The Ionized- and Cool-gas Content of the BR1202—0725 System as Seen by MUSE and ALMA

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Abstract

We present Multi Unit Spectroscopic Explorer (MUSE) observations of the gas-rich major merger BR1202—0725 at z ∼ 4.7, which constitutes one of the most overdense fields known in the early universe. We utilize these data in conjunction with existing Atacama Large Millimeter/submillimeter Array (ALMA) observations to compare and contrast the spatially resolved ionized- and cool-gas content of this system, which hosts a quasar (QSO), a submillimeter galaxy (SMG), the two known optical companion Lyα emitters (“LAE 1” and “LAE 2”), and an additional companion discovered in this work “LAE 3” just 5′′ to the north of the QSO. We find that QSO BR1202—0725 exhibits a large Lyα halo, covering ≈55 pkpc on-sky at surface-brightness levels of SB ≥ 1×10^{−11} erg s cm^{−2} arcsec^{−2}. In contrast, the SMG, of similar far-infrared luminosity and star formation rate (SFR), does not exhibit such a Lyα halo. The QSO’s halo exhibits high velocity widths (1000 km s^{−1}) but the gas motion is to some extent kinematically coupled with the previously observed [C II] bridge between the QSO and the SMG. We note that the object known in the literature as LAE 2 shows no local peak of Lyα emission, rather, its profile is more consistent with being part of the QSO’s extended Lyα halo. The properties of LAE 3 are typical of high-redshift LAEs; we measure F_{Lyα}(LAE 3) = 0.24 ± 0.03 × 10^{−16} erg s cm^{−2} M_{yr}^{−1}, corresponding to SFR_{Lyα} ≈ 5.0 ± 0.5 M_{⊙} yr^{−1}. The velocity width is Δv(LAE 3) ≈ 400 km s^{−1}, and the equivalent width is EW_{Lyα}(LAE 3) ≈ 34.05 Å, consistent with star formation being the primary driver of Lyα emission. We also note a coherent absorption feature at ≈−400 km s^{−1} in spectra from at least three objects; the QSO, LAE 1, and LAE 2, which could imply the presence of an expanding neutral gas shell with an extent of at least 24 pkpc.

Unified Astronomy Thesaurus concepts: Broad-absorption line quasar (183); Quasars (1319)

1. Introduction

The BR1202—0725 system is a prime example of a gas-rich major merger at high redshift, which theory and simulations suggest are key to our understanding of galaxy evolution. Quasi-stellar object (QSO) “BR1202—0725,” was discovered in the Automated Photographic Measuring BRI survey (Irwin et al. 1991)—it was the first object at z > 4 to be detected in CO emission (Ohta et al. 1996), and these molecular gas observations revealed for the first time an optically obscured submillimeter galaxy (SMG) lying ∼4′′ to the northwest of the QSO (Omont et al. 1996b; Iono et al. 2006). Subsequently, the field has been targeted with a multiwavelength campaign of observations to measure its gas content (Wagg et al. 2012; Carilli et al. 2013) and chemical abundances (Decarli et al. 2017; Lehner et al. 2020).

Indeed, the hierarchical growth of structure predicts that QSOs at high redshift are biased tracers of galaxy formation, situated in overdense environments (e.g., Overzier et al. 2009). In the case of QSO BR1202—0725, in addition to the nearby SMG, narrowband data have indicated the presence of two Lyα emitters (LAEs) in the vicinity (Hu et al. 1996; Omont et al. 1996b; Ohyama et al. 2004; Salomé et al. 2012): the source denoted LAE 1, positioned to the northwest of the QSO (in the direction of the SMG) and LAE 2 toward the southwest. Furthermore, [C II]_{158 μm} observations of the entire BR1202—0725 field from the commissioning of the Atacama Large Millimeter Array (ALMA; Wootten & Thompson 2009) suggest the possible presence of a bridge of [C II]_{158 μm} emission between the QSO and the SMG, tracing cooler ionized and/or neutral gas, intriguingly with an indication of a local maximum at the position of LAE 1. Together, this makes BR1202—0725 an ideal system to study a diverse population of galaxies evolving in one of the most overdense regions of the universe known, just ∼1.2 Gyr after the Big Bang.

The nature of the two companion objects denoted LAE 1 and LAE 2 has been debated. The object that appears in HST775w and HST814w imaging, later named LAE 1, was spectroscopically confirmed by the detection of Lyα emission in Hu et al. (1996). The optical line ratios presented in Williams et al. (2014) suggest that the primary source of Lyα emission in LAE 1 is star formation, i.e., neither C IV nor He II emission is detected, which should each be present in the case of photoionization by an active galactic nucleus (AGN).LAE 1 is detected in [C II]_{158 μm} (Wagg et al. 2012; Carilli et al. 2013), and shows a narrow emission line (of width Δν_{FWHM} = 56 km s^{−1}) at FWHM), taking this as an indicator of systemic redshift, the Lyα emission is offset by 49 km s^{−1} from its predicted position in wavelength (Williams et al. 2014). Observations in Decarli et al. (2017), Pavesi et al. (2016), and Lee et al. (2019) detect [N II]_{122 μm}

Although C IV could be suppressed in a low metallicity system, He II should be detectable regardless, and thus places a strong constraint on the powering mechanism of the Lyα emission.
emission from ionized nitrogen at the position of LAE 1, at levels that suggest an origin within \( \text{H} \alpha \) regions.

LAE 2 (Hu et al. 1997; Salomé et al. 2012), appears in narrowband imaging to be an LAE at the redshift of the QSO. Long-slit spectroscopic observations in Williams et al. (2014) confirmed the presence of \( \text{Ly}\alpha \) emission at the position of LAE 2, at approximately the redshift of the QSO, lending support to the idea that the object was indeed an LAE associated with this group. The [C\II] emission from LAE 2 falls at the edge of the ALMA spectral setup, and hence it is not easy to judge the peak frequency or velocity width of the line (see Carilli et al. 2013; Wagg et al. 2012). Decarli et al. (2017) however reported a [N\II]/[C\II] ratio for this object, which indicated that this submillimeter emission in LAE 2 is likely to originate from \( \text{H} \alpha \) dominated regions, and as such the object could be forming stars.

In addition to the presence of companion galaxies at the redshift of the QSO, these massive objects are predicted to reside at the nodes of large-scale structure, composed of sheets and filaments of \( \text{H}1 \) gas, known as the “cosmic web” (e.g., Springel et al. 2006). This gas is too diffuse to form stars, but is instead funneled along the filamentary structure onto massive dark matter halos hosting the QSO and/or other massive collapsed objects (e.g., van de Voort et al. 2011), acting as fuel for their star formation. As a QSO is “fed” by this cool gas (\( T \sim 10^4 \) K), a number of physical processes (whose relative contributions are debated) lead to the emission of \( \text{Ly}\alpha \) photons, which due to their resonant nature in \( \text{H}1 \) gas, require careful interpretation, including modeling of their complex radiative transfer processes (e.g., Michel-Dansac et al. 2020). Although extended \( \text{Ly}\alpha \) halos can arise surrounding a diverse set of objects (e.g., Venemans et al. 2007) in the case of a central QSO, the prime candidates responsible for powering the \( \text{Ly}\alpha \) emission could be any of the following: (A) photoionization of the cool gas by a centrally located AGN (sometimes referred to as \( \text{Ly}\alpha \) fluorescence); Cantalupo 2010; Prescott et al. 2015; (B) “gravitational cooling” of in-falling (pristine) gas, in which collisional excitation of atoms is the dominant power source (Smith & Jarvis 2007; Rosdahl & Blaizot 2012; Daddi et al. 2020); and (C) shock heating of the gas as a result of violent, possibly jet-induced star formation (e.g., Taniguchi et al. 2001). In addition to these processes, star formation within the QSO’s host galaxy, and/or star formation within other satellite galaxies could act as energy sources to also photoionize some fraction of the cool gas.

