A DEEP NARROWBAND IMAGING SEARCH FOR C IV AND He II EMISSION FROM Lyα BLOBS*

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ABSTRACT

We conduct a deep narrowband imaging survey of 13 Lyα blobs (LABs) located in the SSA22 proto-cluster at $z \sim 3.1$ in the C iv and He ii emission lines in an effort to constrain the physical process powering the Lyα emission in LABs. Our observations probe down to unprecedented surface brightness (SB) limits of $(2.1-3.4) \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ per 1 arcsec$^2$ aperture (5σ) for the He ii λ1640 and C iv λ1549 lines, respectively. We do not detect extended He ii and C iv emission in any of the LABs, placing strong upper limits on the He ii/Lyα and C iv/Lyα line ratios, of 0.11 and 0.16, for the brightest two LABs in the field. We conduct detailed photoionization modeling of the expected line ratios and find that, although our data constitute the deepest ever observations of these lines, they are still not deep enough to rule out a scenario where the Lyα emission is powered by the ionizing radiation from an obscured active galactic nucleus. Our models can accommodate He ii/Lyα and C iv/Lyα ratios as low as $\lesssim 0.05$ and $\lesssim 0.07$, respectively, implying that one needs to reach SB as low as $(1-1.5) \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ (at 5σ) in order to rule out a photoionization scenario. These depths will be achievable with the new generation of image-slicing integral field units such as the Multi Unit Spectroscopic Explorer (MUSE) on VLT and the Keck Cosmic Web Imager (KCWI). We also model the expected He ii/Lyα and C iv/Lyα in a different scenario, where Lyα emission is powered by shocks generated in a large-scale superwind, but find that our observational constraints can only be met for shock velocities $v_s \gtrsim 250$ km s$^{-1}$, which appear to be in conflict with recent observations of quiescent kinematics in LABs.

Key words: galaxies: formation – galaxies: high-redshift – intergalactic medium

1. INTRODUCTION

In the current ΛCDM paradigm of structure formation, gas collapses onto the potential wells of dark matter halos, and whether it shock heats to the halo virial temperature and cools slowly or flows in preferentially along cold filamentary streams (Dekel et al. 2009), its gravitational energy is eventually radiated away, as it settles into galactic disks and forms stars. This star formation results in the growth of galactic bulges, and in the innermost regions, the gas could also accrete onto a supermassive black hole powering an active galactic nucleus (AGN). Many have theorized (e.g., Silk & Rees 1998; Fabian 1999; King 2003) that star formation and/or BH accretion could be self-regulating, such that “feedback” processes inject energy back into the interstellar medium (ISM), heating the gas, and preventing further star formation or accretion.

The complex interplay of gas accreted from the intergalactic medium (IGM) and the galactic outflows, which may be the signatures of mechanical/radiative feedback, are poorly understood, particularly at high redshift, where the feedback, processes are often invoked as being most intense. These processes conspire to determine the structure of the circumgalactic medium (CGM), which comprises the intergalactic gas and the IGM. At high redshift, the CGM has been extensively studied by analyzing absorption features in the spectra of background sources. A significant amount of effort has been devoted to the study of the CGM of the so-called LBGs, star-forming galaxies at $z \sim 2$ (Adelberger et al. 2005; Steidel et al. 2010; Crighton et al. 2011, 2013, 2015; Rakic et al. 2012; Rudie et al. 2012). These studies have illustrated that typical star-forming galaxies exhibit a modest $\sim 20\%$ covering factor of optically thick neutral hydrogen (Rudie et al. 2012) and enrichment levels ranging from extremely metal-poor (Crighton et al. 2013) to nearly solar (Crighton et al. 2015). On the other hand, using projected QSO pairs, Hennawi et al. (2006) launched an innovative technique to study the properties of the gas on scales of a few tens of kpc to several Mpc of the much more massive dark matter halos traced by quasars, initiating the Quasars Probing Quasars survey (Hennawi & Prochaska 2007; Prochaska & Hennawi 2009; Hennawi & Prochaska 2013; Prochaska et al. 2013a, 2013b). These studies have revealed a massive ($\gtrsim 10^{10} M_\odot$) reservoir of cool ($T \sim 10^4$ K) gas in the CGM of massive halos (see also Bowen et al. 2006; Farina et al. 2013), which appears to be in conflict with the predictions of hydrodynamical zoom-in simulations of galaxy formation (Fumagalli et al. 2014).

These absorption studies are, however, limited by the paucity of bright background sources and by the inherently one-dimensional nature of the technique. Complementary information can be obtained by directly observing the CGM in emission,
and this emission may be easier to detect in AGN environments. In particular, if an AGN illuminates the cool CGM gas around it, the reprocessed emission (fluorescence) from this cool medium could be detectable as extended Lyα emission (e.g., Rees 1988; Haiman & Rees 2001). Indeed, many searches for emission from the CGM of QSOs have been undertaken, reporting detections on scales of 10–50 kpc around z ~ 2–4 QSOs (e.g., Hu & Cowie 1987; Heckman et al. 1991a, 1991b; Christensen et al. 2006; North et al. 2012). Recently Cantalupo et al. (2014) reported the discovery of an extraordinary extended (~500 kpc) Lyα nebula around the radio-quiet QSO UM287, believed to be fluorescent emission powered by the QSO radiation. This discovery is part of a large homogenous survey of emission from the CGM of quasars that will enable statistical studies of this phenomenon (e.g., Arrigoni Battaia et al. 2013).

Extended Lyα nebulae have also been frequently observed around high-redshift (z ≥ 2) radio galaxies (high-z radio galaxies [HzRGs]; e.g., McCarthy 1993; van Ojik et al. 1997; Nesvadba et al. 2006; Reuland et al. 2007; Villar-Martín et al. 2007). With an average Lyα luminosity of $L_{\text{Ly}\alpha} \sim 10^{44.5}$ erg s$^{-1}$ and a diameter $\gtrsim 100$ kpc, these nebulae tend to be brighter and larger than those around QSOs, although current surveys are very inhomogeneous. But an important difference between these two types of nebulae is that for quasars a strong source of ionizing photons is directly identified, whereas for the HzRGs this AGN is obscured from our perspective (see, e.g., Miley & De Breuck 2008), in accord with unified models of AGNs (e.g., Antonucci 1993; Urry & Padovani 1995; Elvis 2000). Further, the study of the properties of the gas surrounding HzRGs has to take into account the impact of the complicated interaction between the strong radio jets and the ambient gas.

Intriguingly, the so-called Lyα blobs (LABs), large (50–100 kpc), luminous ($L_{\text{Ly}\alpha} \sim 10^{43–44}$ erg s$^{-1}$) Lyα nebulae at z ~ 2–6, exhibit properties similar to Lyα nebulae around QSOs and HzRGs, but without obvious evidence for the presence of an AGN (e.g., Keel et al. 1999; Steidel et al. 2000; Francis et al. 2001; Matsuura et al. 2004, 2011; Dey et al. 2005; Saito et al. 2006; Smith & Jarvis 2007; Ouchi et al. 2009; Prescott et al. 2009, 2012; Yang et al. 2009, 2010). LABs are believed to be the sites of massive galaxy formation, where strong feedback processes may be expected to occur (Yang et al. 2010). However, despite intense interest and multi-wavelength studies, the physical mechanism powering the Lyα emission in the LABs is still poorly understood. The proposed scenarios include photoionization by AGNs (Geach et al. 2009), shock-heated gas by galactic superwinds (Taniuchi & Shioya 2000), cooling radiation from cold-mode accretion (Haiman et al. 2000; Fardal et al. 2001; Dijkstra & Loeb 2009; Faucher-Giguère et al. 2010; Goerdt et al. 2010), and resonant scattering of Lyα from star-forming galaxies (Hayes et al. 2011; Steidel et al. 2011).

Our ignorance of the physical process powering the emission in LABs likely results from the current lack of other emission-line diagnostics besides the strong Lyα line (e.g., Matsuda et al. 2006). In this paper, we attempt to remedy this problem, by searching for emission in two additional rest-frame UV lines, namely, C IV $\lambda 1549$ and He II $\lambda 1640$. We present deep narrowband imaging observations tuned to the C IV $\lambda 1549$ and He II $\lambda 1640$ emission lines of 13 LABs at z ~ 3.1 in the well-known SSA22 proto-cluster field (Steidel et al. 2000; Hayashino et al. 2004; Matsuda et al. 2004). Our observations exploit a fortuitous match between two narrowband filters on VLT/FORS2 and the wavelengths of the redshifted C IV and He II emission lines of a dramatic overdensity of LABs (and Lyα emitters, LAEs) in the SSA22 field (Matsuuda et al. 2004; Figure 1) and achieve unprecedented depth. This overdensity results in a large multiplexing factor, allowing us to carry out a sensitive census of C IV/Lyα and He II/Lyα line ratios for a statistical sample of LABs in a single pointing.

In the following, we review four mechanisms that have been proposed to power the LABs, which could also possibly act together, and discuss how they might generate C IV and He II line emission.

1. Photoionization by a central AGN: As stressed above, it is well established that the ionizing radiation from a central AGN can power giant Lyα nebulae, with sizes up to ~200 kpc, around HzRGs (e.g., Villar-Martín et al. 2003b; Reuland et al. 2003; Venemans et al. 2007) and quasars (e.g., Heckman et al. 1991b; Christensen et al. 2006; Smith et al. 2009; Cantalupo et al. 2014). If the halo gas is already polluted with heavier elements (e.g., C, O) by outflows from the central source, one expects to detect both C IV and He II emission from the extended Lyα-emitting gas. If not, only extended He II emission is expected. Indeed, extended C IV and He II emission have been clearly detected in HzRGs (Villar-Martín et al. 2003a; Humphrey et al. 2006; Villar-Martín et al. 2007) and tentatively detected around QSOs (Heckman et al. 1991a, 1991b; Humphrey et al. 2013) on scales of 10–100 kpc. The photoionization scenario gains credence from a number of studies suggesting that LABs host an AGN that is obscured from our perspective (Geach et al. 2009; Overzier et al. 2013; Yang et al. 2014a; but see Nilsson et al. 2006; Smith & Jarvis 2007).

2. Shocks powered by galactic-scale outflows: Several studies have argued that shell-like or filamentary morphologies, large Lyα line widths (~1000 km s$^{-1}$), and enormous Lyα sizes (~100 kpc) imply that extreme galactic-scale outflows, and specifically the ionizing photons produced by strong shocks, power the LABs (Taniuchi & Shioya 2000; Taniuchi et al. 2001; Ohyama et al. 2003; Wilman et al. 2005; Mori & Umemura 2006). If violent star formation feedback powers a large-scale superwind, the halo should be highly enriched, and with a significant amount of gas at T ~ $10^5$ K. One would therefore also expect to detect extended He II and C IV emission, but with potentially different line ratios than the simple photoionization case. Note that collisional excitations of singly ionized helium peak at T ~ $10^5$ K, making the He II line one of the dominant observable coolants at this temperature (Yang et al. 2006). Note, however, that the relatively quiescent ISM kinematics of star-forming galaxies embedded within LABs appear to be at odds with this scenario (Yang et al. 2011; McClinden et al. 2013; Yang et al. 2014b).

