitters at \( z \sim 6.6 \) are thus found to be much more common than expected, with space densities of \( 1.5^{+1.2}_{-0.5} \times 10^{-5} \) Mpc\(^{-3}\). The results may mean that, because such bright sources can be observed at \( z \sim 6.6 \), we are witnessing preferential re-ionisation happening around the most luminous sources first. Such luminous sources may already be free (in their immediate surroundings) of a significant amount of neutral hydrogen, thus making their Lyα emission observable. Furthermore, these sources open a new window towards exploring the stellar populations of the most luminous Lyα emitters at the epoch of re-ionisation even before the James...
### 4.2 Sample and Spectroscopic observations

#### 4.2.1 The luminous Lyα candidates at z = 6.6

Matthee et al. (2015) used the Subaru telescope and the NB921 filter on Suprime-cam (Miyazaki et al., 2002) to survey $\sim 3$ deg$^2$ in the SA22 (PI: D. Sobral), $\sim 1$ deg$^2$ in COSMOS/UltraVISTA (PI: M. Ouchi) and $\sim 1$ deg$^2$ in UDS/SXDF (PI: M. Ouchi) fields in order to obtain the largest sample of luminous Lyα emitters at the epoch of re-ionisation.

Out of the 135 Lyα candidates found in Matthee et al. (2015), we discover two very bright Lyα candidates in the COSMOS/UltraVISTA field: ‘CR7’ (COSMOS Redshift 7) and MASOSA\(^1\). MASOSA is particularly compact (0.7′′), while CR7 is extended ($\sim 3′′$). We show the location of the Lyα emitters within the COSMOS field footprint in Figure 4.1, in which the size of the symbols scales with luminosity. We also show their properties in Table 4.2.

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\(^1\) The nickname MASOSA consists of the initials of the first three authors of Matthee et al. (2015)
Thumbnails in various wavelengths ranging from observed optical to observed mid-infrared are shown in Figure 4.2. Both candidates show very high rest-frame Lyα EWs\(^2\) in excess of > 200 Å. By taking advantage of the wealth of data in the COSMOS/UltraVISTA field (e.g. Capak et al., 2007; Scoville et al., 2007; Ilbert et al., 2009; McCracken et al., 2012), we obtain multi-band photometry for both sources. The measurements are given in Table 4.2. We re-measure the 3.6 µm and 4.5 µm photometry for CR7, in order to remove contamination from a nearby source. Such contamination is at the level of 10-20%, and is added in quadrature to the photometry errors.

We find that CR7 has very clear detections in the near-infrared and mid-infrared (Figure 4.2), showing a robust Lyman-break (Steidel et al., 1996). CR7 is detected in Spitzer/IRAC, with colors as expected for a \( z \sim 6.6 \) source (Smit et al., 2014), likely due to contribution from strong nebular lines with EWs in excess of a few 100 Å in the rest-frame optical (see Figure 4.2). Because of the detections in the NIR and MIR, the rest-frame UV counterpart of CR7 was already identified as a \( z \sim 6 - 7 \) Lyman-break candidate (Bowler et al., 2012, 2014). However, because of its very uncommon NIR colors in the UltraVISTA DR2 data (i.e. excess in \( J \) relative to \( Y, H \) and \( K \)), the clear IRAC detections, and, particularly, without the NB921 data (Figure 4.2), it was classed as an unreliable candidate, possibly a potential interloper or cool star. MASOSA has a clear detection in the narrow-band and is weakly detected in \( z \), but the \( z \) band detection can be fully explained by Lyα. It is not detected at > 1σ in the NIR (\( J > 25.7, H > 24.5, K > 24.4 \)), although a very weak signal is visible in the thumbnails (Figure 4.2). This indicates that the Lyα EW is very high and highlights that the Lyman-break selection can easily miss such sources, even if they are extremely bright and compact in Lyα, as MASOSA is not detected at the current depth of the UltraVISTA survey (Bowler et al., 2014).

### 4.2.2 Spectroscopic observations and data reduction

Spectroscopic observations were made with the Very Large Telescope (VLT)\(^3\) using X-SHOOTER (for CR7) and FORS2 (for MASOSA). The choice of X-SHOOTER for CR7 was due to the fact that it was detected in the NIR and showed evidence for excess in the \( J \) band, likely indicating strong emission lines. Both sources were observed with DEIMOS on the Keck II telescope (see Table 4.1) as well. Spectra for both sources, obtained with both the VLT and Keck, are shown in Figure 4.3, including the spectra obtained by combining both data-sets.

#### DEIMOS/Keck observations

DEIMOS/Keck observations targeted both ‘CR7’ and ‘MASOSA’ in two different masks and two different nights. Observations were conducted on 28 and 29 December 2014. The seeing was \( \sim 0.5'' \) on the first night, when we observed

\(^2\) EWs computed by using either \( z \) or \( Y \) lead to results in excess of 200 Å. We also present EWs computed based on \( Y \) band and from our spectroscopic follow-up in Table 4.2.

4.2. Sample and Spectroscopic observations

Figure 4.1: Projected positions on sky of all Lyα candidates (green circles) found in the COSMOS/UltraVISTA field. The grey background points represent all detected sources with the NB921 filter, highlighting the masking applied (due to the presence of artefacts caused by bright stars and noisy regions, see Matthee et al., 2015). Lyα candidates are plotted with a symbol size proportional to their Lyα luminosity. CR7 and MASOSA are highlighted in red: these are the most luminous sources found in the field. Their coordinates are given in Table 4.1.

Figure 4.2: Thumbnails of both luminous Lyα emitters in the optical to MIR from left to right. Each thumbnail is $8 \times 8''$, corresponding to $\sim 44 \times 44$ kpc at $z \sim 6.6$. Note that while for MASOSA the Lyα emission line is detected by the NB921 filter at full transmission, for CR7 the Lyα is only detected at $\sim 50\%$ transmission. Therefore, the NB921 only captures $\sim 50\%$ of the Lyα flux: the observed flux coming from the source is $\sim 2 \times$ larger.
‘CR7’, and ∼ 0.7′′ on the second night, when we observed ‘MASOSA’. Observations were done under clear conditions with midpoint airmass of < 1.1 for both sources. We used a central wavelength of 7200 Å and the 600I grating, with a resolution of 0.65 Å pix$^{-1}$, which allowed us to probe from 4550 Å to 9850 Å. We used the 0.75′′ slit.

For CR7, we obtained 4 individual exposures of 1.2 ks and one exposure of 0.6 ks, resulting in a total of 5.4 ks. For MASOSA, we obtained a total of 2.7 ks. A strong, extended and asymmetric line is clearly seen in every individual 1.2 ks exposure prior to any data reduction.

We reduced the data using the DEIMOS spec2d pipeline (Cooper et al., 2012; Newman et al., 2013). The observed spectra were flat-fielded, cosmic-ray-removed, sky-subtracted and wavelength-calibrated on a slit-by-slit basis. We used standard Kr, Xe, Ar and Ne arc lamps for wavelength solution and calibration. No dithering pattern was used for sky subtraction. The pipeline also generates 1D spectrum extraction from the reduced 2D per slit, and we use the optimal extraction algorithm (Horne, 1986). This extraction creates a one-dimensional spectrum of the target, containing the summed flux at each wavelength in an optimised window. We also extract the spectrum of both sources with varying apertures and at various positions, in order to take advantage of the fact that the sources are clearly spatially resolved. The final spectrum is shown in Figure 4.3.

FORS2/VLT observations

FORS2/VLT (Appenzeller et al., 1998) observations targeted ‘MASOSA’ and were obtained on 12 January and 11 February 2015. The seeing was 0.7′′ and observations were done under clear conditions. We obtained individual exposures of 1 ks and applied 3 different offsets along the slit. In total, we obtained 6 ks. We used the OG590+32 filter together with the GRIS300I+11 Grism (1.62 Å pix$^{-1}$) with the 1′′ slit. Lyα is clearly seen in each individual exposure of 1 ks.

We use the ESO FORS2 pipeline to reduce the data, along with a combination of Python scripts to combine the 2D and extract the 1D. The steps implements follow a similar procedure to that used for DEIMOS.

X-SHOOTER/VLT observations

Our X-SHOOTER/VLT (Vernet et al., 2011) observations targeted ‘CR7′ and were obtained on 22 January 2015 and 15 February 2015. The seeing varied between 0.8′′ and 0.9′′ and observations were done under clear conditions. We obtained individual exposures of 0.27 ks for the optical arm, while for NIR we used individual exposures of 0.11 ks. We nodded from an A to a B position, including a small jitter box in order to always expose on different pixels. We used 0.9′′ slits for both the optical and near-infrared arms (resolution of $R \sim 7500$ and $R \sim 5300$, for the optical and near-infrared arms, respectively). In total, for the X-SHOOTER data, we obtained 8.1 ks in the optical and 9.9 ks in the NIR. The differences are driven by the slower read-out time in the optical CCD compared to the NIR detector.
4.2. Sample and Spectroscopic observations

![Graphs showing normalized flux vs. restframe wavelength for CR7 and MASOSA sources.]

**Figure 4.3:** Left: ‘CR7’ 1-D and 2-D optical spectra, showing the strong and clear Lyα emission line. We also show the NB921 filter profile which was used to select the source. Note that Lyα is detected at the wing of the NB921 filter. Thus, while the NB921 photometry already implied the source was very luminous, its true luminosity was still underestimated by a factor of two. We show both our Keck/DEIMOS and VLT/X-SHOOTER spectra, which show perfect agreement, but with X-SHOOTER providing a higher spectral resolution. Right: ‘MASOSA’ 1-D and 2-D optical spectra (FORS2), showing the strong and clear Lyα emission line. We show both the VLT/FORS2 and Keck/DEIMOS spectra, showing they agree very well. The DEIMOS spectrum provides higher resolution, but both clearly reveal the asymmetry of the line, confirming it as Lyα without any doubt.