In recent years, observations from the panoramic integral field spectrograph Multi Unit Spectroscopic Explorer (MUSE; Bacon et al. 2010) have revolutionized the field of study surrounding the detection and analysis of extended \( \text{Ly}\alpha \) halos/nebulae around QSOs and “normal” star-forming galaxies (Bacon et al. 2015, 2017; Wisotzki et al. 2016; Drake et al. 2017a, 2017b; Inami et al. 2017; Lelecrèq et al. 2017). The high spectral (\( \Delta \lambda \sim 1.25 \) Å) and spatial (0.202") resolution have revealed detailed spatially resolved kinematic maps of \( \text{Ly}\alpha \) halos surrounding QSOs at the highest redshifts (Farina et al. 2017, 2019; Ginolfi et al. 2018; Drake et al. 2019), and at \( z \sim 2–3 \) where other rest-frame ultraviolet emission lines are accessible with MUSE), e.g., \( \text{CIV} \) and/or \( \text{HeII} \) potentially enabling constraints on the powering mechanisms of the halos (Arrigoni Battaia et al. 2015a, 2015b, 2019; Borisova et al. 2016; Marino et al. 2019; Also see results from the Keck Cosmic Web Imager, e.g., Cai et al. 2019).

Until now, observations of BR1202–0725’s ionized gas content, traced by \( \text{Ly}\alpha \) emission, have been limited to photometry from broad or narrowbands, long-slit spectroscopy, and early integral field unit (IFU) observations from TIGER (Petitjean et al. 1996). In this paper we present IFU data covering the BR1202–0725 field from MUSE—simultaneously revealing an extended \( \text{Ly}\alpha \) halo around the QSO, allowing the reanalysis of \( \text{Ly}\alpha \) emission from companion galaxies embedded within the halo, and comparing the ionized- and cool-gas properties of both \( \text{Ly}\alpha \) halo and companion objects in the field.

This paper proceeds as follows: in Section 2, we describe the data used in this paper, and its processing before analysis. The data consist of archival Hubble Space Telescope (HST) imaging, an archival ALMA [C\II] datacube, deep ALMA dust-continuum imaging, and finally the MUSE datacube. We also describe briefly here our method for point-spread-function (PSF) subtraction in the MUSE cube. In Section 3, we present MUSE images of the field, and a spectrum of the QSO, followed by the results of our PSF subtraction. Here we analyze the spatial extent and morphology of the \( \text{Ly}\alpha \) halo, and take advantage of the spatial resolution of MUSE to produce moment maps of the \( \text{Ly}\alpha \) emission, and search for overlap or coincidence of \( \text{Ly}\alpha \) and \( \text{CII} \) emission across the field. We speculate on the dominant powering mechanism of the \( \text{Ly}\alpha \) halo and perform a search for extended \( \text{CIV} \) emission. Next, in Section 4, we present images and spectra of a series of companions in the field, including the SMG, LAE 1, and LAE 2. For each object in the system we assess the \( \text{Ly}\alpha \) emission and derive velocity widths, star formation rates (SFRs; where appropriate) and constraints on the rest-frame equivalent widths (EW\( \alpha \)) of \( \text{Ly}\alpha \) (again where possible) before using these measurements to reassess the nature of the proposed companions. We summarize our findings on the QSO’s \( \text{Ly}\alpha \) halo and all accompanying objects in Section 5.

We assume a Lambda cold dark matter cosmology with \( \Omega_m = 0.3, \Omega_{\Lambda} = 0.7 \) and \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\). In this cosmology, 1\("\) = 6.64 pkpc at \( z \approx 4.69 \).

2. Observations and Data Reduction

In addition to our analysis of the new MUSE observations, we make use of two existing data sets from ALMA, allowing a multiwavelength comparison of the ionized and neutral gas content of the BR1202–0725 system and archival HST imaging to give an optical overview of the field at the highest resolution available. The data sets are described below.

2.1. HST Overview of the Field

In Figure 1 we show the archival HST775w image of BR1202–0725, highlighting in the left panel the positions of the QSO, the SMG, the two known LAEs (LAE 1 and LAE 2), and an additional LAE discovered in this work, LAE 3. In the right-hand panel we show the HST775w image again, overlaying submillimeter dust-continuum contours from the deepest ALMA observations of the field, see Section 2.2.1 for a description. Both the archival HST imaging and the dust-continuum maps are used throughout this work for orientation purposes only. We include an overview of previously known objects in the field in Table 1.
overlaid with submillimeter continuum contours from ALMA. Contours are linearly spaced at 1σ = 12.38 mJy beam⁻¹, and negative contours are represented by dotted lines. The presence of the QSO and the optically obscured SMG are both demonstrated at >15σ, with emission of lower-significance present surrounding the positions of LAE 1, LAE 2, and SRC 6.

![Figure 1](image_url)

**Figure 1.** HST775w imaging is displayed in both panels, providing the highest-resolution optical data available for the field. In the left-hand panel we highlight the positions of the QSO, the optically obscured SMG, two known objects dubbed LAE 1 and LAE 2, a previously unreported source that we present in this work, LAE 3, and another previously unreported source that we name Source 6; hereafter “SRC 6.” In the right-hand panel we display the same HST image, this time overlaid with submillimeter continuum contours from ALMA. Contours are linearly spaced at ±1.5, 3.0, 6.0, 12.0, 24.0, 48.0, 96.0, 192.0, and 384.0σ where 1σ = 12.38 mJy beam⁻¹, and negative contours are represented by dotted lines. The presence of the QSO and the optically obscured SMG are both demonstrated at >15σ, with emission of lower-significance present surrounding the positions of LAE 1, LAE 2, and SRC 6.

### Table 1

**Known Objects in the BR1202 System at the Time of Writing**

| Object | z_{C 38} | Vel Offset | Pred λ Lyα | References |
|--------|----------|------------|-------------|------------|
| QSO    | 4.6942   | 0.0        | 6922.27     | McMahan et al. (1994); Isaak et al. (1994) |
| SMG    | 4.6915   | -142.1     | 6918.99     | Omont et al. (1996a); Riechers et al. (2006) |
| LAE 1  | 4.6950   | 42.0       | 6923.24     | Hu et al. (1996); Ohyama et al. (2004) |
| LAE 2  | 4.7055   | 595.5      | 6936.01     | Hu et al. (1997); Wagg et al. (2012); Carilli et al. (2013) |

**Notes.** The second column gives the redshift of the object found in the literature. The third column gives the offset in velocity between this object and the QSO. The fourth column gives the predicted wavelength of Lyα emission given the systemic redshift of the object. In the final column we include references for each object.