3. Gravitational cooling radiation: A large body of theoretical work has suggested that Lyα emission nebulae could result from Lyα cooling radiation powered by gravitational collapse (Haiman et al. 2000; Furlanetto et al. 2005; Dijkstra et al. 2006; Faucher-Giguère...
et al. 2010; Rosdahl & Blaizot 2012). In the absence of significant metal enrichment, collisionally excited Lyα is the primary coolant of $T \sim 10^4$ K gas; hence, cool gas steadily accreting onto halos hosting LABs may radiate away their gravitational potential energy in the Lyα line. However, the predictions of the Lyα emission from these studies are uncertain by orders of magnitude (e.g., Furlanetto et al. 2005; Faucher-Giguère et al. 2010; Rosdahl & Blaizot 2012) because the emissivity of collisionally excited Lyα is exponentially sensitive to gas temperature. Accurate prediction of the temperature requires solving a coupled radiative transfer and hydrodynamics problem, which is not currently computationally feasible (but see Rosdahl & Blaizot 2012). While Yang et al. (2006) suggest that the He II cooling emission could be as high as 10% of Lyα near the embedded galaxies (i.e., point-source emission) where the density of IGM/CGM is highest, the extended ($\gtrsim 20$ kpc) He II emission may be challenging to detect with current facilities (He II/Lyα < 0.1). Note that if Lyα emission arises from cooling radiation of pristine gas, no extended C IV emission is expected.

4. Resonant scattering of Lyα from embedded sources: In this scenario, Lyα photons are produced in star-forming galaxies or AGNs embedded in the LABs, but the extended sizes of the Lyα halos result from resonant scattering of Lyα photons as they propagate outward (Dijkstra & Loeb 2008; Hayes et al. 2011; Cen & Zheng 2013; Cantalupo et al. 2014). In this picture, non-resonant He II emission (if produced in the galaxies or AGNs) should be compact, in contrast with the extended Lyα halos. In other words, if extended He II is detected on the same scale as the extended Lyα emission, this implies that resonant scattering does not play a significant role in determining the extent of the Lyα nebulae. Conversely, as the C IV line is a resonant line, it is conceivable that a contribution to its extended emission, if present, could arise due to scattering by the same medium scattering Lyα, provided that the halo gas is optically thick to C IV, which in turn depends on the metallicity and ionization state of the halo gas. In this context, it is interesting to note that Prochaska et al. (2014) find a high covering factor of optically thick C II and C IV absorption line systems out to >200 kpc around $z \sim 2$ QSOs, implying that the CGM of massive halos is significantly enriched.

In summary, a detection of extended emission in the C IV line will provide us information on the intensity and hardness of an ionizing source or the speed of shocks in a superwind (e.g., Ferland et al. 1984; Nagao et al. 2006; Allen et al. 2008), the metallicity of gas in the CGM of LABs, and the sizes of metal-enriched halos. A detection of extended (non-resonant) He II emission similarly constrains the ionizing spectrum or the speed of shocks and can be used to test whether Lyα photons are resonantly scattered, as well as constrain the amount of material in a warm $T \sim 10^4$ K phase. To date, there are five detections of extended C IV and He II emission from LABs reported in the literature (Dey et al. 2005; Prescott et al. 2009, 2013). The extended C IV and He II emission from these Lyα nebulae has fluxes up to $F_{C IV} \sim 4 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ and $F_{He II} \sim 6 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$, implying C IV/Lyα $\lesssim 0.13$ and He II/Lyα $\lesssim 0.13$. Publication bias, i.e., the fact that searches for these lines that resulted in non-detections are likely to have gone unpublished, makes it challenging to assess the rate of detections in LABs, which is one of the goals of the present work.

This paper is organized as follows. In Section 2, we describe our VLT/FORS2 narrowband imaging observations, the data reduction procedures, and the surface brightness (SB) limits of our images. In Section 3, we present our measurements for C IV and He II lines. Section 4 describes previous measurements for C IV and He II in the literature. In Section 5, we discuss photoionization models and shock models for LABs and compare them with our observations and other sources in the literature. Section 6 summarizes our conclusions. Throughout this paper, we adopt the cosmological parameters $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$. In this cosmology, $1''$ corresponds to 7.6 physical kpc at $z = 3.1$. All magnitudes are in the AB system (Oke 1974).

2. OBSERVATIONS AND DATA REDUCTION

2.1. VLT/FORS2 Observations and Data Reduction

We obtained deep C IV and He II narrowband images of 13 LABs in the SSA22 proto-cluster field, including the two largest LABs that were originally discovered by Steidel et al. (2000). Data were taken in service-mode using the FORS2 instrument on the VLT 8.2 m telescope Antu (UT1) on 2010 August, September, October and 2011 September over 25 nights. We used two narrowband filters, O4/2500+57 and S6+62 matching the redshifted C IV $\lambda 1549$ and He II $\lambda 1640$ at $z = 3.1$, respectively. The O4/2500+57 filter has a central wavelength of $\lambda_c \approx 6354$ Å and has an FWHM of $\Delta \lambda_{FWHM} \approx 59$ Å, while the S6+62 filter has $\lambda_c \approx 6714$ Å and $\Delta \lambda_{FWHM} \approx 69$ Å (Figure 1). These bandwidths provide a line-of-sight depth of $\Delta z \approx 0.038$ and $\Delta z \approx 0.042$, respectively for the O4/2500+57 and S6+62 filter. Thus, given the typical uncertainties in the redshift measurements for the LABs (e.g., $\Delta z_{LAB1} = 3.097 \pm 0.002$, Ohyama et al. 2003; $\Delta z_{LAB2} = 3.103 \pm 0.002$, Matsuda et al. 2005) and the good agreement between the central wavelengths of the three narrowband filters used in this work (see Figure 1), we are confident that, if present, the C IV and He II lines would fall within the targeted wavelength ranges. Note that very large velocity offsets (>2000 km s$^{-1}$) with respect to the Lyα line would thus be required to bring the C IV or He II line outside our set of narrowband filters. Such large kinematic offsets are not expected in these systems (e.g., Prescott et al. 2015).

The FORS2 has a pixel scale of 0''25 pixel$^{-1}$ and a field of view (FOV) of $7' \times 7'$ that allow us to observe a total of 13 LABs in a single pointing. The pointing was chosen to maximize the number of LABs while including the two brightest LABs, LAB1 and LAB2 (Steidel et al. 2000). We show the spatial distribution of ~300 LAEs and 35 LABs in the SSA22 region and mark the LABs within FORS2 narrowband images in Figure 2.

The total exposure time was 19.9 and 19.0 hr for C IV and He II lines, respectively. These exposures consist of 71 and 68 individual exposures of ~17 minutes, taken with a dither pattern to fill in a gap between the two chips, and to facilitate the removal of cosmic rays. Because our targets are extended over 5''-17'' diameter and our primary goal is to detect the extended features rather than compact embedded galaxies, we carried out our observations under any seeing conditions.
Comoving distance probed. Note the nearly perfect match between the narrowband filter and the SII+62 and OI/2500+57 (Matsuda et al. 2004). The images were bias-subtracted and sky subtracted using a background mesh size of 64 × 64 pixels, then projected onto a common WCS using a Lanczos3 interpolation kernel, and average-combined with weights proportional to flat and night-sky flat images. Note that we choose the mesh size to be large enough to ensure that we do not mistakenly subtract any extended emission as sky background. For flux calibration, we use four spectrophotometric standard stars (Beige 110, EG 274, LDS 749B, and G158-100) that were repeatedly observed during our observations. Typical uncertainties in the derived zero points are ≈0.03 mag.

2.2. Subaru Suprime-cam Data

To subtract continuum from our narrowband images and compare the C IV and He II line fluxes with those of Ly α, we rely on previous Subaru observations. The SSA22 field has been extensively observed in B, V, R, I', and NB 497 bands (Hayashino et al. 2004; Matsuda et al. 2004) with the Subaru Suprime-Cam (Miyazaki et al. 2002). These images have a pixel scale of 0′′20 and an FOV of 34′ × 27′. The NB 497 narrowband filter, tuned to the Ly α line at z ~ 3.1, has a central wavelength of 4977 Å and an FWHM of 77 Å. The total exposure time for the Ly α narrowband image was 7.2 hr, with a 5σ sensitivity of 5.5 × 10^-18 erg s^{-1} cm^{-2} arcsec^{-2} per 1 arcsec^2 aperture, which is roughly 1.5–2.5 times shallower than those of FORS2 He II and C IV images. In Table 1, we summarize the Subaru broadband and narrowband images that were used in this work.

Figure 1. Top panel: filter response profiles for the narrowband filters NB 497 (green), SII+62, and OI/2500+57 (blue) and the broadband filters V (orange), R (red), and i (brown) overplotted on a composite radio galaxy spectrum (McCarthy 1993). Bottom panels: Comparison between the NB 497 (green) and the SII+62 and OI/2500+57 (dashed blue) filters shifted to match the narrowband filter used for Ly α (Matsuda et al. 2004). The filter curves are here normalized to their peak value and plotted with respect to the velocity and comoving distance probed. Note the nearly perfect match between the Ly α narrowband filter and the two FORS2 narrowband filters used for C IV λ1549 and He II λ1660 in this work.

Figure 2. Spatial distribution of the Ly α emitters (black filled circles) and Ly α blobs (blue squares) in the SSA22 proto-cluster (Hayashino et al. 2004; Matsuda et al. 2004). The red box is the FOV of our FORS2 imaging (7′ × 7′), which includes 13 LABs (blue filled squares). The green dashed line indicates the high-density region traced by the Ly α emitters.
Using these deep Subaru data, Matsuda et al. (2004) found 35 LABs, defined to be Lyα emitters with the observed EW (Lyα) > 80 Å and an isophotal area larger than 16 arcsec², which corresponds to a spatial extent of 30 kpc at z = 3. The isophotal area was measured above the 2σ SB limit (2.2 × 10⁻¹⁸ erg s⁻¹ cm⁻² arcsec⁻²). In Table 2, we list the properties (e.g., Lyα luminosity and isophotal area) of the 13 LABs that were observed with VLT/FORS2. We refer readers to Matsuda et al. (2004) for more details of this LAB sample.

Table 1: VLT FORS2 Observations and Subaru Data

| Telescope | Instrument | Filter (Target Line) | λ_central | Δλ_FWHM | Seeing | Exp. Time | Depth | Pixel Scale |
|-----------|------------|----------------------|-----------|---------|---------|-----------|-------|-------------|
| VLT       | FORS2      | OⅡ/2500+57 (CⅣ)    | 6354      | 59      | 0.8     | 19.9      | 25.9  | 0.25        |
| VLT       | FORS2      | SⅡ+62 (HeⅡ)        | 6714      | 69      | 0.8     | 19.0      | 26.5  | 0.25        |
| Subaru‡   | S-Cam      | NB 497 (Lyα)        | 4977      | 77      | 1.0     | 7.2       | 26.2  | 0.20        |
| Subaru‡   | S-Cam      | R                    | 6460      | 1177    | 1.0     | 2.9       | 26.7  | 0.20        |

‡ Central wavelength of the filter.