For the January observation a PA angle of 0 deg was used, together with an acquisition source at 10:01:03.156 +01:48:47.885 (J2000). Offsets of $-77.266''$ (R.A.) and $-32.634''$ (Dec.) were used to offset from the acquisition source to CR7. The acquisition for the first OB (OB1, 22 January 2015) was suspected to be relatively off-target due to an unreliable acquisition star centring (acquisition star was not centred in the slit), leading to an apparent lower Lyα flux. In order to avoid problems with acquisition, another acquisition source was used for the February observations: 10:01:00.227, 01:48:42.992 (J2000), applying an offset of $-33.342''$ (R.A.) and $-27.742''$ (Dec.) and this time with a PA angle of $-39.76$ deg, in order to better align the slit with the elongation of the Lyα 2D distribution obtained from the narrow-band imaging.

We use the X-SHOOTER pipeline to reduce the observations in the optical and NIR spectra separately (v2.4.8; Modigliani et al. 2010). Each observing block of one hour is reduced separately, including flux calibration using a standard star. We then median combine the reduced 2D spectra after centering each spectrum on the spatial pixel where the Lyα flux peaks, but we also inspect spectra of individual observation blocks. The final Lyα spectrum, for which we extracted the 1D spectrum using the native pixel scale that oversampled the line spread function, is shown in Figure 4.3.
Table 4.2: A summary of our results for CR7 and MASOSA. These include both the spectroscopic measurements, but also photometry. In order to provide an easy comparison, we also provide the measurements for Himiko, the other luminous source in the Matthee et al. (2015) sample, fully presented in Ouchi et al. (2013).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>CR7</th>
<th>MASOSA</th>
<th>Himiko</th>
</tr>
</thead>
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<tr>
<td>$z_{\text{spec}}$ Lyα</td>
<td>$6.604^{+0.001}_{-0.003}$</td>
<td>$6.541 \pm 0.001$</td>
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<td>β UV slope</td>
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<td>$-2.0 \pm 0.57$</td>
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<td>$211 \pm 20$</td>
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<tr>
<td>Lyα ($\text{EW}_{0,\text{obs,spec}}$, Å)</td>
<td>$&gt;230$</td>
<td>$&gt;200$</td>
<td>—</td>
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<tr>
<td>Lyα ($\log_{10}L$, erg s$^{-1}$)</td>
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<td>$43.38 \pm 0.06$</td>
<td>$43.40 \pm 0.07$</td>
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<td>$&gt;70$</td>
<td>—</td>
<td>—</td>
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<tr>
<td>HeII/Lyα</td>
<td>$0.11 \pm 0.04$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>HeII (EW$_0$, Å)</td>
<td>$25 \pm 15$ ($&gt;20$)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>HeII (FWHM, km s$^{-1}$)</td>
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<td>—</td>
<td>—</td>
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<td>—</td>
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<td>z</td>
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<td>NB921 MAG-AUTO</td>
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4.3 Measurements and SED fitting

4.3.1 Redshifts

In both the VLT (FORS2 or X-SHOOTER) and Keck (DEIMOS) spectra for the two targets, we detect the very strong Ly$\alpha$ line (Figure 4.3) in emission, and no continuum either directly red-ward or blue-ward of Ly$\alpha$. The very clear asymmetric profiles leave no doubts about them being Ly$\alpha$ and about the secure redshift (Figure 4.3). Particularly for CR7, the high S/N > 25 (combined Keck and VLT) at Ly$\alpha$, despite the very modest exposure time for such a high-redshift galaxy, clearly reveals this source is unique. Based on Ly$\alpha$, we obtain redshifts of $z = 6.604$ for CR7 and $z = 6.541$ for MASOSA. The redshift determination yields the same answer for both our data-sets: X-SHOOTER and DEIMOS, for CR7 and FORS2 and DEIMOS, for MASOSA (see Figure 4.3, which shows the agreement). It is worth noting that for CR7 we find that the Ly$\alpha$ emission line is detected in a lower transmission region of the NB921 filter profile (50% of peak transmission). Therefore, the Ly$\alpha$ luminosity of CR7 is higher than estimated from the NB921 photometry, making the source even more luminous than thought.

4.3.2 Spectral line measurements

By fitting a Gaussian profile to the emission lines, we measure the EW (lower limits, as no continuum is detected) and FWHM. Emission line fluxes are obtained by using NB921 and $Y$ photometry (similarly to e.g. Ouchi et al. 2009, 2013), in combination with the NB921 filter profile and the appropriate redshift. We also check that the integrated emission line (without any assumption on the fitting function) provides results which are fully consistent.

For MASOSA, we find no other line in the optical spectrum, and also find no continuum at any wavelength probed (see Figure 4.3). For CR7, we find no continuum either directly blue-ward or red-ward of Ly$\alpha$ in the optical spectrum (both in X-SHOOTER and DEIMOS; Figure 4.3).

4.3.3 Revised analysis of X-SHOOTER/NIR spectrum of CR7

We explore our X-SHOOTER NIR spectrum to look for any other emission lines in the spectrum of CR7. In order to extract 1D spectra, we first smooth the 2D spectrum with a gaussian kernel in the spatial direction with $\sigma = 0.4''$, which is similar to the seeing PSF FWHM of $\approx 0.8 - 0.9''$. Then, we bin the spectrum in the wavelength direction by a factor 3 in order to increase the S/N. This results in a pixel scale of 1.8 $\AA$ px$^{-1}$, still sampling the instrumental resolution with two pixels. The 1D spectrum is extracted using a box of 2.0'' in order to be able to identify slightly off-centred emission lines. In each binning step, the noise level estimated from the X-SHOOTER pipeline is propagated.

We mask all regions for which the error spectrum is too large ($> 1.5 \times$ the error on OH line free regions), including the strongest OH lines. We then inspect
the spectrum for any emission lines. In the full stack, we find a tentative emission line at \( \lambda_{\text{obs,vacuum}} = 12473 \, \text{Å} \) (see Figure 4.4), slightly off-centred from the peak Ly\( \alpha \) emission (0.8″ in the north-west direction). We find no other emission lines in the spectrum (Figure 4.4). The emission line found, at \( z = 6.603 \pm 0.001 \), corresponds to 1640.47 Å, and thus we associate it with He\( \text{II} \). For an optimal extraction of this flux, we shift the centre of our extraction box 0.8″.

Given the line flux \( (1.7 \pm 0.5 \times 10^{-17} \, \text{erg s}^{-1} \, \text{cm}^{-2}) \), and the level of continuum estimated from e.g. \( Y \) and \( H \) bands, the spectrum indicates \( \text{EW}_0 = 25 \pm 15 \, \text{Å} \), lower than the excess indicated by the UltraVISTA DR2 photometry (\( \text{EW}_0 \approx 80 \, \text{Å} \)). We find that the He\( \text{II} \)1640 Å emission line is narrow \( (180 \pm 30 \, \text{km s}^{-1} \, \text{FWHM}) \), and detected at \( \approx 3\sigma \) in the fully combined X-SHOOTER data. Results based on the extraction of the full stack are presented in Table 4.2.

The He\( \text{II} \)1640 Å emission line implies a small velocity offset of \( 100 \pm 50 \, \text{km s}^{-1} \) between the peak of Ly\( \alpha \) and He\( \text{II} \)1640 Å (i.e., the Ly\( \alpha \) peak is redshifted by \( +100 \, \text{km s}^{-1} \) in respect to He\( \text{II} \), which could also be interpreted as an outflow). This means that, not surprisingly, we are only detecting the red wing of the Ly\( \alpha \) line, while both the blue wing and any potential Ly\( \alpha \) component with \( < +160 \, \text{km s}^{-1} \) is being likely absorbed and cannot be observed. This may imply that the intrinsic Ly\( \alpha \) luminosity and the EW will be even larger than measured.

A more detailed analysis of individual one hour observation blocks reveals that the signal can almost solely be attributed to the third observation, performed using a different position angle than the other two. In this OB only, the line is detected at \( \approx 4\sigma \) significance after smoothing and binning the spectrum as described above, and by propagating the noise-model from the pipeline. In this spectrum, shown in Fig. 4.4, the line has a line flux \( 2.3 \pm 0.6 \times 10^{-17} \, \text{erg s}^{-1} \, \text{cm}^{-2} \), implying an \( \text{EW}_0 = 35 \pm 20 \, \text{Å} \). This emphasises the need for spatially resolved spectroscopy in luminous galaxies such as CR7 and careful analysis once observations over multiple position angles are combined.

### 4.3.4 Comparison to Sobral et al. (2015b) X-SHOOTER measurements

The X-SHOOTER NIR measurements presented above differ from those originally published in the Sobral et al. (2015b) article. The two main differences are the redshift at which He\( \text{II} \) is detected and the strength of the He\( \text{II} \) line. The former determines the velocity offset between Ly\( \alpha \) and He\( \text{II} \), while the latter is related to the measured EW and the significance of the detection. The origin of these differences is discussed here.

Our re-analysis of the X-SHOOTER data revealed a problem with the wavelength calibration in Sobral et al. (2015b) due to the use of outdated arc-calibration files. As a result, the wavelength solution was off by \( \sim 6 \, \text{Å} \) around the wavelength at which He\( \text{II} \) was detected. The Sobral et al. (2015b) article

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4 We note that while Sobral et al. (2015b) associated the emission line to clump A, our updated analysis indicates this may not be the case.
states an (air) wavelength of 12464 Å, that corresponds to a vacuum wavelength of 12468 Å, or a He\textsc{ii} redshift of $z = 6.60$. Here, we find that the wavelength of the line (in vacuum) is 12473 Å, corresponding to a He\textsc{ii} redshift of $z = 6.603$. This decreases the velocity offset between He\textsc{ii} and Ly\textsc{a} and also influences the comparison performed by Shibuya et al. (2018), see Appendix C.