* Carilli et al. (2013), formal errors from Gaussian fitting on the redshifts are each <0.0003.

* Object’s velocity offset from the QSO, where negative numbers represent a blueshift and positive numbers a redshift.

#### 2.2. ALMA Observations

##### 2.2.1. Deep Continuum Imaging

In order to obtain a deep millimeter continuum map we explored all public data in the ALMA archive available for our system. Projected baseline lengths for the combined continuum data set are between 14 and 1440 m, with the 80th percentile at 288 m. We decided to combine the data in the frequency range of 190–297 GHz (bands 5, 6, and 7). Inside this 107 GHz bandwidth, 33 GHz was observed with six frequency setups. These setups cover several far-infrared bright molecular emission lines of CO (high excitation rotational CO lines J_{up} = 10, 12, 14) and H2O, and a fine atomic transition line [N II] at 205 μm. A total width of 1500 km s⁻¹ centered at each of the emission lines was excluded from the continuum imaging process. This width choice corresponds to two times the FWHM of the brightest [C II] line detected in the SMG inside this system Carilli et al. (2013). The continuum map was obtained from the remaining line-free channels spanning an effective bandwidth of 25 GHz. Individual spectral setups were observed at roughly similar resolutions, with a synthesized beam FWHM range of 0.6–1.5″, and a position angle of 88°, thus allowing joint imaging of all the data sets. For imaging we use the TCLEAN task contained in the Common Astronomy Software Applications (CASA) package (McMullin et al. 2007). Given the large bandwidth available, we image the data using the multi-term multifrequency synthesis (NTERMS = 2, Rau & Cornwell 2011). The data were imaged with natural weighting to maximize the point source sensitivity. The synthesized beam side-lobes of the combined data set are smaller than 5%. Due to good quality of the final map, no additional weighting of visibilities was deemed necessary. Cleaning was performed with a multiscale algorithm (using scales corresponding to a single pixel, 1× and 3× the beam size) first down to 5σ in the entire map, and then further down to 1.5σ inside manually defined cleaning regions, which outline the observed emission. The final continuum map is given at the

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9 Few band 6 setups partially overlap.

10 CASA version 5.4.0-70.

11 We have checked that reweighing of combined visibilities using the STATWT task in CASA does not further improve the map quality.
monochromatic frequency of 243.5 GHz, resolution of 0.83 × 0.73", and has a rms noise level of 1 σ = 12.38 μJy beam⁻¹.

2.2.2. Archival [C II] Observations

We make use of ALMA 335 GHz (band 7) Science Verification data with a central frequency targeting the [C II] line at the redshift of the QSO and the SMG. The data were first presented in Wagg et al. (2012) and Carilli et al. (2013). We applied a velocity-frame correction to the published data to convert from the observed frame (topocentric) to the local standard of rest for accurate comparison to velocities in the MUSE datacube.

2.3. MUSE Observations

2.3.1. MUSE Data Reduction

MUSE data were taken as part of ESO program 0102.A − 0428(A), PI Farina, and reduced as in Farina et al. (2017, 2019) using the MUSE Data Reduction Software version 2.6 (Weilbacher et al. 2012, 2014). Two exposures of 1426 s were taken, with <5" shifts and 90° rotations. The PSF has a size of 0.6" at the observed wavelengths of the Lyα line (the median delivered PSF on stars in the field is closer to 0.7" ). The 5σ surface-brightness detection limit is 4.2 × 10⁻¹⁷ erg s⁻¹ cm⁻² arcsec⁻² for an aperture of 1 square arcsecond. Data have been corrected for galactic extinction, and emission from night sky lines is removed using the Zurich Atmospheric Purge software (ZAP; Soto et al. 2016).

2.3.2. MUSE PSF Subtraction

With a view to uncovering low-surface-brightness Lyα emission in the MUSE data surrounding QSO BR1202 − 0725, we follow the same procedure as in Drake et al. (2019) to model and subtract the PSF in the data (also demonstrated in Farina et al. 2019). In brief, this entails collapsing several spectral layers of the QSO’s optical continuum, which is dominated by light from the accretion disk of the AGN, and appears as a point source at the resolution of MUSE. By using the quasar itself to create the “PSF image” we avoid issues of spatial PSF variation/interpolation across the field. The wavelength layers chosen to construct the PSF image are highlighted in pink in the right-hand panel of Figure 2. We then work systematically through the MUSE cube, scaling our PSF image such that the flux in the pixel at the image peak becomes equal to the flux of the QSO in the same spatial pixel. By subtracting this scaled PSF image from each wavelength layer we produce an entire PSF-subtracted datacube. Finally, as in Drake et al. (2019), we mask an ellipse on every layer of the datacube of radii equal to the FWHM of a two-dimensional Gaussian fit to the PSF image, and exclude this region from further analysis to avoid residuals near the bright central source, unless otherwise noted.

3. Extended Lyα in the BR1202 − 0725 Field

3.1. Total Flux of Lyα Halo around QSO BR1202 − 0725

In Figure 3 we show a narrowband image comprised of all the Lyα emission in a square 12" region surrounding the QSO. The narrow bandwidth was chosen to encompass the entirety of the red side of the Lyα line after PSF subtraction, and to include emission out to the same velocity blueward of the systemic redshift of the QSO. This amounts to a total of 61 Å, or ≈2640 km s⁻¹. In the right-hand panel of Figure 3 we show the PSF-subtracted spectrum extracted in a 3" diameter aperture shaded in blue, and overplot with a black line the PSF-subtracted spectrum that results from summing all emission within the 1 × 10⁻¹⁷ erg s⁻¹ cm⁻² arcsec⁻² surface-brightness contour. Interestingly the halo’s spectral shape is somewhat “flat topped,” which may be the result of contributions from objects at different velocities within the halo, or simply represent an intrinsically broad line. The flux of diffuse Lyα within the SB = 1 × 10⁻¹⁷ erg s⁻¹ cm⁻² arcsec⁻² surface-brightness contour is F_Lyα = 1.39 ± 0.01 × 10⁻¹⁵ erg s⁻¹ cm⁻², after continuum subtraction, masking both the position of the QSO (across a 1" diameter) and LAE 1 (across a 1.6" diameter). If the halo emission were powered solely by star formation, we could translate this to an SFR according to Equation (1) (Ouchi et al. 2003):

\[
\text{SFR}_{\text{L}y\alpha}(M_\odot \text{ yr}^{-1}) = L_{L\alpha} \times 1.05 \times 10^{24.0} \text{ erg s}^{-1},
\]

where L_Lyα is the Lyα luminosity in cgs units. Our measured flux translates to a luminosity of \( L_{L\alpha} = 3.11 \times 10^{44} \text{ erg s}^{-1} \), which would then correspond to an SFR of almost \( \approx 300 M_\odot \text{ yr}^{-1} \).