Table 2: Properties of the 13 LABs in Our Sample

| Object | F(Lyα) | L(Lyα) | Area | SB (Lyα) | SB (CⅣ) | SB (HeⅡ) | CⅣ/Lyα | HeⅡ/Lyα |
|--------|--------|--------|------|----------|----------|-----------|--------|---------|
| LAB1   | 9.4    | 7.8    | 200  | 4.7      | <0.74    | <0.50     | <0.16  | <0.11   |
| LAB2   | 8.2    | 6.8    | 145  | 5.6      | <0.89    | <0.63     | <0.16  | <0.11   |
| LAB7   | 1.3    | 1.1    | 36   | 3.6      | <1.19    | <0.99     | <0.33  | <0.27   |
| LAB8   | 1.5    | 1.3    | 36   | 4.2      | <1.24    | <0.93     | <0.29  | <0.22   |
| LAB11  | 0.8    | 0.6    | 28   | 2.8      | <1.23    | <1.08     | <0.44  | <0.38   |
| LAB12  | 0.7    | 0.6    | 27   | 2.7      | <1.29    | <1.06     | <0.48  | <0.39   |
| LAB14  | 1.1    | 0.9    | 25   | 4.5      | <1.38    | <1.10     | <0.31  | <0.24   |
| LAB16  | 1.0    | 0.9    | 25   | 4.1      | <1.39    | <1.07     | <0.34  | <0.26   |
| LAB20  | 0.6    | 0.5    | 22   | 2.8      | <1.35    | <1.16     | <0.48  | <0.41   |
| LAB25  | 0.6    | 0.5    | 22   | 2.7      | <1.36    | <1.12     | <0.50  | <0.41   |
| LAB30  | 0.9    | 0.8    | 17   | 5.8      | <1.45    | <1.36     | <0.25  | <0.23   |
| LAB31  | 1.2    | 1.0    | 19   | 6.6      | <1.44    | <1.18     | <0.22  | <0.18   |
| LAB35  | 1.0    | 0.8    | 17   | 5.9      | <1.52    | <1.29     | <0.26  | <0.22   |

Note. (1) Lyα line flux within the isophote in 10⁻¹⁶ erg s⁻¹ cm⁻², (2) Lyα luminosity in 10⁴¹ erg s⁻¹, (3) isophotal area in arcseconds² above 2.2 × 10⁻¹⁸ erg s⁻¹ cm⁻² arcsec⁻², (4) average surface brightness within the isophote, (5) 5σ upper limits on CⅣ surface brightness, (6) 5σ upper limits on HeⅡ surface brightness, (7–8) 5σ upper limits CⅣ/Lyα and HeⅡ/Lyα line ratios. All surface brightnesses are given in unit of 10⁻¹⁸ erg s⁻¹ cm⁻² arcsec⁻².

Figure 3. (a) Distribution of seeings for the OⅡ/2500 + 57 (CⅣ λ1549) images. (b) Same for the SⅡ+62 (HeⅡ λ1640) images. The black dashed lines indicate the cumulative distribution. The median seeing is ~0″8 for both CⅣ and HeⅡ images.
2.3. Continuum Subtraction

To identify the emission in the C\textsc{iv} $\lambda 1549$ and He\textsc{ii} $\lambda 1640$ lines, we subtract the continuum emission underlying the $60/2500+57$ and $5a+62$ filter. We estimate the continuum using the deep Subaru $R$-band image. Because the Subaru and FORS2 images have different pixel scales, we resample the $R$-band images to the FORS2 pixel scale and register them to our WCS in order to compare all the images pixel by pixel. We do not match the point-spread functions (PSFs) given that FORS2 images were obtained with a wide range of seeing, and we are mostly interested in the extended emission. We produce the continuum-subtracted image for each filter (C\textsc{iv} and He\textsc{ii}) using the following relations (Yang et al. 2009):

$$f_{\text{BB}} = \frac{F_{\text{BB}} - F_{\text{NB}}}{\Delta \lambda_{\text{BB}} - \Delta \lambda_{\text{NB}}}$$

$$F_{\text{line}} = F_{\text{NB}} - f_{\text{BB}} \Delta \lambda_{\text{BB}}$$

where $F_{\text{BB}}$ is the flux in the $R$ band and $F_{\text{NB}}$ is the flux in one of the narrowband filters. $\Delta \lambda_{\text{BB}}$ and $\Delta \lambda_{\text{NB}}$ represent the FWHM of the $R$ and narrowband filters, respectively. $f_{\text{BB}}$ is the flux density of the continuum within the $R$ band, and $F_{\text{line}}$ is the line flux (C\textsc{iv} or He\textsc{ii}).

Note that the $R$-band image includes both the C\textsc{iv} and He\textsc{ii} lines, but here we adopt a simple approximation assuming that one emission line within the $R$ band (e.g., He\textsc{ii}) is negligible in estimating the flux of the other emission line (e.g., C\textsc{iv}). For example, we would underestimate the line flux of C\textsc{iv} by $>10\%$ if the flux in He\textsc{ii} were $F_{\text{line}} \gtrsim 2 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$, which is easily detectable in our deep images. We are using these simple equations because we aim to minimize the systemic effects such as poor PSF matching and imperfect sky subtraction. Note that we have also tried the continuum subtraction with two off-band images ($V$ and $i$), as explained in Section 2.4.

2.4. Surface Brightness Limits

We compute a global SB limit for detecting He\textsc{ii} and C\textsc{iv} lines using a global rms of the images. To calculate the global rms per pixel, we first mask out the sources, in particular the scattered light and halos of bright foreground stars, and compute the standard deviation of sky regions using a sigma-clipping algorithm. We convert these rms values into the SB limits per 1 arcsec$^2$ aperture. We find that the 1$\sigma$ detection limit per 1 arcsec$^2$ aperture ($S_{\text{BB}}$) is $4.2 \times 10^{-19}$ and $6.8 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ for He\textsc{ii} and C\textsc{iv}, respectively. These represent the deepest He\textsc{ii} $\lambda 1640$ and C\textsc{iv} $\lambda 1549$ narrowband images ever taken.

The sensitivity required to detect an extended source depends on its size because one can reach lower SB levels by spatially averaging. In an ideal case of perfect sky and continuum subtraction, the 1$\sigma$ SB limit for an extended source is given by $S_{\text{BB}}/(\sqrt{A_{\text{arcsec}}})$, where $A_{\text{arcsec}}$ is the isophotal area in arcsec$^2$ and $S_{\text{BB}}$ is the SB limit per 1 arcsec$^2$ aperture. However, in practice the actual detection limits are limited by systematics resulting from imperfect sky and continuum subtraction. Therefore, we empirically determine the detection limits for extended sources with different sizes as follows.

In the continuum-subtracted line images, we mask all the artifacts (e.g., CCD edges and scattered light from bright stars) and also the locations of the LABs. For each LAB that we consider, we randomly place circular apertures with the same area of the LAB and extract the fluxes ($F_{\text{src}}$) within these apertures. If the images have uniform noise properties in the absence of systematics, the fluxes ($F_{\text{src}}$) from many random apertures should follow a Gaussian distribution with a width of $\sigma_{\text{src}} = S_{\text{BB}}/\sqrt{A_{\text{arcsec}}}$ and the actual Gaussian width ($\sigma_{\text{src}}$) of the distribution is much broader than $\sigma_{\text{src}}$ (Figures 4 and 5). We adopt $F_{\text{lim}} = \sigma_{\text{src}}$ as a 1$\sigma$ upper limit on the total line flux of each LAB. The corresponding upper limit for the SB is given by $S_{\text{BB}}$.

Figures 4 and 5 show the distribution of $F_{\text{src}}/\sigma_{\text{src}}$ for He\textsc{ii} and C\textsc{iv} images, respectively. Note that we normalize the extracted fluxes to the $\sigma_{\text{src}}$ in order to show the distributions for LABs with similar sizes in one plot. As the size of the LABs in our sample spans a large range, we show the distributions for two sub-samples: one for LAB1 and LAB2 with $A_{\text{src}} > 100$ arcsec$^2$ and the other for the remaining LABs with $A_{\text{src}} < 40$ arcsec$^2$. As previously stated, in the ideal case of no systematics, $\sigma_{\text{src}}$ characterizes the noise in $F_{\text{src}}$, and thus the distribution of the quantity $F_{\text{src}}/\sigma_{\text{src}}$ should be a Gaussian with unit variance. For both sub-samples, we find that $F_{\text{src}}/\sigma_{\text{src}}$ histograms show a variance greater than unity, suggesting that imperfect sky and continuum subtraction dominates our error budget. The normalized histograms have a standard deviation of $\approx 3$ on the scale of the bigger LABs (LAB1 and LAB2) and $\approx 2$ on the scale of the smaller LABs. Thus, as our 1$\sigma$ limit on the total line flux of the largest LABs in our sample (LAB1 and LAB2), we adopt $F_{\text{lim}} = \sigma_{\text{src}} = 3\sigma_{\text{src}}$, where $\sigma_{\text{src}} = S_{\text{BB}}/(\sqrt{A_{\text{arcsec}}})$ is computed using the area of the blob. For all of the other blobs in our sample, we follow the same approach but use a value $F_{\text{lim}} = \sigma_{\text{src}} = 2\sigma_{\text{src}}$. We conservatively define our detection threshold to be $5\sigma_{\text{src}}$, which formally means $15\sigma_{\text{src}}$ for LAB1 and LAB2 and $10\sigma_{\text{src}}$ for all the other blobs. In each histogram, we show the values extracted inside the isophotal contours of each LAB (black arrows). These values are well within the distribution of $F_{\text{src}}/\sigma_{\text{src}}$ determined from random apertures (see Table 3).

To test if our derived detection limits are reasonable, we visually confirm the detectability as a function of size by placing artificial model sources in He\textsc{ii} and C\textsc{iv} narrowband images. We adopt circular top-hat sources with a uniform SB corresponding to 1, 2, 3, 4, 5, 8, 10, 20 $S_{\text{BB}}$ limit and an area of 200, 100, 40 and 20 arcsec$^2$, comparable to the size of the LABs in our sample (see Table 2). After placing the simulated sources in the narrowband images, we subtract the continuum in the same way as explained in Section 2.3. Because the detectability strongly depends on the residual structure of the continuum subtraction, we place the model sources at different locations in the narrowband images after masking all the bad regions as explained above. Following Hennawi & Prochaska (2013), we construct a $\chi$ image by dividing the continuum-subtracted image by a “sigma” image. Here, the sigma image (or the square root of the variance image) is calculated by taking into account our stacking procedure, e.g., bad pixels, satellite trails, and sky subtraction. In other words, this variance image is the theoretical photon counting noise variance, taking into account all the bad-behaving pixels. In this calculation, we do not include the variance due to $R$-band continuum, i.e., we ignore the photon counting noise from $R$-band image; thus, it is likely that our sigma image might slightly underestimate the noise. Note, however, that the shallower NB images are very...
likely dominating the noise; thus, the $R$-band contribution to the variance is a small correction.