Another difference between the X-SHOOTER reduction presented here and the one used in Sobral et al. (2015b) is that flux calibration has been performed with a standard star, while Sobral et al. (2015b) used the UltraVISTA DR2 J band photometry. As discussed below in §4.5.5, a more recent version of the UltraVISTA data reveals that the J band magnitude used for the calibration in Sobral et al. (2015b) was over-estimated by 0.5 magnitude, which translates into a significant over-estimate of the He\textsc{ii} line flux by a factor $\approx 2$. This results in a lower revised He\textsc{ii} luminosity and EW.

In the Sobral et al. (2015b) analysis, the He\textsc{ii} line is detected at 6$\sigma$ significance in the full stack, while we find 3$\sigma$ here in the same data (full stack of the three observation blocks). The difference originates from the following: i) Sobral et al. (2015b) smoothed the data using a kernel that corresponds to the point spread function in the spatial direction and the line spread function in the wavelength direction (this kernel is larger than the smoothing kernel used in this analysis), ii) the noise estimate used in this analysis is the propagated pipeline error model, that potentially is overestimated (as can be seen in Fig. 4.4, more than 68 % of the points lie within the 1$\sigma$ noise level; the overestimated propagated noise from the pipeline is discussed in detail in Zabl et al. 2015), Sobral et al. (2015b) contrarily estimate the noise on the actual data in skyline-free regions around the observed feature, iii) the red part of the He\textsc{ii} line is slightly contaminated by a weak skyline that had been masked in Sobral et al. (2015b), but increases the uncertainty of the flux measurement in this analysis. Therefore, the measurement that the line is detected at 3$\sigma$ is on the conservative side.

How does the new X-SHOOTER analysis affect the interpretation of CR7 and how does it affect the discussion section of this Chapter compared to Sobral et al. (2015b)? In fact, it does not make much of a difference if one is willing to assume the detected feature is a real line. The reduced He\textsc{ii} luminosity reduces the hardness of the spectrum somewhat (which was challenging to explain even with the hottest PopIII stars, see §4.6.2) and a slightly lower mass of PopIII-like star formation is required (but within the same order of magnitude and hence likely still problematic to keep unpolluted from metals until $z = 6.6$, see the discussion in Appendix A). The lower He\textsc{ii} EW is still challenging to explain with ‘normal’ binary stellar populations, and requires a highly $\alpha$-enhanced (iron poor) stellar population (Bowler et al., 2017b).

### 4.4 Discovery of the most luminous Ly\textsc{a} emitters

#### 4.4.1 MASOSA

MASOSA is particularly compact (0.7” in diameter, corresponding to 3.8 kpc diameter at $z = 6.541$). It is similar to sources now found by MUSE (e.g. Bacon...
et al., 2015; Karman et al., 2015), that are completely undetected in the continuum and thus similar to typical Lyα emitters that have been found over the last years with e.g. Subaru/Suprime-cam. However, MASOSA is extremely bright in Lyα and thus separates it from the very faint sources found with MUSE in the HDF South and from other Lyα emitters. MASOSA is undetected in all continuum bands at all wavelengths and even the weak detection in z′ can be fully explained by the luminous Lyα line and little to no continuum. The estimated rest-frame EW of the Lyα line from spectroscopy is very high (> 200 Å), thus implying a likely very metal-poor stellar population (Malhotra & Rhoads, 2002). Its nature is likely similar to other metal-poor Lyα emitters (Nagao et al., 2008; Ono et al., 2010, 2012). Given the very high equivalent width (EW) and no continuum detection, MASOSA is likely extremely young, metal-poor and likely contains low stellar mass (< 10^9 M_☉).

The Lyα emission line shows a FWHM of 386 ± 30 km s^-1, and with tentative evidence for two components in the Lyα line (similar to what is found by Ouchi et al., 2010), potentially indicating a merger or radiative transfer effects (e.g. Verhamme et al., 2006). However, with the current ground-base imaging, and the faintness in the continuum, it is not possible to conclude anything about the potential merging nature of the source – only HST follow-up can investigate this. However, what is already clear is that MASOSA provides a new example of a relatively compact Lyα emitter with a similar luminosity to Himiko (Ouchi et al., 2009, 2013), but with a much more extreme EW, revealing that such high
luminosity sources present diverse properties and may have a diverse nature.

4.4.2 CR7

CR7 clearly stands out as the most luminous Lyα emitter at $z \sim 7$, with a luminosity of $L_{\text{Ly} \alpha} = 10^{43.93 \pm 0.05}$ erg s$^{-1}$, $\sim 3 \times$ more luminous than any known Lyα emitter within the epoch of re-ionisation. It also presents a very high rest-frame EW of $> 200$ Å, and thus a likely intrinsic EW which is even higher because of absorption by the ISM. Our measurements are presented in Table 4.2.

CR7 is spatially extended: $3''$ in diameter, corresponding to $\sim 15$ kpc at $z = 6.6$, as seen from its narrow-band image, but also in the spectra. Both the X-SHOOTER and DEIMOS data confirm its spatial extent, with both of them agreeing perfectly on the redshift, extent and FWHM. While the Lyα line profile is narrow (FWHM $\approx 270$ km s$^{-1}$), and particularly for such high luminosity, we see evidence for potentially 2 or 3 components (double peaked Lyα emission and a redshifted component towards the South of the source) and/or signs of absorption (see Figure 4.3), which indicate a complex dynamical structure. It may also mean that the actual intrinsic FWHM is even narrower. However, such tentative evidence requires confirmation with further spectroscopy obtained over different angles, and particularly by exploring deep imaging with high enough spatial resolution with e.g. HST.

4.4.3 Comparison with Himiko

We find that CR7 may be seen as similar to Himiko (but much brighter in Lyα and much higher EW) due to both sources presenting a spatial extent of about $3''$ in diameter. Both could therefore be tentatively classed as Lyα “blobs” (e.g. Steidel et al., 2000; Matsuda et al., 2004; Steidel et al., 2011). However, we note that Himiko is detected at peak transmission in the NB and the NB imaging in which it is detected is 1 mag deeper (see Matthee et al., 2015) than the imaging used for the discovery of CR7. While the CR7 Lyα line profile is very narrow, it consists of 2 or potentially 3 components, which may indicate that the source is a double or triple merger, likely similar to Himiko in that respect as well (see §4.5.4 which shows this is very likely the case for CR7). However, a simpler explanation is radiation transfer, which can easily cause such bumps (e.g. Vanzella et al., 2010). There are other similarities to Himiko, including: detections in NIR and a blue IRAC color. CR7 is however a factor $\sim 3$ brighter in Lyα emission and has an excess in $J$-band (attributed to HeII emission). CR7 is also bluer ($\beta = -2.2 \pm 0.4$, either using $Y - H$ or $H - K$, following equation 1 of Ono et al. 2010) in the rest-frame UV when compared to Himiko (which shows $\beta \sim -2.0$, but note that Himiko shows a red colour from $H$ to $K$ which would imply $\beta \sim 0.2$ if those bands are used). While CR7 shows a tentative HeII1640 Å emission line, no significant HeII is detected in Himiko, even though Zabl et al. (2015) obtained very deep X-SHOOTER data.

MASOSA is quite different. While it has the highest Lyα peak brightness, it is not extended and not detected in NIR or IRAC. Therefore, MASOSA provides
also a new class of sources at the epoch of re-ionisation: as luminous as Himiko, but very compact and with no significant rest-frame UV or rest-frame optical detection at the current UltraVISTA depth.

### 4.5 SED fitting CR7

To interpret the photometry/SED of CR7 we exploit the SED-fitting code of Schaerer & de Barros (2009) and Schaerer & de Barros (2010), which is based on a version of the *Hyperz* photometric redshift code of Bolzonella et al. (2000), modified to take nebular emission into account. We have explored a variety of spectral templates including those from the GALAXEV synthesis models of Bruzual & Charlot (2003), covering different metallicities (solar, $Z_{\odot}$, to $1/200 Z_{\odot}$) and star formation histories (bursts, exponentially declining, exponentially rising). A standard IMF with a Salpeter slope from 0.1 to 100 $M_{\odot}$ is assumed. We refer to these models as “standard”/“enriched” SED fits or “standard”/“enriched” models throughout this paper.

![Figure 4.5: Left: The SED of ‘CR7’, from observed optical (rest-frame FUV) to observed MIR (rest-frame optical) and the best fit with a normal stellar population (not including extremely hot stars). Red crosses indicate the flux predicted for each broad-band filter for the best fit. The fit fails to reproduce the strong Ly$\alpha$ emission line and also the excess in $J$ band, potentially boosted by He$\alpha$ emission. Moreover, and even though the fit is unable to reproduce all the information available for the source, it requires an age of 700 Myr (the age of the Universe is 800 Myr at $z = 6.6$). In this case, the galaxy would have a SFR of $\sim 25 M_{\odot} \, yr^{-1}$ and a stellar mass of $\sim 10^{10.3} M_{\odot}$. This is not able to explain the strong Ly$\alpha$ and the tentative He$\alpha$ emission line. Right: Same observed SED of CR7 as in the left panel plus HST photometry for clumps B+C (magenta triangles). The black line shows a fit with a pure PopIII SED to the rest-frame UV part; the magenta line the SED of an old simple stellar population with 1/5 solar metallicity which matches the flux from clumps B+C; the green line shows the predicted SED summing the two populations after rescaling the PopIII SED by a factor 0.8. The composite SED reproduces well the observed photometry. Although there is a tension between the strength of the He$\alpha$ line and nebular continuum emission (cf. text), a PopIII contribution is required to explain the HeII $\lambda 1640$ line and the corresponding excess in the J-band. Although He$\alpha$ has an unusually high EW ($> 20$ Å), we find no evidence for any other emission lines that would be characteristic of an AGN.](image-url)
In addition, we also use synthetic spectra from metal-free \((Z < 10^{-4}; \text{PopIII})\) stellar populations assuming different IMFs (Salpeter, top-heavy), taken from Schaerer (2002, 2003). Constant SFR or bursts are explored in this case. We also explore SEDs from “composite” stellar populations, showing a superposition/mix of PopIII and more normal populations.