3.2. Morphology of Extended Lyα around QSO BR1202 − 0725

To examine the distribution of the diffuse Lyα in more detail, we show in Figure 4 a narrow velocity range (~200 km s⁻¹, i.e., a collapse of the monochromatic wavelength...
layers between 6927 and 6932 Å). This choice of velocity range reveals filamentary structure at low-surface-brightness levels, highlighting the complex morphology of the halo, while encompassing wavelength layers within which the QSO, LAE 1, LAE 2, and LAE 3 are all visible. In the top left-hand panel we show the Lyα surface brightness, contoured between SB = 5 × 10^{-19} and 5 × 10^{-18} erg s^{-1} cm^{-2} arcsec^{-2}, and again highlight the positions of the QSO, the SMG, and three LAEs in the system. Figure 4 demonstrates that diffuse Lyα connects all three objects, while none is seen surrounding the SMG. Interestingly, the low-surface-brightness emission in Lyα extends directly in the direction of the optically obscured SMG, and fully encompasses the position of LAE 1, however, by the position of the SMG, the halo is no longer visible in this velocity range. The Lyα emission at the position of LAE 2 however appears indistinguishable from the halo extending from the QSO in this image—we return to this in Section 4.2. Finally, LAE 3 appears as a distinct source in Lyα, however, its emission is possibly connected via a low-surface-brightness bridge of Lyα emission to the position of the QSO. In the top right-hand panel we display the same Lyα surface brightness image, but this time overlay contours depicting [C II] emission (Wagg et al. 2012; Carilli et al. 2013) from the entire collapsed datacube. In the lower panels, we show cutouts at three different velocities relative to the systemic redshift of QSO BR1202−0725 (i.e., a velocity slice of the Lyα halo overlaid with contours depicting [C II] emission in the corresponding velocity slice). The velocities shown were here selected from the full series of channel maps presented in Appendix B, and are chosen to highlight a number of features; first, the purported [C II] bridge between the QSO and the SMG. This is seen at negative velocities (corresponding to the slightly lower redshift of the SMG than the QSO), which is seen across multiple channels; second, in the central panel we show the channel closest to systemic redshift, and the extended [C II] persists, with a local maximum thought to define the position of LAE 1’s interstellar medium (ISM). In the final panel, 500 km s^{-1} redward of the QSO, the position of LAE 2 becomes clear. Together, these data begin to highlight the diversity of properties of the objects in this field. While the QSO appears bright in both Lyα and [C II] emission, the SMG appears only at submillimeter wavelengths. LAEs 1 and 2 show [C II] emission most visible in channels at their respective velocities, however, LAE 3 does not show any associated [C II] emission. We will return to each of these features and discuss the objects’ nature in Section 4.

3.3. Kinematic Analysis of Lyα around QSO BR1202−0725

To analyze the internal kinematics of the extended Lyα emission, we present zeroth-, first-, and second-moment maps (representing the total flux, velocity, and dispersion maps, respectively) in Figure 5, relative to the predicted peak of the Lyα line at a systemic redshift of z = 4.6942. We analyze the data in a manner consistent with Drake et al. (2019); we first smooth the datacube in the two spatial directions with a Gaussian kernel of σ = 1.0 pixel, and calculate the nonparametric moments of the data, i.e., we do not assume any functional form for the Lyα spectral shape. In the first panel we show the flux-weighted zeroth-moment. This image/map is essentially the same as that shown on the left-hand side of Figure 3.

In the central panel we show the first moment of the halo’s Lyα emission, which gives the flux-weighted velocity of the halo gas relative to the peak of the emission, applying a uniform post-processing signal-to-noise ratio (S/N) cut of 1.0 on the moment zero image. The velocity structure is clumpy and complex. The majority of the extended emission, which appears to the north of the QSO, is redshifted by a few hundred km s^{-1}, only small patches of emission (∼2″ on-sky) appear blueshifted, and they each appear toward the south of the QSO. LAE 1 does not appear kinematically distinct from the halo. No obvious signs of a flow of gas between the two objects is seen in this map, however, for a more thorough examination of the relative velocities of Lyα and [C II] emission across the field of view we refer the reader to Appendix B where we show a series of “channel maps,” displaying images of the extended Lyα emission seen with MUSE, overlaid with [C II] contours from ALMA (see Carilli et al. 2013; Wagg et al. 2012). The spectral resolution of MUSE at ~7000 Å corresponds to ~Δv = 100 km s^{-1}. The channel spacing in velocity of the [C II] emission seen with ALMA is ~Δv = 35 km s^{-1}. The maps show that the extended Lyα emission is to some extent co-spatial with the [C II], and peaks at the same velocities as the [C II] bridge...
between BR1202−0725 and the SMG proposed in Carilli et al. (2013). The Lyα emission is however much broader than the [C II] emission, and as such Lyα still appears bright in channels beyond the end of the ALMA [C II] coverage.

Finally, in the third panel of Figure 5, we show the second moment, $\sigma$, giving the velocity dispersion of the gas, and applying the same uniform S/N cut of 1.0 on the moment zero image. Velocities close-in to the QSO are very high, of order $\sim 1000 \text{ km s}^{-1}$, with a region of lower values (of order 500 km s$^{-1}$) in the direction of LAE 1.

3.4. Constraints on the Dynamical Mass of the Halo

Using the moment maps, we can roughly estimate the dynamical mass of this gas given a number of assumptions. For instance, in the moment zero flux image (Figure 5, left) where the entire width of the Lyα line is collapsed, emission stretches $\approx 8''$ north–south, and $\approx 8''$ east–west surrounding the QSO. We therefore take an average radius of 4'', which corresponds to $\approx 27 \text{ pkpc}$ at $z = 4.69$. In the moment 1 map (Figure 5, center) we see a gradient of approximately $v \approx \pm 300 \text{ km s}^{-1}$ across the halo. Then, if one assumes rotation of the gas is responsible for the velocity gradient, we solve for dynamical mass $M_{\text{dyn}}$:

$$M_{\text{dyn}} = rv^2/G,$$

where $G$ is the gravitational constant, $r$ is the halo radius, and $v$ is the velocity range across this radius. As we have no information on inclination angle, we place a lower limit on the dynamical mass of the halo: $M_{\text{dyn}} \geq 6 \times 10^{11} M_{\odot}$. Even without any correction for an inclination angle, this is significantly larger than the combined molecular gas mass of the QSO-SMG system reported in the literature ($\approx 10^{11} M_{\odot}$; Omont et al. 1996a; Riechers et al. 2006), and 2 orders of magnitude larger than the QSO’s black hole mass, $M_{\text{BH}} = 1.9 \times 10^9 M_{\odot}$ (Carniani et al. 2013).
3.5. Speculation on Lyα Powering Mechanism

The powering mechanisms of Lyα halos at high redshift have long been debated. BR1202–0725 is an example of a system where any one of the proposed mechanisms outlined in Section 1 could naively be assumed the primary driver of the halo emission, or perhaps more likely, a complex mixture of processes are responsible. The QSO has an obscured SFR in excess of 1000 $M_\odot$ yr$^{-1}$ (Carilli et al. 2013), and as such, in situ star formation could be responsible for the extended Lyα emission. Likewise, copious amounts of pristine gas are required to fuel this major merger which could give rise to gravitational cooling of the gas as it is funneled onto the QSO. It is perhaps of some significance then that QSO BR1202–0725 is accompanied by the SMG of similar gas mass, inferred SFR, and dust content (Carilli et al. 2013), but that displays no prominent Lyα halo. In the absence of any further diagnostics, this lends support to the idea that the Lyα halo is directly linked to the actively accreting supermassive black hole in the QSO, and not to star formation.