To test the detectability of extended emission, we compute a smoothed χ image following the technique in Hennawi & Prochaska (2013). First, we smooth an image:

$$I_{\text{smth}} = \text{CONVOL}[\text{NB} - \text{CONTINUUM}],$$

(3)

where the CONVOL operation denotes convolution of the stacked images with a Gaussian kernel with FWHM $= 2''/35$. Then, we calculate the sigma image ($\sigma_{\text{smth}}$) for the smoothed image ($I_{\text{smth}}$) by propagating the variance image of the unsmoothed data:

$$\sigma_{\text{smth}} = \sqrt{\text{CONVOL}^2 \left[ \sigma^2_{\text{unsmt}} \right]},$$

(4)

where the CONVOL$^2$ operation denotes the convolution of variance image with the square of the Gaussian kernel. Thus, the smoothed χ image is defined by

$$\chi_{\text{smth}} = \frac{I_{\text{smth}}}{\sigma_{\text{smth}}},$$

(5)

Figure 4. Analysis of the systematics in the He ii line image. Left: distribution of the normalized flux, $F_{\text{src}}/\sigma_{\text{src}}$, for random circular apertures with the same extent as LAB1 and LAB2. Here, $F_{\text{src}}$ is a total flux within an aperture and $\sigma_{\text{src}}$ is the expected 1σ flux limit in an ideal case with uniform noise properties, i.e., $\sigma_{\text{src}} = SB_{1}/\sqrt{\text{area}}$. The Gaussian fit to the histogram is highlighted in red. The observed values for LAB1 and LAB2 are shown by the black arrows. Right: same for all the other LABs with $A_{\text{src}} < 40$ arcsec$^2$ in our sample. The black arrows indicate the value of each LAB. Note that in the absence of systematics, i.e., in ideal conditions when the sky and continuum subtractions are perfect, these histograms should be a Gaussian with unit variance, but they are $\approx 3$ or $\approx 2$ times broader, i.e., $\sigma_{\text{src}}' = 2 - 3 \sigma_{\text{src}}$.

Figure 5. Analysis of the systematics in the C iv line image. Left: distribution of the normalized flux, $F_{\text{src}}/\sigma_{\text{src}}$, for random circular apertures with the same extent as LAB1 and LAB2. Here, $F_{\text{src}}$ is a total flux within an aperture and $\sigma_{\text{src}}$ is the expected 1σ flux limit in an ideal case with uniform noise properties, i.e., $\sigma_{\text{src}} = SB_{1}/\sqrt{\text{area}}$. The Gaussian fit to the histogram is highlighted in red. The observed values for LAB1 and LAB2 are shown by the black arrows. Right: same for all the other LABs with $A_{\text{src}} < 40$ arcsec$^2$ in our sample. The black arrows indicate the value of each LAB. Note that in the absence of systematics, i.e., in ideal conditions when the sky and continuum subtractions are perfect, these histograms should be a Gaussian with unit variance, but they are $\approx 3$ or $\approx 2$ times broader, i.e., $\sigma_{\text{src}}' = 2 - 3 \sigma_{\text{src}}$. 

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This $\chi_{\text{smth}}$ is more effective in visualizing the presence of extended emission.

Figures 6 and 7 show the $\chi_{\text{smth}}$ for the simulated sources for He $\parallel$ and C IV images, respectively. For each detection significance and source size, the simulated sources are shown for two different positions within the He $\parallel$ or the C IV images. To guide the eye, these positions are highlighted by a black circle. These simulated $\chi_{\text{smth}}$ images confirm that we should be able to detect extended emission down to a level of $5S_{\text{limt}}$, justifying our choice for this detection threshold. Note again that $S_{\text{limt}}$ includes the correction we made to take into account the systematics.

In addition to the previous analysis, in order to further test our continuum subtraction, we also performed the continuum subtraction using two off-band images (V and I; Hayashino et al. 2004), finding that the results remain unchanged. Note, however, that due to the differences in the telescope PSFs and seeing of the observations, the use of two bands increases the noise. Thus, we prefer to estimate the continuum using only the R-band image.

### 3. OBSERVATIONAL RESULTS

In Figures 8 and 9, we show the postage-stamp images for the 13 LABs in our sample. Each row displays the R band, the continuum-subtracted Ly $\alpha$ line image, the narrowband image of the C IV $\lambda$1549 line, the continuum-subtracted C IV line image, the He $\parallel$ $\lambda$1640 narrowband image, and the continuum-subtracted He $\parallel$ line image, respectively. The red contours indicate the isophotal aperture of LABs defined as the area above the 2$\sigma$ detection limit for the Ly $\alpha$ emission as originally adopted by Matsuda et al. (2004), i.e., $2.2 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. The continuum-subtracted C IV and He $\parallel$ line images are nearly flat and lack significant large-scale residuals, indicating good continuum and background subtraction. Note that these images are not residuals within the isophotal apertures (e.g., LAB2) because of minor misalignment between R-band and our narrowband images. However, these residuals do not affect our flux and SB measurements. We do not detect any extended C IV or He $\parallel$ emission on the scale of the Ly $\alpha$ line in any of the LABs.

In order to better visualize these non-detections, we compute the $\chi$ and $\chi_{\text{smth}}$ described in Section 2.4 for each LAB (using the pure photon counting noise estimates). Figure 10 shows the $\chi$ and $\chi_{\text{smth}}$ images of 30$''$ $\times$ 30$''$ (corresponding to 230 kpc $\times$ 230 kpc at $z = 3.1$) centered on each LAB. A comparison of the $\chi_{\text{smth}}$ images of the individual LABs with the simulated images in Figures 6 and 7 shows that we do not detect any extended emission in the He $\parallel$ and C IV lines for the 13 LABs down to our sensitivity limits of $5S_{\text{limt}}$ defined in Section 2.4. Note that we show images in Figures 6, 7, and 10 with the same stretch and color scheme for a fair comparison.

We thus place conservative upper limits, i.e., $5S_{\text{limt}}$, on both C IV $\lambda$1549 and He $\parallel$ $\lambda$1640 surface brightness for each of the LABs. For LAB1 (area 200 arcsec$^2$), these limits correspond to $S(B(\text{He} \parallel)) = 5.02 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ and $S(B(C \text{ IV})) = 7.36 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. In Table 2, we summarize all of our upper limits, the properties of Ly $\alpha$ lines, and the resulting upper limits on the C IV $\lambda$1549/Ly $\alpha$ and He $\parallel$ $\lambda$1640/Ly $\alpha$ flux ratios. Note that the most stringent limits on these ratios are obtained for the brightest LAB1 and LAB2 given their larger Ly $\alpha$ isophotal area and luminosities. Coincidentally, these two LABs show the same values, $F(\text{He} \parallel)/F(\text{Ly} \alpha) < 0.11$ and $F(C \text{ IV})/F(\text{Ly} \alpha) < 0.16$, because the difference in the area (LAB1 is larger than LAB2) is compensated by the difference in Ly $\alpha$ SB (LAB2 has an SB higher than LAB1). In what follows, we compare our limits to previous constraints on He $\parallel$ and C IV in other nebulae and then discuss the implications of our non-detections.

### 4. PREVIOUS OBSERVATIONS OF He $\parallel$ AND C IV

We compile He $\parallel$ and C IV line observations of extended Ly $\alpha$ nebulae from the literature, finding data for five Ly $\alpha$ blobs (Dey et al. 2005; Prescott et al. 2009, 2013, summarized in Table A1 in Appendix A), Ly $\alpha$ nebulae associated with 53 high redshift radio galaxies (Villar-Martín et al. 2007; Humphrey et al. 2008, which is a compilation mainly from Roettgering et al. 1997; DeBreuck et al. 2001; Vernet et al. 2001), and five radio-loud QSOs (Heckman et al. 1991a, 1991b; Humphrey et al. 2013). However, a straightforward comparison is restrained by the following issues. First of all, these data are obtained with various different techniques (e.g., narrowband imaging, long-slit spectroscopy, integral-field unit spectroscopy) and employ varied analysis methods (e.g., different extraction apertures), which result in different definitions of SB limits. Thus, a major uncertainty in comparing our data with the previous measurements is differences in the aperture for which these line fluxes or ratios are reported. In particular, our upper limits are computed over the entire Ly $\alpha$ nebulae defined by the 2$\sigma$ Ly $\alpha$ isophotal apertures of Matsuda et al. (2004) (e.g., see Figures 8 and 9), above an Ly $\alpha$ SB limit of $2.2 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, and because of the use of narrowband imaging, we can probe the whole extent of the source. On the other hand, in the case of LABs (Dey et al. 2005; Prescott et al. 2013) and HzRGs (Villar-Martín et al. 2007), the lines are extracted from smaller aperture forcedly defined by the slit, sampling a particular position within the nebula. For example, in the case of HzRGs (De Breuck et al. 2000), the lines are typically measured from one-dimensional spectra extracted by choosing the aperture that

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**Table 3. Extracted Fluxes and Significance for the 13 LABs in Our Sample**

| Object | $F(\text{He} \parallel)$ (1) | $F(\text{C IV})$ (2) |
|--------|-----------------------------|-----------------------|
| LAB1   | $-2.98 \pm 0.41$            | 31.19 (3.34)          |
| LAB2   | 17.81 (2.88)                | 2.74 (3.45)           |
| LAB7   | $-4.63 \pm 1.51$           | 2.38 (0.60)           |
| LAB8   | 5.69 (1.84)                 | 3.22 (0.81)           |
| LAB11  | 2.56 (0.83)                 | 1.96 (0.49)           |
| LAB12  | $-4.04 \pm 1.52$           | $-8.68 \pm 2.53$      |
| LAB14  | 2.59 (1.00)                 | 2.49 (0.75)           |
| LAB16  | 4.64 (1.79)                 | $-3.56 \pm 1.07$      |
| LAB20  | 4.78 (1.97)                 | 7.69 (2.46)           |
| LAB25  | $-0.89 \pm 0.37$           | $-3.91 \pm 1.25$      |
| LAB30  | 7.06 (3.35)                 | 10.67 (3.94)          |
| LAB31  | 3.02 (1.35)                 | 9.74 (3.39)           |
| LAB35  | $-0.76 \pm 0.36$           | 5.75 (2.09)           |

Note: (1) He $\parallel$ line flux in $10^{-18}$ erg s$^{-1}$ cm$^{-2}$ extracted within the isophotal area defined in Matsuda et al. (2004); (2) C IV line flux in $10^{-18}$ erg s$^{-1}$ cm$^{-2}$. For each value the statistical significance with respect to the $\sigma_{\text{unc}}$ is given in brackets.

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includes the most extended emission line, and typically the slit is oriented along the radio axis.

To further complicate the comparison, for HzRGs and QSOs where a bright central source is known to exist, it is difficult to separate the emission generated near the central source from the nebula itself. For example, for the radio-loud QSOs, Heckman et al. (1991a, 1991b) carefully removed the contribution from the central QSOs in both the imaging and the spectroscopic analysis; thus, these line ratios should only reflect the line emission in the extended nebulae. In the case of HzRGs, the narrow-line regions (NLR) can contaminate the emission on scales of a few kpc from the central source. However, in the measurements for HzRGs no attempt is made to exclude a possible contribution from this emission. While in the case of the LABs, the neglect of the contribution of the sources within the Lyα emission is not relevant because the star-forming galaxies embedded in the nebulae should scarcely emit in C IV and He II lines (e.g., Shapley et al. 2003) and constitute only a small fraction of the area in the aperture.