Nebular emission from continuum processes and emission lines are added to the spectra predicted as described in Schaerer & de Barros (2009). Nebular emission from continuum processes and emission lines are proportional to the Lyman continuum photon production. Whereas many emission lines are included in general, we only include H and He lines for the PopIII case (cf. Schaerer, 2003). The intergalactic medium (IGM) is treated with the prescription of Madau (1995). Attenuation by dust is described by the Calzetti law (Calzetti et al., 2000). We note that in our PopIII-like SED, the \([\text{OIII}]4959,5007\) lines are expected to be very weak due to small amounts of oxygen.

### 4.5.1 SED fitting with a normal population

Part of the photometry of CR7 is explained relatively well with “standard” models, as illustrated in Figure 4.5 (left panel). The shortcomings of these fits is that they cannot account for the relative excess in the UltraVISTA DR2 \text{J} band with respect to \text{Y}, \text{H}, and \text{K}, and that the Ly\(\alpha\) emission is not strong enough to reproduce the entire flux observed in the NB921 filter. Both of these shortcomings thus relate to the presence of the strong emission lines (Ly\(\alpha\) and He\(\text{II}\)) observed in spectroscopy and also affecting the broad-band photometry.

The typical physical parameters derived from these SED fits which only include “normal” stellar populations indicate a stellar mass \(M_\ast \sim 2 \times 10^{10} \text{M}_\odot\), SFR \(\sim 25 \text{M}_\odot \text{yr}^{-1}\), and a fairly old age (\(\sim 700 \text{Myr}\); the Universe is \(\sim 800 \text{Myr}\) old at \(z = 6.6\)). The SED fits and the derived parameters do not vary much for different star-formation histories (SFHs): both for exponentially declining and rising cases, the fits prefer long timescales (i.e. slowly varying SFHs). Whereas for exponentially declineing SFHs and for constant SFR the best-fit attenuation is negligible \((A_V = 0)\), a higher attenuation is needed for rising SFHs, as expected (cf. Schaerer & Pelló, 2005; Finlator et al., 2007). Depending on the assumed metallicity, this may reach from \(A_V = 0.5\) (for \(1/5\) solar) to 0.25 (for \(1/200\) \(Z_\odot\)). The corresponding SFR is \(\sim 30 - 40 \text{M}_\odot \text{yr}^{-1}\). The typical specific SFR, \(s\text{SFR}\), obtained from these fits is \(s\text{SFR} \sim 1.2 - 1.9 \text{Gyr}^{-1}\), as expected for a “mature” stellar population with SFH close to constant (c.f. González et al., 2014).

### 4.5.2 SED fitting with contribution from PopIII-like stars

The presence of strong Ly\(\alpha\) and He\(\text{II}\) emission lines, plus the absence of other UV metal emission lines (cf. above), may be due to exceptionally hot stars with a strong and hard ionizing flux, resembling that expected for PopIII stars (cf. Tumlinson et al., 2001; Schaerer, 2002). A fit with PopIII templates (from Schaerer, 2002, 2003) is shown in Figure 4.5 (right panel: black line). PopIII models (Schaerer, 2002, 2003) show that at 3.6 \(\mu\text{m}\) (for \(z = 6.6\)) there are strong He\(\text{II}\).
and He lines, apart from Hβ, and that these Helium emission lines should have fluxes comparable to that of Hβ in the case of PopIII (Schaerer, 2002). Specifically, 3.6 µm should be contaminated by He ii 4686, He i 4471 and He i 5016. For 4.5 µm, apart from Hα, the He i 5876 should be detected and could be comparable to Hβ. The general features of our fits with PopIII templates (considering bursts or constant SFR, as well as different IMFs) are the following:

- The UV rest-frame part of the SED is very well reproduced and a PopIII-like stellar population is required to “boost” the J-band flux (due to the presence of the He ii line) and for a stronger Lyα line due to a higher Lyman continuum flux (for the same UV flux). The exact strength of these emission lines is very sensitive to the “details” of the population, such as the upper end of the IMF, the age or star formation history (see more details in e.g. Raiter et al., 2010). The fits with PopIII also reproduce all other NIR detections: Y, H and K (see Figure 4.5).

- Populations with very strong line-emission also have a strong nebular continuum emission red-ward of Lyα and increasing towards the Balmer limit (see e.g. Schaerer, 2002). The observations (H and K band photometry) do not permit a much stronger contribution from the nebular continuum, as that would mean an increasing redder H-K colour, which is not observed. This limits the maximum strength of the predicted emission lines, except if the two emission processes (recombination line emission and nebular continuum emission, which is due to two-photon and free-bound emission) could be decoupled, and emission lines could be increased without significantly increasing the nebular continuum emission.

- All the available PopIII templates fitting the (rest-)UV part of the spectrum, predict a relatively low flux in the IRAC bands with or without accounting for emission lines. Therefore, a pure metal-free population does not seem
to be able to completely reproduce the observed rest frame UV–optical SED of this source. In any case, a PopIII only explanation would not seem very likely. Therefore, a metal-free population alone (without decoupling between recombination line emission and nebular continuum emission) is not able to reproduce the observed rest-frame UV-optical SED of this source.

4.5.3 PopIII and a more chemically evolved stellar population

As a consequence of our findings, we are led to consider a hybrid SED consisting of two populations (the source may well be a merger, and these components may well be completely separated, avoiding pollution by metals into the potentially metal-free region): a young metal-free stellar population and a more chemically evolved population. This can be fully confirmed by using HST and appropriate filters that can easily isolate Lyα, the rest-frame UV, and HeII.

A superposition of a young PopIII component dominating in the UV and an older population of “normal” metallicity (in this case, 0.2 $Z_{\odot}$) dominating the rest-frame optical flux of CR7 is shown in the right panel of Figure 4.5. In practice, we add 80% of a metal-free simple stellar population with an age of 16 Myr (shown by the black line; although younger ages of $\sim$ 5 Myr are preferred to produce the strongest HeII emission) to a 360 Myr old burst of 1/5 $Z_{\odot}$ (magenta curve), giving the total flux shown in green. As can be seen, an “old” population of $\sim 1.6 \times 10^{10}$ $M_{\odot}$ can make up for the missing rest-frame optical flux, whereas a young PopIII (or another kind of stellar population with extremely hot stars) burst can dominate the UV and the emission lines. There is some tension/uncertainty in the age or age spread of the metal-free population, as very young ages ($\lesssim$ 5 Myr) are preferred to produce the strongest HeII emission, whereas slightly older ages are preferred to avoid too strong nebular continuum emission (cf. above). For indication, the mass of the metal-free component would be $1 \times 10^{9}$ $M_{\odot}$ for a Salpeter IMF from 1 to 500 $M_{\odot}$, i.e. $\sim$ 6 % of mass of the old population. However, significantly less mass could be needed if the PopIII IMF was flat or top-heavy, lacking e.g. completely low mass stars (stars below 10 $M_{\odot}$). This could mean that $\sim 10^{7}$ $M_{\odot}$ of PopIII stars would be needed in order to fully explain the flux for an IMF peaking at $\sim 60$ $M_{\odot}$, or even less if the IMF peaks at even higher masses. This reveals that the presence of a young, metal-free population, forming for example in a yet un-polluted region of the galaxy, in an slightly evolved galaxy at $z = 6.6$, could reproduce the observed features of CR7 (consistent with theoretical predictions from e.g. Scannapieco et al., 2003; Tornatore et al., 2007).

4.5.4 HST imaging of CR7

In order for our best interpretation to be valid, CR7 would require to be clearly separated/resolved, with HST resolution, into at least two different spatial components: one being dominated by a PopIII-like stellar population (dominating the UV light but with only a very small fraction of the mass), and another, redder
Table 4.3: Resolved HST photometry, rest-frame UV magnitudes and UV slopes of the different components in CR7. F110W photometry is corrected for the contribution from Lyα emission using NB921 data.

<table>
<thead>
<tr>
<th>Component</th>
<th>F110W</th>
<th>F160W</th>
<th>M_{1500}</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>24.65 ± 0.05</td>
<td>24.70 ± 0.12</td>
<td>−22.2 ± 0.1</td>
<td>−2.2 ± 0.4</td>
</tr>
<tr>
<td>A</td>
<td>25.16 ± 0.05</td>
<td>25.25 ± 0.12</td>
<td>−21.6 ± 0.1</td>
<td>−2.3 ± 0.4</td>
</tr>
<tr>
<td>B</td>
<td>27.18 ± 0.15</td>
<td>26.88 ± 0.25</td>
<td>−19.6 ± 0.2</td>
<td>−1.0 ± 1.0</td>
</tr>
<tr>
<td>C</td>
<td>26.72 ± 0.10</td>
<td>26.80 ± 0.23</td>
<td>−20.1 ± 0.1</td>
<td>−2.3 ± 0.8</td>
</tr>
</tbody>
</table>

in the UV (and fully dominating the mass), with fluxes similar to those shown in Figure 4.5. While this requires more detailed follow-up, we find that CR7 has been fortuitously observed and is in the FoV of previous WFC3 observations in F110W (broad YJ filter that also contains Lyα) and F160W (H) of a different project (ID: 12578, PI: Forster-Schreiber). We explore such data in order to investigate the rest-frame UV morphology of CR7 and to conduct a first study of the rest-frame UV colours. Observations in F110W and F160W were obtained for 2.6 ks each.

We show the data in Figure 4.6, including a comparison with the NB921 imaging. Figure 4.7 presents a false-colour image combining data obtained with NB921, F110W and F160W. We find that CR7 is, beyond any doubt, split in different components (see Figures 4.6 and 4.7), in line with our best interpretation of a PopIII-like stellar population which dominates the UV, and a redder stellar population, found to be physically separated by at least 5 kpc (projected). In fact, we actually find three different components, which we label as A, B and C (see Figures 4.6 and 4.7). We obtain photometry for each of the clumps separately, in order to quantitatively test if they could explain the UV photometry predicted for the two components in §4.5.3. We use 0.4" apertures for components B and C and 1" for component A, more spatially extended. Our results are summarised in Table 4.3.