Several studies in the literature have recently taken steps toward identifying the powering mechanisms of Lyα halos around QSOs through the use of additional diagnostic lines (Arrigoni Battaia et al. 2018). Motivated by these studies, we take advantage of the spectral coverage of MUSE to search for any extended C IV emission surrounding BR1202–0725. The metal line C IV indicates whether the Lyα-emitting gas has been enriched (i.e., it originated within the host galaxy) or is pristine (falling onto the halo for the first time). In Appendix C, Figure C1, we show the MUSE spectrum of QSO BR1202–0725 again, and overlay a composite quasar spectrum (Selsing et al. 2016), “redshifted” to $z = 4.6942$. We highlight on this spectrum the predicted observed wavelengths of various emission lines, in particular C IV $\lambda_{\text{em}} = 1549$ Å. We extract an image and spectrum exactly as for Lyα in Figure 3, but this time centered on the predicted wavelength of C IV. We detect no extended C IV emission down to a surface-brightness limit of $0.19 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ in a square arcsecond. Given however that metal lines in high-redshift QSOs are frequently observed to be blueshifted with respect to the systemic velocity, we repeat this exercise in the 8500–8700 Å region where we see a subtle, a broad “bump” in the QSO spectrum, but find no evidence for extended emission in this region either. Unfortunately these results do not place any strong constraint on the powering mechanism of this Lyα halo, i.e., in the absence of strong radio emission C IV luminosities are so much fainter than Lyα emission (e.g., typically C IV/Lyα $\lesssim 0.13$ in Lyα “blobs” where no definitive power source has been determined; Arrigoni Battaia et al. 2018). Although radio continuum has been observed in both the QSO and SMG here, the emission is consistent with a weak AGN or extreme star formation (Yun & Carilli 2002; Carilli et al. 2013) and not the powerful high-redshift radio galaxies that are known to exhibit significant extended C IV (e.g., Matsuoka et al. 2009).

4. Companions in the Field

In this section, we present new spectra from MUSE of the two known LAEs in addition to LAE 3 discovered in this work. We present measurements of the Lyα flux, velocity width, and rest-frame EW$_{\alpha}$, and discuss the results below. In addition we investigate the existence of an additional source, dubbed SRC 6, motivated by an alignment of dust-continuum emission and a compact object seen in HST775w imaging. The diversity of object properties (and their staggered discovery) means that the data set in which each object’s position is defined varies. Where possible, we take the object’s position directly from Table 1 of Carilli et al. (2013) (i.e., for the QSO, SMG, LAE 1, and LAE 2). For the QSO, SMG, and LAE 2 this is the dust-continuum position. For LAE 1 this is the [C II] position. LAE 3 is defined by its MUSE detection, and the position of SRC 6 is defined as the center of the dust emission.

4.1. Lyα Properties of Companions

In Table 2 we summarize our measurements of Lyα emission from the MUSE cube for each of the objects known in the BR1202–0725 field, plus LAE 3, and the potential source SRC 6. We also include cutout images and spectra in Appendix A to demonstrate our choice of aperture size and the MUSE MUSE from which we measure the Lyα flux (Table 2 column 5).

The complexity of the BR1202–0725 system and the diffuse Lyα emission in the field make it difficult to identify individual objects’ Lyα in an image as objects are essentially “embedded” within the diffuse Lyα halo stretching across the entire field. For this reason we choose very narrow velocity ranges over which we display the corresponding Lyα image in the final column of Figure A1. We then choose an aperture on these images to encapsulate the emission from a particular object.
For two objects, LAE 1 and LAE 3, the Lyα flux can be estimated simply by fitting a Gaussian profile to the 1D spectral extraction. For these two objects we also place constraints on the rest-frame EW0 of Lyα from the MUSE spectrum. Accurate measurements of LAEs’ EW0 at this redshift are potentially of great interest due to their ability to distinguish between powering mechanisms of Lyα emission. Models based on standard IMFs, stellar populations, and metallicity ranges for instance predict a maximum value of $EW_0 = 240\,\text{Å}$ for emission powered by star formation (see Schaerer 2003; Hashimoto et al. 2017). For LAE 2 it is difficult to produce a good fit from the 1D spectrum, so we first fix the peak of the Gaussian to the predicted wavelength of Lyα emission corresponding to LAE 2’s systemic redshift. For the remaining objects (the QSO, the SMG, and SRC 6) we simply sum the flux across a 50 Å window (i.e., ≈twice the measured FWHM of LAE 1).

We recover a Lyα flux estimate for LAE 1 of $F_{\text{Lyα}} = 1.54 \pm 0.05 \times 10^{-16}\,\text{erg}\,\text{s}^{-1}\,\text{cm}^{-2}$ over an aperture of diameter 1.5″. This flux measurement and its associated velocity width and EW0 can be compared to the values in the literature from long-slit spectroscopy presented in Williams et al. (2014). Our flux measurement for LAE 1 is actually somewhat smaller than the result in the literature ($F_{\text{Lyα}} = 2.53 \pm 0.08 \times 10^{-16}\,\text{erg}\,\text{s}^{-1}\,\text{cm}^{-2}$), possibly due to the halo contaminating the end of the long slit[12] but we find a large velocity width of FWHM = 1149 ± 45 km s⁻¹, almost consistent with the value found in the literature value (FWHM = 1381 ± 124 km s⁻¹). We also measure the equivalent width, and find $EW_0(Ly\alpha) = 72.9 \pm 2.2\,\text{Å}$. This is a fairly large EW0, although smaller than the published estimate ($EW_0 = 103 \pm 15\,\text{Å}$) from long-slit spectroscopy. The difference is possibly explained by factors such as contamination of the long slit by light from the QSO (which would boost the measured Lyα flux and hence the EW0). Even so, our flux estimate may be subject to overestimating the Lyα originating within LAE 1 as we too observe the object through the QSO’s Lyα halo, and fit a 1D Gaussian fit to this line. Conversely, however, factors such as underestimating the true extent on-sky of LAE 1 and the inaccuracy of a Gaussian fit may result in our missing some flux.

LAE 2 has a low Lyα flux with emission that appears diffuse on-sky and with a large velocity width. Taking an aperture of 1.5″ in diameter driven by the object’s appearance in HST imaging, we measure a flux of $F_{\text{Lyα}} = 0.54 \pm 0.05 \times 10^{-16}\,\text{erg}\,\text{s}^{-1}\,\text{cm}^{-2}$, and a velocity width of FWHM = 2480 ± 275 km s⁻¹. The numbers we derive are similar to previous results (Williams et al. 2014) measure a flux of $F_{\text{Lyα}} = 0.33 \pm 0.06 \times 10^{-16}\,\text{erg}\,\text{s}^{-1}\,\text{cm}^{-2}$, a velocity width of FWHM = 1225 ± 257 km s⁻¹, and an EW0 = 67 ± 15 Å).

In the vicinity of the SMG we measure faint Lyα emission, but are unable to force a fit to this line in order to measure a flux, velocity width, or EW0. Summing the flux over 50 Å (for consistency with LAE 1), in an aperture of diameter 1.5″, we measure a low-level of Lyα emission at $F_{\text{Lyα}} = 0.04 \pm 0.01 \times 10^{-16}\,\text{erg}\,\text{s}^{-1}\,\text{cm}^{-2}$.