Despite these caveats, in Figure 11 we plot all the available data in the literature for completeness to show the ranges spanned by these different types of sources in an He II/Lyα versus C IV/Lyα diagram. But we caution again the reader that a direct comparison of objects from different studies in this plot could be problematic. The upper limits for the 13 LABs in our sample are shown in red.

Figure 11 illustrates that our upper limits are consistent with the previous measurements and, more interestingly, that there are sources in the literature with line ratios even lower than our strongest upper limits (LAB1 and LAB2, gray shaded region). Indeed, although our narrowband images constitute the deepest absolute SB limits ever achieved in the C IV and He II emission lines, some previous searches probed to smaller values of the line ratios because they observed brighter Lyα nebulae (e.g., in the case of HzRGs) or because they probed only the central part of the nebula where the Lyα emission is expected to be brighter. For example, Prescott et al. (2013) probed down to lower line ratios (e.g., the lowest green point in the plot, i.e., the LAB PRG2) because they focus on the brightest part of the blob in Lyα. Indeed, while the approximate isophotal area for this LAB is 103 arcsec², they covered only a smaller aperture (175 × 78 84) with their long-slit spectra. Thus, notwithstanding our efforts, Figure 11 is clearly indicating that in order to explore the full range of line ratios, one requires either deeper observations or brighter samples of Lyα emission nebulae (see e.g., Cantalupo et al. 2014).

In addition to the sources with giant Lyα emission nebulae, Figure 11 also shows line ratios for star-forming galaxies at z = 2–3, for which the C IV and He II line ratio is not powered by an AGN. In particular, we show the line ratios determined from the composite spectrum of Lyman break galaxies (LBGs).
from Shapley et al. (2003) and for a peculiar galaxy (Q2343-BX418) studied in detail by Erb et al. (2010) that exhibits particularly strong HeII emission. We show the corresponding line ratios for LBGs because it has been proposed that some LABs could be powered by star formation (Ouchi et al. 2009), albeit with extreme star formation rates $\sim 1000 M_\odot$ yr$^{-1}$.

Indeed, the stacked Ly$\alpha$ narrowband images of LBGs also exhibit diffuse Ly$\alpha$ emission extending as far as $\sim 50$ kpc (Steidel et al. 2011), although the Ly$\alpha$ luminosity and surface brightness of these halos are $\geq 10\times$ fainter than the LABs and the Ly$\alpha$ nebulae associated with HzRGs and QSOs. However, if the LABs represent some rare mode of spatially extended star formation, then the C IV and He II line ratios of star-forming galaxies could thus be relevant.

The origin of the He II and C IV emission observed in the spectra of star-forming galaxies is not completely understood. Shapley et al. (2003) noted relatively broad (FWHM $\sim 1500$ km s$^{-1}$) He II emission in the composite spectrum of LBGs and speculated that it arises from the hot, dense stellar winds of Wolf–Rayet (W–R) stars, which descend from O stars with masses of $M > 20$–$30 M_\odot$. The C IV line in LBGs exhibits a

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**Figure 8.** Postage-stamp images of 30″ × 30″ (corresponding to about 230 kpc × 230 kpc at $z = 3.1$) centered on LAB1, LAB2, LAB7, LAB8, LAB11, and LAB12. From left to right: R band, Ly$\alpha$, O I/2500+57 (NB C IV), C IV λ1549, Si=+62 (NB He II), and He II λ1640. On the R band, C IV λ1549, and He II λ1640 is overplotted the $2\sigma$ isophotal aperture of the Ly$\alpha$ emission (red line) as adopted by Matsuda et al. (2004). Note the lack of extended emission in the C IV λ1549 and He II λ1640 in comparison with the outstanding Ly$\alpha$ line. North is up, east is left.

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\(14\) We use the values quoted for their subsample of LBGs that have strong Ly$\alpha$ emission, i.e., EW(Ly$\alpha$) = 52.63 ± 2.74 (Shapley et al. 2003).
characteristic P Cygni-type profile, which presumably arises from a combination of stellar wind and photospheric absorption, plus a strong interstellar absorption component due to outflows (Shapley et al. 2003). There could also be a narrow nebular emission component powered by a hard ionizing source. In Figure 11 we adopt the strict upper limit of C iv/Lyα < 0.02 of the non-AGN subsample in Shapley et al. (2003), whereas for the He II/Lyα ratio we use the global value.

Figure 9. Postage-stamp images of 30″ × 30″ (corresponding to about 230 kpc × 230 kpc at z = 3.1) centered on LAB14, LAB16, LAB20, LAB25, LAB30, LAB31, and LAB35. From left to right: R band, Lyα, O i/2500+57 (NB C iv), C iv λ1549, Si+62 (NB He ii), and He II λ1640. On the R band, C iv λ1549, and He II λ1640 is overplotted the 2σ isophotal aperture of the Lyα emission (red line) as adopted by Matsuda et al. (2004). Note the lack of extended emission in the C iv λ1549 and He II λ1640 in comparison with the outstanding Lyα line. North is up, east is left.
for the first quartile with the Lyα line in emission because no He II/Lyα value was quoted for the non-AGN subsample. Erb et al. (2010) studied a young (<100 Myr), low-metallicity (Z ~ 1/6 Z⊙) galaxy at z = 2.3 that exhibits exceptionally strong He II emission, which they however argued is not powered by an AGN. Erb et al. (2010) interpreted the He II emission as a combination of a broad component due to W-R stars and a narrow nebular component, powered by a hard ionizing spectrum. Although the He II emission is strong in comparison with other typical z ~ 2–3 LBGs, indicative of a harder ionizing

**Figure 10.** Postage-stamp χ and χ_smoth images of the 13 LABs in our sample (Section 2.4). Each postage-stamp has a size of 30″ × 30″ (corresponding to about 230 kpc × 230 kpc at z = 3.1). To guide the eye, on each image is overplotted the 2σ isophotal aperture of the Lyα emission (red line) as adopted by Matsuda et al. (2004). A comparison with Figures 6–7 suggests that we did not detect any extended emission from any of the sources in our sample. Note that we used the same stretch and colormap as in Figures 6 and 7. Residuals from bright foreground objects due to minor mis-alignment between our data and SUBARU data are clearly visible. North is up, east is left.
and with an average LL

Note.

PRG4 1.03 4.09 1.68 <0.08 0.07 1

PRG2 4.92 41.8 7.84 0.18 0.18 7

PRG1 4.36 58.1 5.0 0.21 0.57 5

″

10

and CIV/Lyα

Figure 11. HeII/Lyα vs. C IV/Lyα log–log plot. Our upper limits on the He II/Lyα and C IV/Lyα ratios are compared with the values quoted in the literature for HzRGs, QSOs, and LABs (see text for references). Due to their larger extent, LAB1 and LAB2 define the strongest limits on these ratios; the gray shaded area highlights the regime constrained by these limits. Note, however, that these data are quite difficult to compare because of their heterogeneity.

5. DISCUSSION

In what follows we discuss our upper limits in light of a photoionization or a shock scenario. Here, we briefly outline the physics underlying the models and the parameters used, but we refer the reader to Hennawi & Prochaska (2013) and our subsequent paper (F. Arrigoni-Battaia et al. 2015, in preparation) for further details and a complete analysis.

5.1. Comparison with Photoionization Models

It is well established that the ionizing radiation from a central AGN can power giant Lyα nebulae, with sizes up to ~200 kpc, around HzRGs (e.g., Reuland et al. 2003; Villar-Martín et al. 2003b; Venemans et al. 2007) and quasars (e.g., Heckman et al. 1991b; Christensen et al. 2006; Smith et al. 2009), together with extended He II and C IV emission (Villar-Martín et al. 2003a). Although HzRGs are more rare (n ~ 10⁻⁶ Mpc⁻³; Miley & De Breuck 2008), the similarity between the volume density of LABs (n ~ 10⁻⁵ Mpc⁻³; Yang et al. 2010) and luminous QSOs (n ~ 10⁻⁵ Mpc⁻³; Hopkins et al. 2007) suggests that the LABs could represent the same photoionization process around obscured QSOs. Unified models of AGNs invoke an obscuring medium that could extinguish a bright source of ionizing photons along our line of sight (e.g., Urry & Padovani 1995). Indeed, evidence for obscured AGNs has been reported for several LABs (e.g., Buza-Zych & Scharf 2004; Dey et al. 2005; Geach et al. 2007; Barrio et al. 2008; Geach et al. 2009; Overzier et al. 2013; Yang et al. 2014a), lending credibility to a photoionization scenario; however, this is not always the case (Nilsson et al. 2006; Smith & Jarvis 2007; Ouchi et al. 2009).

Despite these circumstantial evidences in favor of the photoionization scenario, detailed modeling for He II and C IV lines due to AGN photoionization in the context of large Lyα nebulae has not been carried out in the literature, with the exceptions of some studies focusing on the modeling of emission lines in the case of extended emission line regions (EELRs) of HzRGs (e.g., Humphrey et al. 2008). Although many authors have modeled the NLR of AGNs (e.g., Groves et al. 2004, Nagao et al. 2006, Stern et al. 2014), the physical conditions (i.e., gas density, ionization parameter) on these small scales >1 kpc (e.g., Bennett et al. 2006; Hainline et al. 2014) are expected to be very different from the ~100 kpc scale emission of interest to us here. As such, we model the photoionization of gas on scales of 100 kpc from a central AGN to predict the resulting level of the He II and C IV lines, relative to the Lyα emission.

To select the parameters of the models in order to recover the Lyα SB of LABs, we follow the simple picture described by Hennawi & Prochaska (2013) and assume an LAB to be powered by an obscured QSO with a certain luminosity at the Lyman limit (L_{lim}). In this picture, the QSO halo is populated with spherical clouds of cool gas (T ~ 10⁴ K) at a single uniform hydrogen volume density n_H and with an average column density N_H, and uniformly distributed throughout a halo of radius R, such as they have a cloud covering factor f_C (see Hennawi & Prochaska 2013 for details). We consider two limiting regimes for recombination: the optically thin (N_H < 10⁻³ cm⁻²) and thick (N_H > 10⁻³ cm⁻²) to the Lyman continuum photons, where N_H is the neutral column density of a single spherical cloud. In this scenario, once the

Table A1

| Object  | F(μm) | SB(μm) | Extent | F(C IV) | F(He II) | Aperture | Reference |
|---------|-------|--------|--------|---------|-----------|----------|-----------|
| LABd05 | 28.9 | 3.10 | (NB) | 9.20/45.9 | 20 | 0.42 | 0.41 | 4.5×1.5 | Dey et al. 2005 |
| PRG1   | 4.36 | 58.1  | 5.0    | 0.21    | 0.57 | 5×1.5 | Prescott et al. 2009 |
| PRG2   | 4.92 | 41.8  | 7.84   | 0.18    | 0.18 | 7×1.5 | Prescott et al. 2013 |
| PRG3   | 1.02 | 12.1  | 5.60   | <0.08   | <0.08 | 5×1.5 | Prescott et al. 2013 |
| PRG4   | 1.03 | 40.9  | 1.68   | <0.08   | 0.07 | 1×1.5 | Prescott et al. 2013 |

Note. (1) Lyα line flux in 10⁻¹⁸ erg s⁻¹ cm⁻², (2) Lyα surface brightness in 10⁻¹⁸ erg s⁻¹ cm⁻² arcsec⁻², (3) maximum extent in arcseconds, (4) C IV line flux in 10⁻¹⁶ erg s⁻¹ cm⁻² arcsec⁻², (5) He II line flux in 10⁻¹⁶ erg s⁻¹ cm⁻² arcsec⁻², (6) apertures used to extract the values by the authors in the references.