We find that the sum of the two redder, fainter clumps (B+C) matches our evolved stellar population remarkably well (see Figures 4.5 and 4.8). Note that the photometry of the two redder clumps was not used to derive such fit. We find that the central clump (A) is the one that dominates the rest-frame UV light (Figure 4.8). Figure 4.7 also shows the rest-frame colours of components A, B and C. The clumps are physically separated by ∼ 5 kpc.

The HST imaging reveals that CR7 may be either a triple merger (similar to Himiko), and/or a system where we are witnessing a PopIII star formation wave, which may have moved from the reddest clump (C) to the other (B) and we are observing the brightest UV clump at the right time (A). It is therefore possible that the other clumps have emitted as much or even more of such radiation a few ∼ 100 Myrs before, preventing what is now the site of young massive stars (A) to form before and potentially allowing for that pocket of metal free gas to remain metal free. There are of course, other potential interpretations of our observations. In §5.7 we discuss the different potential scenarios in detail.
4.5. SED fitting CR7

In addition to the indications of a Heii emission line in the spectrum, additional evidence for the presence of one or more strong emission lines in the NIR originates from a relatively bright J band magnitude compared to Y and H (Sobral et al., 2015b). This J band ‘excess’ had been measured in UltraVISTA DR2 (McCracken et al., 2012) data and resembles the colour excesses that are being found in galaxies at $z \sim 6 - 7$ with the Spitzer/IRAC filters, used to infer Hβ+[OIII] (e.g. Smit et al., 2014). Besides the Sobral et al. (2015b) article, indications of a J band excess were also found by Bowler et al. (2014), who identified CR7 independently as a Lyman-break galaxy candidate at $z \sim 7$, although with poorly fitted SED (due to this excess) and therefore unreliable redshift.

The evidence for a J band excess disappeared in the new UltraVISTA DR3 data (March 2016). Compared to DR2, the released data from UltraVISTA DR3 had been re-reduced and the exposure time around CR7 roughly doubled (private communication with the UltraVISTA team). While CR7’s magnitude in the Y and H band does not change significantly, the difference in the J band magnitudes between DR2 and DR3 ranges from +0.1 and +0.5 magnitude (depending on the aperture).

The changes in the J band magnitude are larger than the measurement uncertainty provided in Table 4.2. The measurement uncertainty may have been under-estimated by a factor two (in flux density) due to correlated noise (private communication with the UltraVISTA team). Correlated noise originates from
resampling the data to a smaller pixel scale than the native pixel scale, and is known to be under-estimated by SExtractor. Furthermore, the variation in the $J$ band magnitude is not statistically significant compared to the changes in the $J$ band magnitude for all detections within a 5″ radius from CR7. Using these detections, we find that $\approx 5\%$ of the objects with similar brightness as CR7 have a $J$-band magnitude variation $> 0.4$ magnitude between DR2 and DR3. This implies that the largest change in CR7’s $J$ band magnitude is a 1.7$\sigma$ fluctuation.

As a result, the evidence for the photometric excess is decreased with new photometry and the flux calibration of the X-SHOOTER spectrum in Sobral et al. (2015b) had been overestimated. As discussed in Bowler et al. (2017b), the high He$\text{ii}$ EW of 80 Å Sobral et al. (2015b) is ruled out in the DR3 photometry, but an EW of $\approx 25$ Å, similar to the revisited X-SHOOTER reduction, is possible within their conservatively measured uncertainties.

### 4.6 Discussion

CR7, with a luminosity of $L_{\text{Ly}\alpha} = 10^{43.93\pm0.05}$ erg s$^{-1}$ is $\sim 3 \times$ more luminous than any known Ly$\alpha$ emitter within the epoch of re-ionisation (e.g. Ouchi et al., 2013).

X-SHOOTER data provides a near-infrared spectrum, allowing to investigate the significant excess seen in the $J$ band photometry from UltraVISTA DR2 (McCracken et al., 2012; Bowler et al., 2014), indicative of emission line(s). No continuum is detected in the NIR spectrum. However, and despite the relatively low integration time, a strong He$\text{ii}$1640 Å line was found ($\approx 3\sigma$, $\text{EW}_0 = 25 \pm 15$ Å), although not strong enough to explain the full observed excess in the $J$ band (see Figure 4.5). He$\text{ii}$ can only be produced if the intrinsic extreme UV spectrum is very hard, i.e., emits a large number of ionising photons with energies above 54.4 eV, capable of ionising He completely. The line we detect is also narrower than Ly$\alpha$, with FWHM of $180 \pm 30$ km s$^{-1}$, as He$\text{ii}$1640 Å does not scatter easily as Ly$\alpha$, as the line is not self-resonant.

While in principle there are a variety of processes that could produce both high EW Ly$\alpha$ and He$\text{ii}$1640Å, some of them are very unlikely to produce them at the luminosities we are observing, such as X-ray binaries or shocks. However, in principle, cooling radiation could produce strong Ly$\alpha$ emission with luminosities similar to those measured for CR7. Faucher-Giguère et al. (2010) provides predictions of the total Ly$\alpha$ cooling luminosity as a function of halo mass and redshift. Under the most optimistic/extreme assumptions, it would be possible to produce a Ly$\alpha$ luminosity of $\sim 10^{44}$ erg s$^{-1}$ for a dark matter halo mass of $M > 5 \times 10^{11} M_\odot$. Since such dark matter haloes should have a co-moving number density of about $\sim 10^{-5}$ Mpc$^{-3}$ at $z \sim 6.6$, their number densities could potentially match the luminous Ly$\alpha$ emitters that we have found. However, in the case of cooling radiation, the He$\text{ii}$ emission line should likely be weaker than what we measure (with intrinsic He$\text{ii}$/Ly$\alpha$ of 0.1 at most; e.g. Yang et al. 2006b), and cooling radiation in a massive dark matter halo should also result in a broader Ly$\alpha$ line than what we observe.
Figure 4.8: HST imaging in YJ and H allows us the physically separate CR7 in two very different stellar populations and show remarkable agreement with our best-fit composite SED derived in §4.5.3. While clump A (see e.g. Figure 4.7) is very blue and dominates the rest-frame UV flux, B+C may be somewhat redder and likely dominate the rest-frame optical and the mass. Note that we simply show the HST data together with our best fit composite model derived in §4.5.3 which was solely based on the full photometry and did not make use of any resolved HST data.

There are, nonetheless, four main sources known to emit an ionising spectrum that can produce high luminosity, high EW nebular Lyα and HeII as seen in our spectra (see also similar discussion in e.g. Prescott et al., 2009; Cai et al., 2011; Kashikawa et al., 2012):

1) strong AGN (many examples have been found, particularly on e.g. radio galaxies: De Breuck et al. 2000), with typical FWHM of lines being $\sim 1000 \text{ km s}^{-1}$;

2) Wolf-Rayet (WR) stars (many cases known in e.g. SDSS: Shirazi & Brinchmann 2012; or see Erb et al. (2010) for a higher redshift example), with typical FWHM of lines being $\sim 3000 \text{ km s}^{-1}$;

3) Direct collapse black hole (DCBH), which have been predicted and studied theoretically (e.g. Agarwal et al., 2013, 2016), although none has been identified yet, but they should produce strong HeII 1640Å (Johnson et al., 2011);

4) PopIII-like, extremely hot and low metallicity stars (e.g. Schaerer, 2003; Raiter et al., 2010), which should produce high EW, narrow HeII emission lines (FWHM of a few $\sim 100 \text{ km s}^{-1}$).

Many potential candidates for PopIII have been identified based on their colours and/or high EW Lyα, but either no HeII was found (e.g. Nagao et al., 2008), HeII was found but with clear signatures of AGN activity (De Breuck et al., 2000; Matsuoka et al., 2009), or HeII had very low EW (Cassata et al., 2013). Thus, so far, not a single source has been found with high EW Lyα, HeII detection with high EW, no AGN signatures, no WR star signatures (e.g. P-
Cygni profiles, broad lines, and many other metal lines e.g. Brinchmann et al. 2008; see also Gräfener & Vink 2015) and with no other metal lines.

4.6.1 The nature of CR7: AGN or WR stars?

In order to test the possibility of CR7 being an AGN, we start by checking X-ray data. We find no detection in the X-rays, with a limit of $< 10^{44}$ erg s$^{-1}$ (Elvis et al., 2009). We also find no radio emission, although the limit is much less stringent than the X-ray emission. The X-SHOOTER and DEIMOS spectra were carefully investigated for any metal lines, particularly NV, Oxygen and Carbon lines (see Table 4.2 and also Figure 4.4). No such lines were found, and thus we place 1σ upper limits on their fluxes, to constrain the nature of the source, finding, e.g. Lyα/NV $> 70$. Our Lyα and HeII emission lines are narrow (both FWHM $\sim 100 – 300$ km s$^{-1}$), thus excluding broad-line AGN. Narrow-line AGNs with HeII emission typically have CIII$\alpha$/HeII $\sim 1.5 \pm 0.5$ (e.g. De Breuck et al., 2000); such line ratio would result in a strong CIII$\alpha$1909 detection in our X-SHOOTER spectrum (see Figure 4.4). We do not detect CIII$\alpha$1909 and obtain an upper limit of CIII$\alpha$1909/HeII $< 0.5$ (1σ; see Figure 4.4), which greatly disfavours the AGN hypothesis. The strong limit on Lyα/NV $> 70$ also disfavours the AGN hypothesis and points towards very low metallicities.

There are no indications of WR stars, due to the very narrow HeII line ($\sim 180$ km s$^{-1}$, compared to typical FWHM of $\sim 3000$ km s$^{-1}$ for WR stars, c.f. Brinchmann et al. 2008) and no other metal lines.