Next we measure a Lyα flux and line properties for the newly discovered source LAE 3. We find a flux of $F_{\text{Lyα}} = 0.24 \pm 0.03 \times 10^{-16}\,\text{erg}\,\text{s}^{-1}\,\text{cm}^{-2}$ over a diameter of 1.5″. The velocity width measures FWHM = 471 ± 62 km s⁻¹, significantly narrower than LAE 1, or indeed any of the other objects in the system. We do not see continuum emission from LAE 3 in the MUSE data, therefore, we place a lower limit on the EW0 of LAE 3. To do so, we use the rms of an image of Δλ = 700 Å, redward of the emission line, to place an upper limit on the continuum, and in combination with the flux measurement, derive a 5σ upper limit of $EW_0(Ly\alpha)^{\text{lim}} > 34.05\,\text{Å}$.

The final object for which we measure a Lyα flux is SRC 6. Motivated by an alignment of dust-continuum emission and a compact object seen in HST1775w, we extracted a spectrum at the HST1775w position to search for Lyα emission. We see no evidence for significant Lyα emission originating from the object seen in HST imaging, although a marginal detection is seen ~0.2″ south. We report in Table 2 the flux seen in a 1″ aperture at this position, and the redshift if the corresponding tentative detection in the ALMA cube is [C II] emission.

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**Table 2**

| Object | Position (J2000) | $z_{\text{best}}$ | $\lambda_{\text{obs, Ly}\alpha}$ (Å) | $F_{\text{Lyα}}(10^{-16})$ (erg s⁻¹ cm⁻²) | FWHM$_{\lambda_{\text{Ly}\alpha}}$ (km s⁻¹) | EW$_{\lambda_{\text{Ly}\alpha}}$ (Å) | SFR$_{\lambda_{\text{Ly}\alpha}}$ ($M_\odot$ yr⁻¹) |
|--------|-----------------|-----------------|-----------------------------|----------------------------------------|---------------------------------|-----------------------------|---------------------------------|
| QSO    | J120523.13–074232.6 | 4.6942          | No peak                     | 13.9 ± 0.18                            | ...                            | ...                         | 296.0 ± 4.0                   |
| SMG    | J120522.98–074229.5 | 4.6915          | 6941.86                     | 0.12 ± 0.02                            | ...                            | 11.9 ± 0.04                  | 32.9 ± 3.3                    |
| LAE 1  | J120523.06–074231.2 | 4.6850          | 6932.25                     | 1.54 ± 0.05                            | 1149 ± 45                     | 72.9 ± 2.2                  | 32.9 ± 3.3                    |
| LAE 2  | J120523.04–074234.3 | 4.7055          | 6936.00 (fx)                | 0.54 ± 0.05                            | 2480 ± 275                    | 72.9 ± 2.2                  | 32.9 ± 3.3                    |
| LAE 3  | J120523.19–074227.7 | 4.7019          | 6931.65                     | 0.24 ± 0.03                            | 471 ± 62                      | 72.9 ± 2.2                  | 32.9 ± 3.3                    |
| SRC 6  | J120523.46–074232.1 | 4.7035          | 6932.44 (fx)                | 0.03 ± 0.01                            | ...                            | ...                         | 5.0 ± 0.5                     |

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**Notes.** The first column lists the name of each object. The second column provides the position of each object (see the text for details). The third column provides the best estimate of the object’s redshift; either the [C II] redshift from Carilli et al. (2013), or the Lyα redshift measured here. The fourth column provides the observed peak wavelength of Lyα emission from fitting the peak of the 1D spectra. The fifth column provides the flux within an aperture of 1.5″ in diameter (except for the QSO halo and SRC 6, see footnotes). The sixth column provides the velocity width of the Lyα line (FWHM), where it was possible to fit the 1D spectrum with a Gaussian. The seventh column provides the rest-frame Lyα EW0 (or a 5σ lower limit) where appropriate. The last column provides the SFR calculated from each object’s Lyα emission, again where appropriate.

*a $EW_0 = (F_{\text{Lyα}}/F_{\text{cont}}) \times (1/(1 + z_{\text{best}}))$.

*b $z_{\text{best}}$.

*c For the QSO halo we report the flux summed within the SB $> 10^{-17}\,\text{erg}\,\text{s}^{-1}\,\text{cm}^{-2}\,\text{arcsec}^{-2}$ contour across the entire field. Both the residuals from PSF subtraction, and the position of LAE 1 are masked.

[12] See Figure 1 in Williams et al. (2014) for their slit placement.
Figure 6. Cutout images and spectra of companion objects in the vicinity of the QSO-SMG system at $z \sim 4.7$. In the left-hand panels we show a cutout of the object in the Hs775w image, overlaid with Ly$\alpha$ contours (log spaced with the lowest contour at 1$\sigma$) from the MUSE cube, at the velocity of interest (either $\lambda$ Ly$\alpha_{\text{pred}}$, or the peak of the Ly$\alpha$ emission if there is no C II detection). In the central panels we take the same approach using the submillimeter data, and show a cutout of the object from the ALMA dust-continuum map, overlaid with contoured C II emission at the relevant velocity (contours are log spaced with the lowest contour at 1.5$\sigma$). In the right-hand panels we show Ly$\alpha$ and C II spectra extracted within the aperture shown on the left-hand side. On the spectra a dotted black line represents the velocity shown in contours. For the relevant objects (the QSO, LAE 1 and LAE 2) we include an arrow to indicate the coherent absorption feature seen in these objects.
4.2. Nature of Companions

In combination with our measurements of Lyα emission from the sources in this field, we use existing ALMA data to compare the Lyα and [CII] images and spectra, together with high-resolution optical HST775w images, and our dust-continuum map from ALMA. We evaluate the most likely physical scenarios leading to each object’s appearance in these data sets based on Figure 6, also taking note of the channel maps shown in Appendix B, Figure B1. In each row of Figure 6, we show a single object. In the left-hand panel, we show an HST775w image representative of the optical stellar light, overlaid with Lyα contours extracted from the MUSE cube at the redshift of the object. These cutouts demonstrate the extended nature of Lyα emission compared to our previous best impression of the objects’ optical sizes. In the central panel we show a dust-continuum map, overlaid with contours depicting [CII] emission at each object’s peak velocity. Finally in the right-hand panels we show the Lyα and [CII] spectra in velocity space, relative to the systemic redshift of the QSO.

Interestingly, for those objects with [CII] emission (and hence a systemic redshift), it is not evident that Lyα emission is always present at the same velocity, or even at the objects’ positions on-sky at all. Likewise, the brightest objects shining in Lyα do not always correspond to a detection in [CII].

4.2.1. QSO

The QSO’s continuum and PSF-subtracted spectrum were shown in Figure 3, and we discussed the flux measurement in Section 3.1. No distinct “peak” is seen at the predicted wavelength of Lyα, but copious amounts of emission remain across a broad range of velocities. As seen in Figure 3, when the emission greater than $1 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ is summed, the line profile becomes more centrally concentrated in wavelength. The most striking feature of this spectrum is the distinct absorption feature seen at $\approx 6912$ Å. The absorption saturates indicating a high column density of H I gas approximately 400 km s$^{-1}$ from the QSO. This kind of signature has sometimes been interpreted in the literature as an expanding shell of neutral gas surrounding a QSO (e.g., van Ojik et al. 1997; Binette et al. 2000).