The author of the reference quoted a conservative aperture of 10 arcsec radius in which they calculated all their quantities in the narrowband (NB) image.
size of the halo is fixed, in the optically thick case the Lyα SB scales with the luminosity at the Lyman limit of the central source, \( SB_{\text{Ly}\alpha}^{\text{thick}} \propto f_C L_{\nu,\text{Ly}\alpha} \), while in the optically thin regime \((N_H < 10^{17.2} \text{ cm}^{-2})\) the SB does not depend on \( L_{\nu,\text{Ly}\alpha} \), \( SB_{\text{Ly}\alpha}^{\text{thin}} \propto f_C n_H N_H \), provided that the AGN is bright enough to keep the gas in the halo ionized.

To cover the full range of possibilities, we thus construct a grid of \( \sim 5000 \) Cloudy models with parameters in the following range (see Appendix B for additional information on how the parameters were chosen):

- \( n_H = 0.01-100 \text{ cm}^{-3} \) (steps of 0.2 dex);
- \( \log N_H = 18-22 \) (steps of 0.2 dex);
- \( \log L_{\nu,\text{Ly}\alpha} = 29.3-32.2 \) (steps of 0.4 dex).

Finally, we decide to fix the covering factor to unity \( f_C = 1.0 \). The assumption of a high or unit covering factor is driven by the observed diffuse morphology of the Lyα nebulae, which do not show evidence for clumpiness arising from the presence of a population of small unresolved clouds. We directly test this assumption as follows. We randomly populate an area of 200 arcsec\(^2\) (area ofLAB1) with point sources such that \( f_C = 0.1-1.0 \), and we convolve the images with a Gaussian kernel with an FWHM equal to our median seeing value, in order to mimic the effect of seeing in the observations. We find that the smooth morphology observed for LABs cannot be reproduced by images with \( f_C < 0.5 \), as they appear too clumpy.

We perform photoionization calculations using the Cloudy photoionization code (v10.01), last described by Ferland et al. (2013). As the LABs are extended over \( \sim 100 \text{ kpc} \), whereas the radius of the emitting clouds is expected to be much smaller, we assume a standard plane-parallel geometry for the emitting clouds illuminated by the distant central source. Note that we evaluate the ionizing flux at a single location for input into Cloudy, specifically at \( R/\sqrt{3} \) (where \( R = 100 \text{ kpc} \)). Capturing the variation of the physical properties of the nebula with radius is beyond the purpose of this work. Indeed, given that for the objects in the literature radial trends for the C IV/Lyα and He II/Lyα ratios are not reported, and given that we have non-detections, modeling the emission as coming from a single radius is an acceptable first-order approximation. Further, given the ionization energies for the species of interest to us in this work, i.e., 1 Ryd = 13.6 eV for hydrogen, 4 Ryd = 54.4 eV for He II, and 64.5 eV for C IV, we have decided to stick to standard parameterizations above 1 Ryd. However, note that the UV range of the SED is so far not well constrained (see Lusso et al. 2014 and reference therein). In particular, we model the quasar SED using a composite quasar spectrum that has been corrected for IGM absorption (Lusso et al. 2014). This IGM-corrected composite is important because it allows us to relate the i-band magnitude of the central source to the specific luminosity at the Lyman limit \( L_{\nu,\text{Ly}\alpha} \). For energies greater than 1 Ryd, we assume a power-law form \( L_{\nu} = L_{\nu,\text{Ly}\alpha}(\nu/\nu_{1\text{Ryd}})^{\alpha_{\text{UV}}} \) and adopt a slope of \( \alpha_{\text{UV}} = -1.7 \), consistent with the measurements of Lusso et al. (2014). We determine the normalization \( L_{\nu,\text{Ly}\alpha} \) by integrating the Lusso et al. (2014) composite spectrum against the SDSS filter curve and choosing the amplitude to give i-band apparent magnitudes of \( i = 16-23 \), in steps of unity. We extend this UV power law to an energy of 30 Ryd, at which point a slightly different power law is chosen, \( \alpha = -1.65 \), such that we obtain the correct value for the specific luminosity at 2 keV \( L_{\nu}(2 \text{ keV}) \) implied by measurements of \( \alpha_{\text{OX}} \), defined to be

\[ L_{\nu}(2 \text{ keV})/L_{\nu}(2500 \text{ Å}) \equiv (\nu_{2500 \text{ Å}}/\nu_{2 \text{ keV}})^{\alpha_{\text{OX}}} \].

We adopt the value \( \alpha_{\text{OX}} = -1.5 \) measured by Strateva et al. (2005) for SDSS quasars. An X-ray slope of \( \alpha_X = -1 \), which is flat in \( \nu J_{\nu} \), is adopted in the interval of 2–100 keV, and above 100 keV, we adopt a hard X-ray slope of \( \alpha_{HX} = -2 \). For the rest-frame optical to mid-IR part of the SED, we splice together the composite spectra of Lusso et al. (2014), Vanden Berk et al. (2001), and Richards et al. (2006). These assumptions about the SED are essentially the standard ones used in photoionization modeling of AGNs (e.g., Baskin et al. 2014). See also Arrigoni Battaia et al. (2015) for further details on the SED.

Finally, we consider only models with solar metallicity, and from our model grid, we select only models with \( SB_{\text{Ly}\alpha} = (1-9) \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2} \), comparable to LABs.

It is important to stress here that we neglect the contribution due to the resonant scattering of Lyα photons produced by the quasar itself. Indeed, radiative transfer simulations of radiation from a bright quasar \( (i = 17.28) \) through a simulated gas distribution have shown that the scattered Lyα line photons from the quasar do not contribute significantly to the Lyα SB of the nebula on large scales, i.e., \( \gtrsim 100 \text{ kpc} \) (Cantalupo et al. 2014). This is due to the great efficiency of the resonant scattering in diffusing the photons both spatially and in the velocity space.

In Figure 12 we compare our photoionization model predictions in the He II/Lyα versus C IV/Lyα diagram to our LAB limits and the data points from the literature. The left panel and right panels show the optically thin and optically thick regimes, respectively. Note that this division into optically thin and thick models corresponds to a division in the ionizing luminosity of the central source (which in the case of LABs and HzRGs is obscured from our vantage point and is thus unknown). Specifically, in the optically thin regime we find that for the range of \( SB_{\text{Ly}\alpha} \) considered, the central source must have \( L_{\nu,\text{Ly}\alpha} \gtrsim 10^{35.5} \text{ erg s}^{-1} \text{ Hz}^{-1} \) or \( i \lesssim 20 \). On the other hand, because in the optically thick limit \( SB_{\text{Ly}\alpha} \propto L_{\nu,\text{Ly}\alpha} \), the ionizing luminosity is fixed to be in a relatively narrow range \( L_{\nu,\text{Ly}\alpha} \approx 10^{37.9} - 10^{38.3} \text{ erg s}^{-1} \text{ Hz}^{-1} \) \( (i \approx 22-23) \).

For clarity, in Figure 12 we show only the models with \( N_H = 10^{15}, 10^{16}, 10^{17}, 10^{18}, 10^{19} \text{ cm}^{-2} \). The model grids are color coded according to the ionization parameter \( U \), which is defined to be the ratio of the number density of ionizing photons to hydrogen atoms \( (U \equiv \Phi_{1\text{Ryd}}/n_H \times L_{\nu,\text{Ly}\alpha}/n_H) \) and provides a useful characterization of the ionization state of the nebulae. Because photoionization models are self-similar in this parameter (Ferland 2003), our models will exhibit a degeneracy between \( n_H \) and \( L_{\nu,\text{Ly}\alpha} \). Nevertheless, we decided to construct our model grid in terms of \( n_H \) and \( L_{\nu,\text{Ly}\alpha} \), in order to explore the possible ranges of both parameters.

Figure 12 illustrates that, overall, our photoionization models can cover the full range of He II/Lyα and C IV/Lyα line ratios that are observed in the data. Note that previous studies of EELRs around HzRGs favored models with \( \log U \sim -1.46 \) (e.g., Humphrey et al. 2008), which are consistent with our results. Note, however, that two HzRGs with He II/Lyα \( \approx 1 \) and C IV/Lyα \( \approx 1 \) are not covered by our models. For both of these data, emission from the central source has not been excluded, and thus we speculate that these very high line ratios arise because of contamination from the narrow-line region of the

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15 This constraint follows from the definition of an optically thin cloud, i.e., \( N_H \ll 10^{17.2} \text{ cm}^{-2} \).
observed AGN, where Lyα photons have been destroyed by dust. Indeed, both of these objects, MG1019+0535 and TXS0211−122, have a C iv/He ii ratio similar to the bulk of the HZRG population, but they exhibit unusually weak Lyα lines (Dey et al. 1995; van Ojik et al. 1994). Note, however, that while destruction of Lyα by dust grains can have a large impact on these line ratios for emission emerging from the much smaller scale narrow-line region, dust is not expected to significantly attenuate the Lyα emission in the extended nebulae around QSOs (see discussion in Appendix A of Hennawi & Prochaska 2013) given the physical conditions characteristic of the CGM, and thus we neglect destruction of Lyα photons by dust in our modeling.

The optically thin regime (see left panel) seems to better reproduce the range of high He ii/Lyα and C iv/Lyα ratios and seems to have difficulties in reproducing the low ratios implied by our observations (see below). To understand why the optically thin models do not cover low He ii/Lyα ratios, we describe here the trajectory of the optically thin models through the He ii/Lyα and C iv/Lyα diagram. We follow the curves from low to high $U$. Recall that in the optically thin regime $SB_{\text{Ly}\alpha} \propto n_H N_H$, but is roughly independent of the source luminosity $L_{\text{Ly}\alpha}$. Thus, by fixing $N_H$ and requiring that $SB_{\text{Ly}\alpha} = (1-9) \times 10^{-18} \text{erg s}^{-1} \text{cm}^{-2}$, we also fix $n_H$. Thus, $U$ increases along this track because the central source luminosity $L_{\text{Ly}\alpha}$ is increasing, which hardly changes the Lyα emission but results in significant variation in both He ii and C iv.

First consider the trend of the He ii/Lyα ratio. He ii is a recombination line, and thus, once the density is fixed, its emission depends basically on what fraction of helium is doubly ionized. For this reason, the He ii/Lyα ratio is increasing from log$U = -3.3$ and reaches a peak at log $U \sim -2.0$, corresponding to an increase in the fraction of the He++ phase from about 20% to 90% of the total helium. Further increases $U$ result in only modest changes to the He++ fraction but result in an increase in gas temperature. These higher temperatures change the value at which the He ii/Lyα ratio saturates. In particular, at higher temperatures, if both hydrogen and helium are completely ionized, the He ii/Lyα saturation value decreases (see Arrigoni Battaia et al. 2015).