We note, nonetheless, that while CR7 is strongly disfavoured as an AGN, it shows characteristics of what has been predicted for a direct collapse black hole (e.g. Johnson et al., 2011; Agarwal et al., 2013, 2016). This is because it shows $\beta = -2.3$ (as predicted), no metal lines, and high luminosity. The detection of the other nearby sources about $\sim 5$ kpc away (see Figure 4.6) are also a key prediction from Agarwal et al. 2015, while the relatively high observed HeII/Lyα would also match predictions for a direct collapse black hole (Johnson et al., 2011). However, CR7 does not show any broad line, as predicted by Agarwal et al. (2013), and the observed Lyα and HeII luminosities are higher by about $\sim 2$ orders of magnitude when compared to predictions by e.g. Johnson et al. (2011) for the case of $\sim 1 – 5 \times 10^4 M_\odot$ black holes. Another key distinction between a direct collapse black hole and stellar population(s) is X-ray emission: if it is a black hole, it must be emitting much more X-ray flux than a PopIII-like stellar population, and thus would likely be detectable with Chandra given the high line luminosities measured. Deeper Chandra observations could in principle test this.

4.6.2 On the hardness of the ionizing source of CR7

The theory of recombination lines relates, to first order, the ratio of HeII to Hydrogen recombination lines to the ratio between the ionizing photon flux above 54 eV, $Q(\text{He}^+)$, and that above 13.6 eV, $Q(H)$, the energies needed to
4.6. Discussion

ionize He$^+$ and H respectively. For the relative intensity HeII/Lyα one thus has:

\[ I(1640)/I(Ly\alpha) \approx 0.55 \times \frac{Q(\text{He}^+)}{Q(H)}, \tag{4.1} \]

where the numerical factor depends somewhat on the electron temperature, here taken to be \( T_e = 30 \) kK (Schaerer, 2002). The observed line ratio HeII/Lyα ≈ 0.15 therefore translates to \( Q(\text{He}^+)/Q(H) \approx 0.2 \), which indicates a very hard ionizing spectrum.

For metal-free stellar atmospheres such a hardness is only achieved in stars with very high effective temperatures, typically \( T_{\text{eff}} > 110 \) kK (or \( > 70 \) kK for 1 σ lower limit), slightly hotter than the (already hot) zero-age main sequence predicted for PopIII stars which asymptotes to \( T_{\text{eff}} \approx 100 \) kK for the most massive stars (e.g. Schaerer, 2002).

For integrated stellar populations consisting of a ensemble of stars of different masses, a maximum hardness \( Q(\text{He}^+)/Q(H) \approx 0.1 \) is expected for zero or very low metallicities (Schaerer, 2002, 2003), higher than inferred from the observed HeII/Lyα ratio of CR7. This could indicate that only a fraction of the intrinsic Lyα emission is observed, or that a source with a spectrum other than predicted by the above PopIII models (e.g. an AGN) is responsible for the ionization or contributing at high energies (> 54 eV). In fact the observed HeII equivalent width of 25 ± 15 Å is in broad agreement with the equivalent width predicted for PopIII models (Schaerer, 2002). This supports the explanation that \( \sim 75\% \) of the intrinsic Lyα emission may have escaped our observation, e.g. due to scattering by the IGM, internal absorption by dust, or due to a low surface brightness halo, processes which are known to affect in general Lyα emission (e.g. Atek et al., 2008; Dijkstra et al., 2011; Steidel et al., 2011). If the intrinsic Lyα emission is \( \gtrsim 2 - 3 \) times higher than observed, the hardness ratio is compatible with “standard” PopIII models. Future observations and detailed photoionization models may yield further insight on the properties of the ionizing source of CR7.

4.6.3 CR7: A PopIII-like stellar population?

As the AGN and WR stars hypothesis are strongly disfavoured (although we note that a direct collapse black hole could still explain most of our observations), could CR7 be dominated by a PopIII-like stellar population? For this to be the case, such stellar population would have to explain the detection, FWHMs, EWs and fluxes of Lyα and HeII (including the strong excess in J band), the UV continuum and continuum slope (\( \beta = -2.2 \pm 0.4 \)) and the IRAC detections which imply very high EW rest-frame optical lines. We have shown in §4.5.3 and §4.5.4 that a composite of PopIII models (Schaerer, 2002, 2003; Raiter et al., 2010) with a more evolved stellar population can match all our observations, including spatially resolved HST data. This scenario requires that the majority of mass is in clumps B and C, which can be tested with future high resolution MIR imaging. We note that the intrinsic HeII/Lyα line ratio predicted for PopIII would be \( \sim 0.05 - 0.1 \) (Schaerer, 2002, 2003), but that can easily result in an observable
ratio of $\sim 0.2$ if a significant fraction of the Ly$\alpha$ line is absorbed.

A key question, of course, is whether it is even possible or expected to observe Lyman-$\alpha$ coming from PopIII stars alone, even if such line is ultraluminous. The most massive PopIII stars should be short-lived (a few Myr), and, without any previous contribution to ionise their surroundings from e.g. neighbour star clusters or other nearby proto-galaxies, the most massive PopIII stars would have to be able to emit enough ionising photons to produce an ionised sphere larger than 1 Mpc after less than a few Myrs (Cen & Haiman, 2000), before the most massive stars reach the supernovae phase and likely start enriching the local environment. However, such process (for a single PopIII population in full isolation, and fully surrounded by neutral Hydrogen) should take at least $\sim 3$ Myrs to happen: this is simply set by the speed of light. However, if neighbouring sources (either PopIII or PopII stars) have already contributed towards ionising a local bubble, and if PopIII star formation can proceed in a wave-like pattern, likely from the highest density regions to the lowest densities, by the time later PopIII stars form (still in pristine gas which was not contaminated due to being sufficiently far away), they will be in ideal conditions to be directly observed in Ly$\alpha$. Thus, it may be much more likely to observe potentially composite populations than to observe pure PopIII stellar populations. Furthermore, and despite the nature of the stellar populations, it is likely that the observability of very luminous Ly$\alpha$ emitters is strongly favoured in complex systems which already have older stellar populations like CR7 (that were able to ionise local bubbles before and thus allowing for strong Ly$\alpha$ emission from young stellar populations to be observable).

### 4.7 Conclusions

We presented the spectroscopic follow-up of the two most luminous $z \sim 6.6$ Ly$\alpha$ candidates in the COSMOS field ($L_{\text{Ly} \alpha} \sim 3 - 9 \times 10^{43}$ erg s$^{-1}$): ‘MASOSA’ and ‘CR7’. These sources were identified in Matthee et al. (2015), revealing that such luminous sources are much more common than previously thought and have number densities of $\sim 1.5 \times 10^{-5}$ Mpc$^{-3}$. Our main results are:

- We used X-SHOOTER and FORS2 on the VLT, and DEIMOS on Keck, to confirm both candidates beyond any doubt. We find redshifts of $z = 6.604$ and $z = 6.541$ for ‘CR7’ and ‘MASOSA’, respectively. ‘CR7’ has an observed Ly$\alpha$ luminosity of $10^{43.93^{0.05}}$ erg s$^{-1}$ ($\sim 3\times$ more luminous than Himiko) and is the most luminous Ly$\alpha$ emitter ever found at the epoch of re-ionisation.

- MASOSA has a strong detection in Ly$\alpha$, with very high Ly$\alpha$ EW (EW$_0 > 200$ Å), implying very low stellar mass and a likely young stellar population. It is, nonetheless, undetected in all other available bands and Ly$\alpha$ is also rather compact.

- CR7, with a narrow Ly$\alpha$ line with $266\pm15$ km s$^{-1}$ FWHM, is detected in the NIR (rest-frame UV), with $\beta = -2.2 \pm 0.4$, an excess in publicly available
4.7. Conclusions

UltraVISTA DR2 \( J \) photometry compared to the \( Y \) and \( H \) bands, and it is strongly detected in \textit{Spitzer}/IRAC.

- We detect a tentative He\textsc{ii}1640Å narrow emission line at \( z = 6.603 \pm 0.001 \) with X-SHOOTER in CR7, which contributes to the excess seen in the \( J \) band photometry. We find no other emission lines from the UV to the NIR in our X-SHOOTER spectra. No AGN line is seen, nor any signatures of WR stars, as the He\textsc{ii}1640Å emission line is narrow (FWHM = 180 ± 30 km s\(^{-1}\)). The He\textsc{ii} emission line implies that we are seeing the peak of Ly\textsc{a} emission redshifted by +100 km s\(^{-1}\) and thus that we are only seeing the red wing of the Ly\textsc{a} (the intrinsic Ly\textsc{a} flux is thus likely much higher than seen), or we are witnessing an outflow.

- Based on the narrowness of Ly\textsc{a} and He\textsc{ii} and the absence of C\textsc{iv} and N\textsc{v}, the AGN and WR stars interpretation of the nature of CR7 are strongly disfavoured. An alternative interpretation is that the source hosts a direct collapse black hole, although the lack of broad emission lines and the lack of X-ray detection also disfavours this interpretation. Given all the current data, we conclude that CR7 may host an unseen, extreme stellar population and it is therefore the strongest candidate for PopIII-like stellar population found so far.

- We find that CR7 cannot be described only by a PopIII-like stellar population, particularly due to the very strong IRAC detections. Our best interpretation of the full data (spectroscopy and photometry), which is fully consistent with many theoretical predictions, is a combination of a PopIII-like stellar population, which dominates the rest-frame UV and the emission lines, and an older, likely metal enriched stellar population, which is red, and that dominates the mass of the system. This interpretation fits remarkably well with high resolution \textit{HST}/WFC3 imaging that reveals two red components, each about 5 kpc away from the peak of the rest-frame UV, Ly\textsc{a} and He\textsc{ii}1640Å emission and that have the fluxes predicted by our SED fitting.