4.2.2. SMG

In the literature, optical emission from the SMG has evaded detection. As described above, in the MUSE datacube we place an aperture at the position of the SMG and are able to measure Lyα emission, which would be equivalent to an instantaneous SFR$_{Ly\alpha}$ $\approx 2$ $M_\odot$ yr$^{-1}$. The line profile however is remarkably similar to the QSO’s Lyα halo, and indeed no source is visible by eye in the Lyα channel maps at the position of SMG. We conclude that the Lyα line detected at this position arises from the edge of the QSO’s extended Lyα halo, and so we choose not to report a Lyα velocity width, EW$_0$ or SFR for the SMG in Table 2. The channel maps in Appendix B present interesting features in the Lyα emission in the vicinity of the SMG. In particular, multiple channels spanning a few hundred kms$^{-1}$ display very low-surface-brightness emission elongated west of the SMG.

4.2.3. LAE 1

LAE I is well studied, and the measurements we report here are broadly consistent with the results in the literature. As already noted by other studies, including Williams et al. (2014), the EW$_0$(Lyα) is high, although it is consistent with being powered by star formation. In addition, Williams et al. (2014) argue that since no C IV or He II emission is detected in this source, there can be at most a 10% contribution to LAE I’s...
Ly$\alpha$ flux from AGN-powered photoionization. So in conclusion, there may be multiple powering mechanisms at work for the Ly$\alpha$ emission falling into the aperture. (A) Some star formation occurring within LAE 1, (B) perhaps up to a 10% contribution from an AGN, and (C) the Ly$\alpha$ halo extending from the QSO, within which LAE 1 is embedded. Previous measurements of the SFR using various techniques reported values for LAE 1 in the range of SFR$_{UV} = 13 \, M_{\odot} \, yr^{-1}$ (Ohyama et al. 2004) to SFR$_{CII} = 19 \, M_{\odot} \, yr^{-1}$ (Williams et al. 2014). Transforming our Ly$\alpha$ flux to an SFR we find an SFR$_{Ly\alpha} \approx 32 \pm 3 \, M_{\odot} \, yr^{-1}$. We also note that the Ly$\alpha$ line profile is symmetric, which is not always typical of LAEs at high redshift due to the very low neutral fraction ($10^{-4}$) required to absorb all photons blueward of 1215.67 Å, often leading to an asymmetric line (e.g., Fan et al. 2001). Williams et al. (2014) were the first to infer that the symmetric profile of LAE 1 places a constraint on the size of the ionized bubble surrounding QSO BR1202−0725, and we concur with this conclusion. Finally, we note that the absorption feature visible clearly in the spectrum of the QSO at $z = 0.725$, at some $\sim 6932 \, \AA$, is broad, and offset in velocity from the predicted position according to the peak of [C II] in LAE 1. Note this is greater than the previously reported value in the literature due to our velocity-frame correction (Section 2.2.2). Upon close inspection of the channel maps shown in Appendix B, it is interesting to note that the [C II] coordinate reported for LAE 1 (most apparent in the channel at $23.93 \, \text{km s}^{-1}$) is offset by $\sim 0.6''$, although the aperture within which we extract spectra and measure flux contains both peaks. Furthermore, the purported [C II] “bridge” of emission between the QSO and the SMG, appears to “swirl” around the position of LAE 1, appearing for instance both to the east and to the west of the Ly$\alpha$ peak of LAE 1 at velocities either side of the peak. Assuming that both the [C II] and Ly$\alpha$ originate from the source known as LAE 1, this could be indicative for example of tidal disruption of LAE 1’s ISM during a merger between itself, the SMG, and the QSO. Regardless, we conclude that LAE 1 is indeed likely to be a star-forming LAE associated with this group of merging galaxies, and embedded within the extended Ly$\alpha$ halo of the QSO, possibly shielded by an expanding “shell” of optically thick gas giving rise to the absorption feature.

4.2.4. LAE 2

As we reported in Section 4.1, the Ly$\alpha$ line that we measure is broad, and offset in velocity from the [C II] line at the position of LAE 2. Until now this has not presented difficulty for the physical interpretation of Ly$\alpha$ emission in the vicinity of LAE 2. Taking advantage of the simultaneous spectral and spatial coverage of MUSE, however, we see that the Ly$\alpha$ emission-line profile is remarkably similar to that from the QSO’s halo. Furthermore, although LAE 2 appears distinct in HST775w imaging, stepping through channels of the MUSE cube, no particular layer shows spatially peaked Ly$\alpha$ emission relative to the diffuse emission across the field. Specifically, we check the predicted wavelength of Ly$\alpha$ from LAE 2’s [C II] emission, but in addition extend the search outward to both positive and negative velocities. No spectral region suggests the presence of an object in the MUSE datacube. This implies that perhaps the emission seen in HST775w is stellar continuum, which is outshone by diffuse Ly$\alpha$ in the BR1202−0725 halo in the MUSE cube. Indeed, we see in the channel maps that diffuse Ly$\alpha$ emission appears to extend toward the position of LAE 2 in the velocity channels preceding LAE 2, we speculate that LAE 2 is perhaps passing through the QSO’s Ly$\alpha$ halo, with a peculiar velocity directly away from the observer. From the information added here from MUSE, we conclude that the object often referred to in the literature as LAE 2 is in fact not responsible for powering the Ly$\alpha$ emission seen at this position in previous data sets, and this Ly$\alpha$ line is entirely consistent with being part of the extended halo surrounding QSO BR1202−0725. We do once again see the absorption feature at 6912 Å, indicating that this position on-sky is also covered by the absorbing gas.

4.2.5. LAE 3

The newly discovered LAE 3 shows a bright Ly$\alpha$ line peaking at 6931 Å, placing the LAE at a redshift of $z_{Ly\alpha} = 4.7019$. We measure properties for LAE 3 more consistent with typical LAEs at high redshift, e.g., Drake et al. (2017a, 2017b), Hashimoto et al. (2017), Wisotzki et al. (2016), and Leclercq et al. (2017). The measured flux for LAE 3 translates to an SFR $= 5 \pm 0.5 \, M_{\odot} \, yr^{-1}$. We place a lower limit on the EW$_{0}$ of LAE 3 of EW$_{0}(Ly\alpha_{5100}) \geq 34.05$ Å. This is consistent with in situ star formation as the primary power source of the Ly$\alpha$ line, although we cannot rule out contributions from an AGN, or perhaps the edge of the QSO’s halo also.

No [C II] or dust-continuum emission is detected at the position of LAE 3. This is not altogether surprising, given the young ages and low metallicities typical of the high-redshift LAE population. Therefore, LAE 3 is most likely to be a star-forming LAE at the redshift of the QSO. Interestingly, the profile of the Ly$\alpha$ line appears symmetric just as in LAE 1. Following the arguments in Williams et al. (2014), we here propose that the symmetric profile of LAE 3 indicates a new lower limit on the radius of the H II sphere/proximity zone of QSO BR1202−0725, at some $\sim 30$ pkpc away (also see Bosman et al. 2020 for a discussion on proximate LAEs at high redshift). Finally, the coherent absorption feature seen in the spectra of the other objects is at a bluer wavelength than the edge of this narrow Ly$\alpha$ line, and as such we cannot say if the proposed absorbing shell extends to the position of LAE 3.