Our photoionization models indicate that the C iv emission line is an important coolant and is powered primarily by collisional excitation. Figure 12 shows that our models span a much wider range in the C iv/Lyα ($\sim 3$ dex) ratio than in He ii/ Lyα ($\lesssim 2$ dex). The strong evolution in C iv/Lyα results from a combination of two effects. First, increasing $U$ increases the temperature of the gas, and the C iv collisional excitation rate coefficient has a strong temperature dependence (Groves et al. 2004). Second, the efficacy of C iv as a coolant depends on the amount of carbon in the C+3 ionic state. As log$U$ increases from $\approx -3.3$ to $\approx -2$, the C+3 fraction increases from 1% to 37%. These two effects conspire to give rise to nearly three orders of magnitude of variation in the C iv emission.

From the left panel of Figure 12, it is clear that our optically thin models with solar metallicities populate the region below our most stringent upper limits (LAB1 and LAB2) only for very low $U$ (log$U \sim -3.0$), i.e., which means at very high density $n_H \gtrsim 6 \text{ cm}^{-3}$. These are models for which helium is not completely ionized, and thus low He ii/Lyα ratios are allowed. This result agrees with Cantalupo et al. (2014) and Arrigoni Battaia et al. (2015), who invoke the presence of dense clouds to explain the Lyα emission around the UM287 quasar in the optically thin regime. In a next paper we explore this scenario and understand the dependence of this density threshold on metallicity and on the luminosity of the central source.

**Figure 12.** He ii/Lyα vs. C iv/Lyα log−log plot. Same data points as in Figure 11. Our upper limits on the He ii/Lyα and C iv/Lyα ratios are compared with the Cloudy photoionization models. In the left panel we plot the optically thin models, while in the right panel is shown the optically thick regime. For clarity, we plot only the models with $N_H = 10^{19}, 10^{20}, 10^{21}, 10^{22} \text{ cm}^{-2}$. The grids are color coded following the ionization parameter (see colorbar on the right), and the value of hydrogen column density is indicated. Note that there are no optically thick models with $N_H = 10^{19} \text{ cm}^{-2}$. Note that the x-axis is on a different scale than Figure 11.
On the other hand, the optically thick models (see right panel of Figure 12) can also populate the area below the upper limits for LAB1 and LAB2, namely, the lower part of the observed He ii/Lyα–C iv/Lyα diagram. Note that given the range of $L_{\text{ion}}$ and $n_{\text{H}}$ in our parameter grid, models with $N_{\text{H}} = 10^{18} - 10^{19}$ cm$^{-2}$ are never optically thick, which explains why we only show optically thick models with $N_{\text{H}} = 10^{20}, 10^{21}, 10^{22}$ cm$^{-2}$. The bulk of these models reside on a sequence with almost constant He ii/Lyα (around He ii/Lyα = 0.04–0.05) for a wide range of C iv/Lyα, which is driven by variation in $U$. The models departing from this sequence are characterized by $N_{\text{H}}$ slightly greater than $10^{17.2}$ cm$^{-2}$, and they can thus be seen as a transition between the optically thick case and the optically thin case.

It is worth to stress here that some of the HzRGs show lower Lyα emission, and thus higher ratios in these plots, because of intervening neutral hydrogen (e.g., Wilman et al. 2004). It has been shown that this absorption is mainly caused by strong absorbers, i.e., $N_{\text{H}} > 10^{18}$ cm$^{-2}$. For example, van Ojik et al. (1997) show that strong H i absorption ($10^{18}$ cm$^{-2} < N_{\text{H}} < 10^{20}$ cm$^{-2}$) is found in 11 out of 18 sources in their sample. As we are not taking into account the absorption in our modeling and as we do not have complete information to correct the data for absorption, one needs to be cautious, particularly when comparing our models with the data of HzRGs.

To summarize, the photoionization models produce line ratios that are consistent with our upper limits and that span the values observed in the literature. In the next section we consider the degree to which shock powered emission can explain line ratios in Lyα nebulae.

5.2. Comparison with Shock Models

Taniguchi & Shioya (2000) and Mori & Umemura (2006) have speculated that intense star formation accompanied by successive supernova explosions could power a large-scale galactic superwind, and radiation generated by overlapping shock fronts could power the Lyα emission in the LABs. However, it is well known that it is difficult to distinguish between photoionization and fast shocks using line ratio diagnostic diagrams (e.g., Allen et al. 1998). Furthermore, for AGN narrow-line regions, the Lyα line is typically avoided in these diagrams because of its resonant nature and the fact that it may be more likely to be destroyed by dust, although we have argued that it is not an issue for CGM gas. It is thus interesting to study how shock models populate the He ii/Lyα versus C iv/Lyα diagram in comparison with photoionization models and our observational limits.

To build intuition about the line ratios expected in a shock scenario, we rely on the modeling of fast shocks by Allen et al. (2008). We thus imagine the Lyα emission as the sum of overlapping shock fronts with shock velocity $v_s$, moving into a medium with preshock density $n_{\text{H}}$. In the case of such shocks, Allen et al. (2008) showed that the Lyα emission depends strongly on $v_s$, i.e., $I_{\text{Ly}α} \propto n_{\text{H}} v_s^3$ (their Table 6). In order to test a realistic set of parameters in the case of LABs, we limit the grid of models presented by Allen et al. (2008) to:

1. $n_{\text{H}} = 0.01, 0.1, 1.0, 10, 100$ cm$^{-3}$
2. shock velocities, $v_s$, from 100 to 1000 km s$^{-1}$ in steps of 25 km s$^{-1}$.

We consider only models with solar metallicity. The magnetic parameter $B n^{1/2}$, where $B$ is the magnetic field in $\mu$G, determines the relative strength of the thermal and magnetic pressure. We adopt a magnetic parameter $B n^{1/2} = 3.23 \mu$G cm$^{3/2}$, which represents a value expected for ISM gas assuming

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16 Note that in this regime the Lyα emission is not completely independent of the luminosity of the central source. Indeed, this scaling neglects small variations due to temperature effects, which Cloudy is able to trace.

17 This lower limit on the density is determined by the lower luminosity for which our models are optically thin, i.e., $i$-mag ~ 20. Higher luminosities select even higher densities.

18 We found optically thick models for $N_{\text{H}} > 10^{19.2}$ cm$^{-2}$.
equipartition of magnetic and thermal energy. However, note that, given the very strong dependence of the ionizing flux on the shock velocity $F_{\text{UV}} \propto v_s^4$, the line ratios do not vary so markedly with either the metallicity or the magnetic field (see Allen et al. 2008 for further details).

In Figure 13 we show two sets of shock models. On the left, we plot the models for which the emission is coming solely from the shocked region, where the gas, moving at about $v_s$, is ionized and excited to high temperatures by the shock. Temperatures ahead of the shock front are of the order of $10^4$ K, whereas temperatures as high as $10^6$ K can be reached in the post-shock gas (Allen et al. 2008). On the right, we plot a combination of the emission coming from the shocked gas and from the “static” precursor, i.e., the pre-shock region, which is photoionized by the radiation emitted upstream from the shocked region. The trends of the models can be explained as follows. The models for the shock component (left panel of Figure 13) show a rapid decrease in the $C^{+}V/Ly\alpha$ ratio for increasing $v_s$. This is due to a rapid increase in the $Ly\alpha$ line due to the strong scaling of the ionizing flux with $v_s$, and to a decrease in the $C^{+}V$ line due to the lack of carbon in the $C^{+}$ phase for high velocities (i.e., carbon is in higher ionization species; see Figure 9 of Allen et al. 2008). The $He\pi/Ly\alpha$ ratio depends more strongly on the gas density because $n_H$ sets the volume of the shocked region and thus the recombination luminosity of helium, i.e., at fixed $v_s$, a higher density corresponds to a smaller shocked volume and less helium emission (see Figure 6 of Allen et al. 2008).

The combination of shock and precursor models mainly alters the ratios for models with high $v_s$ (see right panel of Figure 13). This is because the precursor component is adding the contribution of a photoionized gas at temperature of the order of $10^4$ K, and the ionizing flux scales strongly with shock velocity $F_{\text{UV}} \propto v_s^4$. For velocities $v_s \gtrsim 400$ km s$^{-1}$, the resulting hard radiation field results in a large fraction of double ionized helium He$^{++}$ over a significant volume of the precursor, significantly increasing the He$\pi$ emission and the He$\pi$/Ly$\alpha$ ratio. This photoionized precursor similarly increases the abundance of the $C^{+}$ phase, giving rise to a higher $C^{+}/$Ly$\alpha$ ratio. Thus, adding the precursor contribution to the shock models causes the models to fold over each other at high velocities.

Figure 13 illustrates that the shock models with $v_s > 250$ km s$^{-1}$ are capable of populating the line ratio diagram below our tightest upper limits (i.e., LAB1 and LAB2) (see Figure 13). However, the shock velocities above $\sim 250$ km s$^{-1}$ could be in potential disagreement with recent observations of outflow velocities (Yang et al. 2011, 2014a, 2014b). Using the velocity offset between the $Ly\alpha$ and the non-resonant [O m] or H$\alpha$ line, the offset of stacked interstellar metal absorption lines, and the [O m] line profile, Yang et al. (2011, 2014b) find that the kinematics of gas along the line of sight to galaxies in LABs are consistent with a simple picture in which the gas is stationary or slowly outflowing at velocities of a few hundred km s$^{-1}$ from the embedded galaxies. In addition, Prescott et al. (2009) showed that the He$\pi$ line detected in an LAB at $z = 1.67$ is narrow: FWHM $\lesssim 500$ km s$^{-1}$. Therefore, these observations seem to rule out the shock-only models (left panel of Figure 13), where the gas velocities, i.e., the observed velocities, are expected to be similar to the shock velocity $v_s$.

In the case of a combination of shock and precursor (right panel of Figure 13), the interpretation is more complicated. As we explained above, the emission from the precursor dominates the line ratios at $v_s \gtrsim 250$ km s$^{-1}$, where the models lie below our upper limits. As the precursor is static, if we are preferentially seeing this state of the gas, we would measure velocities lower than $v_s$. In this case, as the shock is behaving as a photoionizing source, it would be difficult to disentangle the combination of shock and precursor from the photoionization case. Furthermore, it is important to note that we are not taking into account any deceleration of the shock. A detailed modeling of a superposition of blast waves that are slowing down with time is beyond the scope of this work.

It is worth stressing again here that these models suffer from uncertainty in the Ly$\alpha$ calculation. In particular, the additional contribution from scattering is not taken into account, thus making the Ly$\alpha$ line weaker. As a consequence, these grids may be shifted to lower values on both axes. Note also that we fix the metallicity to the solar value. However, a decrease in the $C^{+}$V emission is expected for sub-solar metallicity, weakening the constraints on the shock velocities. The trends with metallicity are beyond the scope of this work, and we are going to address them in a subsequent paper (F. Arrigoni Battaia et al. 2015, in preparation). Another caveat is that the line ratios of HzRGs can be biased because the absorption of Ly$\alpha$ due to the intervening hydrogen was not taken into account.