We may be witnessing, for the first time, direct evidence for the occurrence of waves of PopIII-like star formation which could happen from an original star cluster outwards (resulting from strong feedback which can delay PopIII star formation), as suggested by e.g. Tornatore et al. (2007). In this scenario, the reddest clump in CR7 (C, see Figures 4.7 and 4.8), which formed first (reddest and oldest), was likely responsible for not only starting to ionise a local bubble, but also for photoionisation feedback that may have prevented star-formation to occur in the vicinity of clump C. Star-formation likely proceeded to the second clump once stellar feedback from C declined (B, see Figure 4.7), with similar effects (preventing star-formation outside such region, but further ionising a local bubble), and we are observing source A (see Figure 4.7) at the right time to see an intense PopIII-like star formation episode. Most importantly, this scenario also provides a very simple explanation of why Ly\textsc{a} photons can easily escape the CR7 galaxy, as we see a significant amount of older stars which were able
to emit a significant amount of UV photons for a few hundred million years before observations, enough to ionise a bubble of $> 1 \text{ Mpc}$ around the source. It may be that any previous episodes of star-formation could have prevented the gas around those star-forming regions to form stars. Furthermore, we note that while radiation is able to affect the surroundings as it travels fast, significant metal enrichment is very inefficient on scales larger than $\sim 1 \text{ kpc}$ (e.g. Scannapieco et al., 2003; Tornatore et al., 2007; Ritter et al., 2014), both due to the larger time-scales for metals (from supernovae) to travel outwards (compared to the speed of light), but also due to the continued infall of metal-free gas from the cosmic web. It is therefore likely that in some cases, scales beyond 1-2 kpc of previous star formation activity can easily have the pristine gas necessary to allow PopIII to form (e.g. Ritter et al., 2012, 2014) even at $z \sim 6.6$, and to be detectable at redshifts even below $z \sim 5$ (e.g. Scannapieco et al., 2003; Tornatore et al., 2007). Tornatore et al. (2007), for example, predict that the peak of PopIII star formation rate density to occur at $z \sim 6 - 8$.

The spectroscopic confirmation of MASOSA and CR7, along with the high S/N spectroscopic and photometric data, allowed us to have a first glimpse into sources likely similar to Himiko and brighter, that are much more common than previously expected and have a remarkable nature. The follow-up of the full Matthee et al. (2015) Lyα sources at even higher luminosities found in the SA22 field will allow us to explore even more the diversity and nature of such unique targets. Such luminous Lyα emitters are the ideal first targets for JWST, particularly due to the likely very high EW and bright optical rest-frame emission lines, which may not be restricted to bright [O III]5007, Hβ and Hα, but actually include Heii4686, Hei4471, Hei5016 and Hei5876. In the case of CR7, a composite of a PopIII-like stellar population and a likely enriched stellar population which is physically separated by $\sim 5 \text{ kpc}$ (Figure 4.7) is currently strongly favoured, and it is possible that similar stellar populations will be found in the other Lyα emitters. We may have found an actual population with clear signatures of PopIII-like stars, besides CR7. JWST will, in only a short exposure time, clearly show if the rest-frame spectra is made up of only He+H lines, confirming PopIII beyond any doubt, or if [O III] is also present and exactly where each of the lines is coming from.

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4.A. Summaries of articles interpreting CR7

Several theoretical articles have been written about the nature of CR7 after the publication from Sobral et al. (2015b). The findings of these articles are summarised below, in order of their publication date. I also comment on their validity after updated measurements of the He\textsuperscript{ii} line strength and the ALMA results presented in Chapter 5.

- ‘The brightest Ly\textsubscript{a} emitter: Pop III or black hole?’ (Pallottini et al., 2015). This article analyses recent cosmological hydrodynamical simulations and finds that several simulated galaxies indeed form PopIII stars from unpolluted pockets of pristine gas at relatively late cosmic times (\(z = 6.0\)). However, these pockets have an order of magnitude lower mass (in time windows of \(< 5\) Myr) than required to explain the Sobral et al. (2015b) He\textsuperscript{ii} luminosity. As PopIII stars only lead to strong He\textsuperscript{ii} emission for \(< 10\) Myr, the authors conclude that a PopIII explanation is highly unlikely. They conclude that a metal poor direct collapse black hole (that has a high He\textsuperscript{ii} luminosity for a much longer time) is more likely. Even with the revised lower He\textsuperscript{ii} luminosity, the simulations do not produce such a massive burst of PopIII star formation at \(z = 6.6\). A caveat is that the simulation volume is limited to \(10^3\) Mpc\(^3\) and therefore does not include simulated galaxies with similar mass as CR7, nor does it capture possible rare merger events. Regardless, other articles agree with Pallottini et al. (2015) that it is challenging to keep a large gas mass unpolluted until \(z = 6.6\).

- ‘Lya Signatures from Direct Collapse Black Holes’ (Dijkstra et al., 2016a). The authors discuss the Lya profile of CR7 in the context of Lya photons originating from cooling radiation from the gravitational heating of a collapsing cloud and the photoionisation by a central source. The Lya luminosity of CR7 indicates a black hole mass \(> 10^7\) M\(_\odot\), higher than the mass of a direct collapse black hole. The Lya profile indicates a low neutral hydrogen
column density and outflows, and is similar to the Ly\textalpha\ profile of normal LAEs at \(z \sim 2 - 3\). Hence, the Ly\textalpha\ properties indicate that the ISM in CR7 is already evolved and the current physical conditions are different from those in which the central supermassive black hole formed (in case CR7 is powered by this AGN). ALMA observations (Chapter 5) find a velocity shift that is in perfect agreement with the value estimated from the Ly\textalpha\ profile and a [CII]-UV luminosity ratio that is similar to the ISM in more normal galaxies, corroborating the findings of Dijkstra et al. (2016a).

- ‘Formation of massive Population III galaxies through photoionization feedback: a possible explanation for CR7’ (Visbal et al., 2016). This article proposes that the ionising radiation emitted by clumps B and C (assuming they formed earlier than clump A) heated the gas cloud that eventually forms clump A. This prevents the gas cloud from collapsing and forming stars until \(z \approx 6.6\). This way, a higher gas mass can remain unpolluted until \(z = 6.6\), compared to the model from e.g. Pallottini et al. (2015) that ignores this effect. The authors find that the number density of observable PopIII galaxies that form this way is \(\approx 10^{-7} \text{Mpc}^{-3}\) at \(z = 6.6\), a factor ten lower than the number density of CR7. The updated He\textsc{ii} luminosity likely makes this scenario more likely, as a lower gas mass is required to be sufficiently photo-heated. On the other hand, this scenario requires assumptions about the ionising photon escape fraction from clumps B and C, and likely depends on a somewhat fine-tuned/rare combination of star formation histories of nearby halos. Regardless of the nature of CR7, the photoionization feedback mechanism could help delaying the formation of PopIII stars by delaying the collapse of pristine gas clouds in the environments of massive galaxies, facilitating their observability in future surveys.

- ‘Evidence for a direct collapse black hole in the Lyman \textalpha source CR7’ (Smith et al., 2016b). This article explores 1D radiation-hydrodynamical simulations incorporating ionising radiation and Ly\textalpha\ feedback to study the impact of the spectrum of the ionising source on the observed properties of the Ly\textalpha\ line. This study focusses on the observed velocity offset and the surface brightness profile. They argue that the ionising spectrum of a stellar ionising source (similar to a blackbody with T=10^5 K) ionises its environment very efficiently, such that no velocity offset between the systemic redshift and the Ly\textalpha\ line would be observed. The observed velocity offset of +160 km \(\text{s}^{-1}\) in Sobral et al. (2015b), similar to the ALMA result, thus indicates a Compton thick AGN. The observed extended Ly\textalpha\ surface brightness profile also indicates the AGN scenario due to more resonant scattering in neutral hydrogen. The revised X-SHOOTER analysis reveals a slightly smaller velocity offset between the Ly\textalpha\ and He\textsc{ii} lines, although the velocity offset between Ly\textalpha\ and [CII] observed with ALMA agrees with the conclusion in Smith et al. (2016b). The authors conclude that future deep X-ray observations could help constraining the nature of CR7.

- ‘Detecting direct collapse black holes: making the case for CR7’ (Agarwal et al., 2016). After performing their own deconfusion techniques to measure
4.A. Summaries of articles interpreting CR7

Spitzer/IRAC photometry and performing their own SED fits of the individual components, the authors reconstruct the history of the local Lyman-Werner background around CR7 using the star formation histories of clumps B and C. They also use a halo merger tree, based on assuming $M_{\text{halo}} = 10^{12} \, M_\odot$ for clump A at $z = 6.6$, to trace the formation of clump A's halo and the likelihood of metal pollution due to nearby star formation in the other two clumps. Combining these constraints, the authors find that a direct collapse black hole could have formed at $19 < z < 23$ in clump A with a resulting black hole mass of $\approx 4.4 \times 10^6 \, M_\odot$ at $z = 6.6$ after a sub-Eddington accretion period. The authors note that their SED fit cannot explain the [3.6] flux at clump A, likely due to under-estimated Hβ+[OIII] emission (see also Appendix B and Bowler et al. 2017b). The presence of oxygen in clump A would require additional star formation and chemical enrichment between the time of BH formation and $z = 6.6$, but here it is not discussed whether this is theoretically possible.

- ‘Ab Initio Cosmological Simulations of CR7 as an Active Black Hole’ (Smidt et al., 2016). This article presents a full hydrodynamical simulation that simulates a system similar to CR7, roughly reproducing the Lyα luminosity and line-profile. The authors find that the AGN heats the gas in the halo, preventing further star formation and chemical enrichment. This is at odds with the [CII] detection by ALMA and the inferred presence of strong Hβ+[OIII] by Bowler et al. (2017b), as discussed above in the summary of Agarwal et al. (2016). The authors also use their simulation to predict a synchrotron radio luminosity of $\approx 10^{40} - 41 \, \text{erg s}^{-1}$ in the AGN scenario, which can be tested with future observations.