4.2.6. SRC 6

SRC 6 is detected primarily in the dust continuum. In addition, we see tentative [C II] emission coincident with part of the area of dust emission, and an even less convincing Ly$\alpha$ detection. If the [C II] detection is real, this places the object at $z = 4.7025$. It is notable also, that low-surface-brightness Ly$\alpha$ emission in this region could once again be part of the QSO’s Ly$\alpha$ halo, appearing coincident with an unrelated object along the line of sight.

5. Summary

We have presented new optical IFU data from MUSE across the BR1202−0725 field, which is one of the most overdense regions of the early universe known at $z = 4.69$. BR1202−0725 is clearly a very extreme system, undergoing a major
merger and demonstrating drastic tidal disruption of the smaller galaxies in the vicinity. Prior to this work, BR1202−0725 was already one of the most-studied single targets at high redshift, acting as a laboratory for the study of diverse galaxies typically detected via different selection techniques, all evolving in the same environment. Here, we examine the Lyα halo surrounding QSO BR1202−0725 and measure Lyα properties for companions in the field, including a new LAE discovered in this work. In conjunction with existing ALMA observations we examine and compare the neutral and ionized gas content of the BR1202−0725 system’s Lyα halo and constituent objects, which provides us with the best view to date of the physical processes under way in BR1202−0725 until new facilities (e.g., the James Webb Space Telescope (JWST) and the Guaranteed Time Observations program) become available. Our main findings can be summarized as follows:

1. QSO BR1202−0725 exhibits a large Lyα halo, stretching across at least ~8″ on-sky (~55 pkpc at z = 4.6942) at surface-brightness levels greater than 1 × 10^{-17} erg s^{-1} cm^{-2} arcsec^{-2}.

2. In contrast, no Lyα halo is detected around the SMG, which has a similar gas mass and SFR as the QSO.

3. We do not find evidence for extended CIV emission surrounding the QSO down to a surface-brightness limit of SB ~ 0.19 × 10^{-16} erg s^{-1} cm^{-2} arcsec^{-2} in a square arcsecond, and hence cannot place any constraint on the dominant powering mechanism of the Lyα halo.

4. The optical NW companion of QSO BR1202−0725 known as LAE1 appears to be a Lyα-emitting galaxy embedded within the larger region of diffuse Lyα emission. Taking an aperture of 2″ in diameter, we measure a Lyα flux, velocity width consistent with the measurements in the literature from long-slit spectra. We measure an EW(Lyα) = 72.9 ± 2.2 Å; this is probably due to a combination of powering mechanisms for the Lyα.

5. The optical SW companion of QSO BR1202−0725, confirmed in C II and N II emission, known as LAE2 is not necessarily responsible for the Lyα emission previously reported at this position. Although we detect a Lyα line, it appears diffuse on-sky, with no local maximum coinciding with the position of LAE2. The Lyα line profile, peak, and FWHM are also more consistent with being part of the QSO's diffuse halo.

6. We detect an additional LAE in the BR1202−0725 system ~5″ to the north of the QSO, and denote it LAE3. The object was discovered serendipitously in the MUSE datacube, and exhibits a bright but narrow Lyα line of flux 0.24 ± 0.03 × 10^{-16} erg s^{-1} cm^{-2} (1″5), a velocity width of 471.23 km s^{-1}, and EW(Lyα) ≥ 34.05 Å. This LAE is more aligned with typical properties of Lyα emitters at high redshift, with Lyα emission consistent with powering by star formation.

7. The symmetric profile of Lyα in LAE3 places a new constraint on the size of the H II bubble surrounding QSO BR1202−0725 of ~60 pkpc in diameter.

8. We see coherent absorption, possibly indicative of an expanding shell of H I gas, 400 km s^{-1} in front of BR1202−0725 across at least 4″ on-sky, corresponding to ~24 pkpc (diameter). The feature is blueward of the edge of Lyα from LAE3 and hence we cannot confirm whether LAE3 is covered by the H I gas.

These results demonstrate the efficiency of MUSE for detecting low-surface-brightness Lyα emission in addition to the instrument’s use as a “redshift machine” for the detection of emission-line galaxies. Furthermore, the combined power of MUSE and ALMA to examine both ionized- and cool-gas components offers unprecedented insights on the nature of a diverse population of objects at high redshift. This work also highlights the need for follow-up of Lyα halos with future facilities (such as JWST) with a view to unambiguously detecting/ruling out the presence of, e.g., metal lines, to finally disentangle the processes powering these giant structures.

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Software: Astropy (Astropy Collaboration et al. 2013); CASA (McMullin et al. 2007), MUSE data reduction pipeline (Weilbacher et al. 2012), (Weilbacher et al. 2014), ZAP (Soto et al. 2016), MPDAF (Piqueras et al. 2017).

Appendix A

We include here in Figure A1 the spectra and images from which we measure the Lyα properties of each source. In the left-hand panels we show a cutout of the object in the high-resolution HST775w image, in the central panels we show a spectrum extracted from the MUSE cube within the aperture shown on the HST775w image, and in the right-hand panels we show a cutout image extracted from the MUSE cube across the wavelength range shaded in orange on the spectrum. Apertures are centered on the [C II] positions reported in Carilli et al. (2013) where possible, otherwise the peak of the Lyα emission seen in MUSE is taken. For the objects where no 1D Gaussian fit could be performed, we shade in red the region of the spectrum that is summed to estimate the Lyα flux.
Figure A1. Cutout images and spectra of companion objects in the vicinity of the QSO-SMG system at $z \sim 4.7$. 
Figure A1. (Continued.)
Appendix B

Figure B1 shows the MUSE and ALMA channel maps depicting the extended Ly$\alpha$ and [C II] emission at a series of velocities relative to the QSO’s systemic redshift in Figure A1.

Figure B1. MUSE Ly$\alpha$ channel maps, overlaid with [C II] contours from ALMA, where contours are linearly spaced at $\pm 1.5$, 3.0, 6.0, 9.0, 12.0, and 15.0$\sigma$, and negative contours are represented by dotted lines. MUSE data have been rebinned in velocity for comparison to the lower velocity resolution of the ALMA channels.
Figure B1. (Continued.)
Figure B1. (Continued.)
Figure B1. (Continued.)
Figure B1. (Continued.)
Appendix C

This appendix demonstrates our search for extended CIV emission surrounding QSO BR1202−0725 discussed in Section 3.4; see Figure C1.

Figure C1. In the top panel we show the QSO spectrum extracted in a 2″ diameter aperture (black line, blue filled) and its associated noise (gray). This is overlaid with a QSO template from Selsing et al. (2016) (dark red, offset for clarity) that gives the predicted positions of emission lines in the spectrum. In the lower two panels we show the same two cutouts as in Figure 3, however, this time centered on the blueshifted wavelength region corresponding to CIV emission. No extended CIV emission is detected.
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