Thus, even though our models can give us a rough idea of the line emission in the shock scenario, these plots should be treated with caution.

### 5.3. Comparison to Previous Modeling of Extended Ly$\alpha$ Emission Nebulae

As stated in the previous sections, rigorous modeling of photoionization of large Ly$\alpha$ nebulae in the context of LABs has never been performed. However, Prescott et al. (2009) reported a detection of extended He$\pi$ and modeled simple, constant density gas clouds assuming illumination from an AGN, Pop III, and Pop II stars. They are not quoting all the parameters of their Cloudy models (e.g., $N_{\text{HI}}$), and thus it is not possible to make a direct comparison. However, they found that the data are in agreement with photoionization from a hard ionizing source, due to either an AGN or a very low metallicity stellar population ($Z < 10^{-2}$ to $10^{-3} Z_{\odot}$). They conclude that, in the case of an AGN, this source must be highly obscured along the line of sight. They also showed that their observed ratios are inconsistent with shock ionization in solar metallicity gas.

On smaller scales, photoionization has been modeled in the case of EELRs of HzRGs. In particular, Humphrey et al. (2008), using the code MAPPINGS Ic (Binette et al. 1985), shows that the data are best described by AGN photoionization with the ionization parameter $U$ varying between objects, in a range comparable with our grid. However, they found that a single-slab photoionization model is unable to explain adequately the high-ionization (e.g., N$\pi$) and low-ionization (e.g., C$\pi$), [N m], [O m]) lines simultaneously, with higher $U$ favored by the higher ionization lines. They also demonstrated that shock models alone are overall worse than photoionization models in reproducing HzRGs data. In the shock scenario an additional source of ionizing photons is required, i.e., the obscured AGN, in order to match most of the line ratios studied by Humphrey et al. (2008). However, note that shocks with precursor models can explain some ratios, e.g., N$\pi$/N$\alpha$,
which are hardly explained by a single-slab photoionization model (Humphrey et al. 2008).

6. SUMMARY AND CONCLUSIONS

We obtained the deepest ever narrowband images of He II and C iv emission from 13 LABs in the SSA22 protocluster region to study the poorly understood mechanism powering the LABs. By exploiting the overdensity of LABs in the SSA22 field, we were able to conduct the first statistical multi-emission-line analysis for a sample of 13 LABs, and we compared their emission line ratios to Lyα nebulae associated with other Lyα blobs, HzRGs, and QSOs. We compared these results to detailed models of He II/Lyα and C iv/Lyα line ratios assuming that the Lyα emission is powered by photoionization (a) from an AGN (including the contribution of scattering) or (b) in a shock scenario. The primary results of our analysis are:

1. We do not detect extended emission in the He II and C iv lines in any of the 13 LABs down to our sensitivity limits, (2.1 and 3.4)×10^{-18} erg s^{-1} cm^{-2} arcsec^{-2} (5σ in 1 arcsec^2) for He II and C iv, respectively.
2. Our strongest constraints on emission-line ratios are obtained for the brightest LABs in our field (LAB1 and LAB2) and are thus constrained to be lower than 0.11 and 0.16 (5σ) for He II/Lyα and C iv/Lyα, respectively.
3. Photoionization models, accompanied by a reasonable variation of the parameters (N_H, n_H, i) describing the gas distribution and the ionizing source, are able to produce line ratios smaller than our upper limits in the He II/Lyα versus C iv/Lyα diagram. Although our data constitute the deepest observations of these lines, they are still not deep enough to rule out photoionization by an obscured AGN as the power source in LABs. These same photoionization models can also accommodate the range of line ratios in the literature for other Lyα nebulae. In particular, optically thin models populate the region below our upper limits only for really low ionization parameters (log(U) ~ 3.0) and high densities (n_H ≥ 6 cm^{-3}). On the other hand, the bulk of the optically thick models lie below our LAB limits, on a sequence with almost constant He II/Lyα (around He II/ Lyα = 0.04–0.05).
4. Shock models can populate an He II/Lyα versus C iv/Lyα diagram below our LAB limits only if high velocities are assumed, i.e., v_s ≥ 250 km s^{-1}, but they do not reproduce the higher line ratios implied by detections of He II and C iv in the HzRGs. While the “shock-only” models seem to be ruled out by observations of relatively weak outflow kinematics in the central galaxies embedded in LABs (Prescott et al. 2009; Yang et al., 2011, 2014b), we note that the composite models of shock and precursor might be in agreement with observed gas velocities lower than v_s and thus allow v_s ≥ 250 km s^{-1}.

Deeper observations of the He II and C iv emission lines in the SSA22 field are required in order to make more definitive statements about the mechanism powering the LABs. For example, our photoionization modeling suggests that line ratios as low as He II/Lyα ≈ 0.05 and C iv/Lyα ≈ 0.07 can be produced by combinations of physical parameters (N_H = 10^{19} – 10^{21} cm^{-2}, n_H = 1–10 cm^{-3}, i = 17) that are still plausible. This implies that SBs as low as (1 and 1.5) × 10^{-18} erg s^{-1} cm^{-2} arcsec^{-2} per 1 arcsec^2 aperture (5σ) must be achieved to start to rule out photoionization. For bright giant Lyα nebulae around QSOs, as have been recently discovered (Cantalupo et al. 2014), photoionization modeling is much more constrained, because the ionizing luminosity of the central source is known. Sensitive measurements of line ratios from deep observations can thus constrain the properties of gas in the CGM, as we will discuss in a future paper (F. Arrigoni-Battaia 2015, in preparation). These questions will be addressed by a new generation of image-slicing integral field units, such as the Multi Unit Spectroscopic Explorer (Bacon et al. 2004) on VLT or the Keck Cosmic Web Imager. By probing an order of magnitude deeper than our current observations, this new instrumentation will usher in a new era of emission studies of the CGM. This unprecedented sensitivity, combined with the modeling methodology described here, will constitute an important step forward in solving the mystery of the LABs.

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APPENDIX A

PREVIOUS OBSERVATIONS OF HE II AND C IV IN EXTENDED LYα NEBULAE

In Table A1, we compile the previous observations of He II and C iv in extended Lyα nebulae.

APPENDIX B

PHOTOIONIZATION MODELING

In this work we have presented results of photoionization models of LABs. A complete description and more detailed analysis of dependence of our models on the input parameters will be presented in a future paper (F. Arrigoni-Battaia 2015, in preparation). In this appendix, we provide additional information on how the parameters of the photoionization models were chosen.

Our photoionization modeling was restricted to cloud column densities of log(N_H) ≤ 22 because for larger columns the implied total gas mass of the nebula alone becomes too large. Quasars at z ~ 2–3 are hosted by dark matter halos of M_{DM} = 10^{12.5}M_☉ (White et al. 2012), and there is circumstantial evidence based on the strong clustering of LABs that they inhabit a similar mass scale (Yang et al. 2010). The total mass of cool (~10^{4} K) gas in our simple model can be shown to be (Hennawi & Prochaska 2013)

\[ M_c = 3.3 \times 10^{10} \left( \frac{R}{100 \text{ kpc}} \right)^2 \left( \frac{L}{10 \text{ L}_\odot} \right) \left( \frac{N_H}{10^{20} \text{ cm}^{-2}} \right) M_\odot. \] (B.1)

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20 http://mpia-hd.mpg.de/ENIGMA/
Note that this value is reasonable, given the recent estimate by Prochaska et al. (2013a) that shows that the cool gas mass of the CGM of such massive halos is \( M_c > 10^{10} M_\odot \), based on absorption-line spectroscopy. As the smooth morphology of LAB emission constrains the covering factor to be \( f_c > 0.5 \), we consider models up to \( \log N_H = 22 \), which would result in very high cool gas masses \( M_c = 10^{12.2} M_\odot \) for the lowest covering factor, \( f_c = 0.5 \).

Additionally, we limit \( n_{HI} \) to be \( \lesssim 100 \, \text{cm}^{-3} \). Although such high densities are typically adopted in the previous modeling of EELRs around HzRGs (e.g., Humphrey et al. 2008; Matsuoka et al. 2009), for halo gas on a scale of \( \sim 100 \, \text{kpc} \), i.e., in the so-called CGM, this would represent extreme gas densities. Indeed, for gas in the CGM of QSO halos, gas densities this high can be ruled out by absorption-line observations using background QSOs (e.g., Hennawi et al. 2006; Hennawi & Prochaska 2007). For example, Prochaska & Hennawi (2009) used absorption in the collisionally excited \( \text{CII}^* \) fine-structure line to obtain an estimate of \( n_{HI} \approx 1 \, \text{cm}^{-3} \) at an impact parameter of \( R_i = 108 \, \text{kpc} \); however, weak or absent \( \text{CII}^* \) in the majority of sightlines probing the QSO CGM suggests that even \( n_{HI} = 1 \, \text{cm}^{-3} \) is an extreme value. Note further that the ratio \( N_H/n_{HI} \) is roughly the size of the emitting clouds, and even for the largest values of \( N_H \sim 10^{21} \, \text{cm}^{-2} \), densities as large as \( n_{HI} = 100 \, \text{cm}^{-3} \) would imply extremely small cloud sizes of the order of parsecs, and even more implausibly small values for lower \( N_H \). These limits on \( n_{HI} \) and \( N_H \) are particularly important in the optically thin regime where \( \Sigma_{\text{HI}} \propto n_{HI} N_H \).

For the luminosity of the central QSO, we limit the models to \( i > 16 \, \text{mag} \) because the number density of sources with brighter ionizing fluxes is much less than the observed number density of the LABs that we study. At \( z \sim 3 \), QSOs with \( i < 17 \) have a number density of \( 1.16 \times 10^{-9} \, \text{Mpc}^{-3} \) in comoving units (Hopkins et al. 2007), whereas, although current estimates are fairly rough, bright LABs with sizes of \( \sim 100 \, \text{kpc} \) are much more abundant \( (n \sim 10^{-5} \text{ to } 10^{-6} \, \text{Mpc}^{-3}) \); Yang et al. 2009, 2010). For reference, the quasar luminosity function of Hopkins et al. (2007) implies that QSOs with \( 23 < i < 21 \) have a number density of \( \sim 3 \times 10^{-6} \, \text{Mpc}^{-3} \) at \( z = 3.1 \), comparable to that of LABs.

Our photoionization models assume a single population of clouds with the same properties, and we vary the ionization parameter (by changing \( N_H \) and the source luminosity). However, it has been argued that a single population of constant-density clouds is not able to simultaneously explain both the high- and low-ionization lines around HzRGs, and instead a mixed population of completely ionized clouds and partially ionized clouds is invoked (e.g., Binet et al. 1996), or the clouds are assumed to be in pressure equilibrium with the ionizing radiation (Dopita et al. 2002; Stern et al. 2014). It is unclear whether multiple cloud populations need to be invoked to explain the LABs, given the sparseness of the current data on emission-line ratios, and this issue clearly goes beyond the scope of the current work, but should be revisited when more data are available.

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