- ‘Exploring the nature of the Lyman-α emitter CR7’ (Hartwig et al., 2016). This article uses semi-analytical models to explore different formation scenarios of CR7 by randomly sampling dark matter merger trees. As the PopIII SFR density in their model peaks at $z \sim 15$ and chemical enrichment is efficient and ubiquitous (although ignoring photoionisation feedback that is proposed by Visbal et al. 2016), a PopIII scenario cannot explain CR7’s HeII luminosity at $z = 6.6$. The authors also argue that the metallicity (which they constrain to be $Z < 10^{-2}$ using CLOUDY modelling) is too low to explain CR7 with a black hole that formed as a PopIII remnant, as it would require a growth through mergers that would have chemically enriched the gas even further. Hence, the authors conclude that a black hole that formed in a low metallicity environment that remains metal poor (the case for a direct collapse black hole), is most likely. The revised HeII strength and the ALMA detection of [CII] emission allow for a higher, more normal metallicity in CR7. As a result, it is harder to determine the formation mechanism of the supermassive black hole, in case CR7 is powered by an AGN.

- ‘The nature of the Lyman-α emitter CR7: a persisting puzzle’ (Pacucci et al., 2017). This is the first article that appeared after the Bowler et al. (2017b) article and therefore discusses whether the blue [3.6]-[4.5] IRAC colour in
component A could only indicate the presence of strong [OIII] emission. Instead, the authors find that the IRAC photometry of CR7 can also be explained by strong He\textsubscript{i}\textlambda 4714 and He\textsubscript{ii}\textlambda 4687 emission, compatible with only a minor contribution from [OIII]\textsubscript{5007} emission. The authors therefore conclude that the current data are insufficient to distinguish between different AGN formation scenarios and detailed MIR spectroscopy is required.

- ‘Metallicity evolution of direct collapse black hole hosts: CR7 as a case study’ (Agarwal et al., 2017). This article addresses the issue whether metal pollution can take place after the formation of a supermassive black hole through direct collapse. They show that the star formation histories of clumps B and C from Agarwal et al. (2016) could pollute the metallicity in clump A to \( \approx 1/100 \; Z_{\odot} \) at \( z = 6.6 \), which is slightly higher than the metallicity inferred by Bowler et al. (2017b). Similar to Pacucci et al. (2017), this result implies that the current data do not rule out that the supermassive black hole in CR7 has not formed through a direct collapse. However, since the [CII]-UV ratio measured from ALMA indicates a metallicity that is \( > 1/10 \; Z_{\odot} \) (Chapter 5), additional star formation in clump A has likely occurred.

### 4.B Comparison to Bowler et al. (2017b)

In their article ‘No evidence for Population III stars or a Direct Collapse Black Hole in the \( z = 6.6 \) Lyman-\( \alpha \) emitter ‘CR7’’, Bowler et al. (2017b) re-analyse the photometric data of CR7. Compared to the analysis in this Chapter, Bowler et al. (2017b) analyse deeper Spitzer/IRAC [3.6] and [4.5] data and apply de-confusion methods. They also analyse new data from the UltraVISTA survey (DR3, versus DR2 in Sobral et al. 2015b).

As shown in Section 4.5.5, the \( J \) band photometry in the public UltraVISTA DR3 data is different from the public DR2 photometry, while photometry in other filters remains mostly unchanged. As also noted by Bowler et al. (2017b), this reduces the inferred strength of the He\textsubscript{ii} emission: \( EW_0 = 40 \pm 30 \; \text{Å} \) compared to the original value in Sobral et al. (2015b) of \( EW_0 \approx 80 \; \text{Å} \). A lower He\textsubscript{ii} EW requires less exotic ionising populations and can plausibly be explained by a normal faint AGN or a low metallicity, \( \alpha \)-enhanced binary stellar population. These results are consistent with our updated analysis from Sobral, Matthee et al. (submitted) and with the He\textsubscript{ii} EW presented in this Chapter.

As the PSF-FWHM of the Spitzer/IRAC data are considerably larger than the \( HST/WFC3 \) F110W and F160W data\footnote{The mean FWHM of the IRAC [3.6] and [4.5] images are 1.95" and 2.02", mapped on a pixel scale of 1.2". The FWHM of \( HST/WFC3 \) images are \( \approx 0.13 " \) around 1200 nm, mapped on a 0.123" pixel scale.}, the individual components of CR7, separated by \( \approx 1" \), are significantly blended in the IRAC images. It is therefore challenging to measure the IRAC fluxes of the individual components. Typically, high-redshift studies use deblending techniques based on detailed knowledge of the IRAC PSF and a higher resolution image (e.g. Labb\`e et al., 2015), typically...
4.B. Comparison to Bowler et al. (2017b)

from HST. A caveat of this technique is that it adopts that there are no strong
colour gradients, as it assumes that the IRAC morphology is the same as the
HST/WFC3 morphology. In practice, for a galaxy at $z = 6.6$, this means that
the technique adopts no color gradients between $\lambda_0 \approx 1500$ Å and $\lambda_0 \approx 4500 –
6000$ Å. Therefore, this may not be the case if there is a strong Balmer break
around 4000 Å due to an older stellar population or if there is differential dust
attenuation.

Bowler et al. (2017b) applies such deconvolution technique to measure the
IRAC fluxes for each of the three UV components of CR7 separately. They use
the HST/WFC3 images as a high resolution prior and find that the majority
of the flux in the [3.6] and [4.5] bands is associated to component A, that is
the brightest in the UV. The [3.6]-[4.5] color is very blue ($-1.20^{+0.29}_{-0.32}$), which
indicates strong Hβ+[OIII] line emission at the position of component A. Due
to their faintness, the IRAC colours of the fainter UV components are poorly
constrained. These measurements led Bowler et al. (2017b) to conclude that
strong oxygen emission is present in component A from CR7, refuting an ex-
treme ‘PopIII’ explanation. They also conclude that the majority of stellar mass
is present in component A, contrarily to Sobral et al. (2015b) and Agarwal et al.
(2016) who speculate/argue the majority of stellar mass resides in components
B and C. Having a large fraction of the stellar mass outside the brightest UV
component is a requirement for the direct collapse black hole scenario. There-
fore, Bowler et al. (2017b) also rule out the direct collapse black hole scenario,
and their most likely explanation of the nature of CR7 is a ‘normal’, faint AGN.

While the presence of a blue IRAC colour and hence Hβ+[OIII] line emission
in CR7 had also been noted (but not quantified) in Matthee et al. (2015), the
main difference from the Bowler et al. (2017b) analysis with the Sobral et al.
(2015b) analysis is that IRAC measurements are performed with deconvolution
techniques and that SED fitting was performed on a component-by-component
basis. In the main text of this Chapter and in Sobral et al. (2015b), the SED fitting
was performed using blended ground based NIR and IRAC photometry, without
using HST photometry. As discussed in the main text, a dual-component fit was
required to simultaneously match the NIR and the IRAC photometry, leading
to the assumption that the majority of mass did not coincide with the peak UV
brightness. HST photometry was consistent with these fits, providing further
confidence in their validity.

As discussed above, the method used in Bowler et al. (2017b) assumes that
the three UV components have similar colours between $\approx 1500 – 5000$ Å. With-
out higher resolution MIR imaging (possible with JWST), this can currently not
be tested. On the other hand, the ALMA measurements (Matthee et al. 2017e
and Chapter 5) show that the highest dynamical mass within CR7 is co-located
with component A. This is consistent with the result from Bowler et al. (2017b)
and indicates that CR7 is an ongoing merger with several components whose
light is dominated by ‘normal’ stellar populations. However, ALMA also re-
veals a [CII] emitting component that is not detected in the UV, but with similar
dynamical mass as component A. This component is located between the three
UV components of CR7 and could contribute to the IRAC photometry, but this
remains to be evaluated.


Shibuya et al. (2018) independently reduced and analysed the X-SHOOTER spectrum of CR7. While they confirm the Lyα line, the authors do not find an emission line at > 2σ significance in the NIR spectrum. They measure a detection significance of < 1σ at λ = 1640 Å in the full stack, ruling out the HeII line as presented in Sobral et al. (2015b). They conclude no HeII is observed in CR7.

A detailed comparison to the analysis of Shibuya et al. (2018) is challenging, as they do not specify over which spatial positions their 1D spectrum was extracted and whether their spectrum is converted to vacuum wavelength. Since we find that the centroid of the tentative line is slightly off-centred, the 1D spectrum of Shibuya et al. (2018) may miss part of the flux. Based on private communication with the authors and visual inspection of their Figure 8, it is clear that Shibuya et al. (2018) compare their data (reduced with correct wavelength calibration files) with those from Sobral et al. (2015b) that had been reduced with the wrong wavelength solution. Therefore, their measurement of < 1σ significance at the position of HeII had been performed at a different wavelength.

As noted in Shibuya et al. (2018) and as is visible in their Figure 8, they find tentative flux at a slightly redder wavelength – similar to the wavelength where we identify the tentative the HeII line in the updated analysis in this Chapter. They measure that this flux is at the 1.8σ level, but (as they also note) this tentative line is contaminated by a nearby skyline (see also Fig. 4.4), in particular because they smooth in the wavelength direction. It is unclear how this affects their measured significance. Finally, as discussed in §4.3.3, we found in our revised analysis that the flux originates predominantly from a single observing block, such that its measured significance would increase if only this OB had been used.

Therefore, while the analysis of Shibuya et al. (2018) motivated us to revisit our own analysis, point out the inaccuracies in the wavelength calibrations and explore the origins of the tentative signal, we conclude too few details are given in Shibuya et al. (2018) to fully assess the differences between the analyses. While we agree that the significance may not be as high as initially presented, we leave it to the reader to conclude whether a line is ‘detected’. Importantly, further observations that carefully take into account potential spatial variations of the spectrum are clearly required. Note that, compared to other studies in the literature, the ≈ 3 hours of VLT/X-SHOOTER time invested in the CR7 observations have been very modest. For example, Zabl et al. (2015) observed Himiko with X-SHOOTER for 10 hours, Laporte et al. (2017b) observed three z ∼ 7 galaxies for 11-12 hours each and Vanzella et al. (2014) did not detect a z ∼ 7 galaxy candidate combining 52 hours of integration time with VLT/FORS-2 from multiple programs.