The Detection of Intergalactic Hα Emission from the Slug Nebula at $z \sim 2.3$

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ABSTRACT

The Slug Nebula is one of the largest and most luminous Lyman-α (Lyα) nebulae discovered to date, extending over 450 kiloparsecs (kpc) around the bright quasar UM287 at $z=2.283$. Characterized by high surface brightnesses over intergalactic scales, its Lyα emission may either trace high-density ionized gas (“clumps”) or large column densities of neutral material. To distinguish between these two possibilities, information from a non-resonant line such as Hα is crucial. Therefore, we analyzed a deep MOSFIRE observation of one of the brightest Lyα emitting regions in the Slug Nebula with the goal of detecting associated Hα emission. We also obtained a deep, moderate resolution Lyα spectrum of the nearby brightest region of the Slug. We detected an Hα flux of $F_{\text{Hα}} = 2.62 \pm 0.47 \times 10^{-17}$ erg/cm$^2$/s (SB$_{\text{Hα}} = 2.70 \pm 0.48 \times 10^{-18}$ erg/cm$^2$/s/Å) at the expected spatial and spectral location. Combining the Hα detection with its corresponding Lyα flux (determined from the narrow-band imaging) we calculate a flux ratio of $F_{\text{Hα}}/F_{\text{Lyα}} = 5.5 \pm 1.1$. The presence of a skyline at the location of the Hα emission decreases the signal to noise ratio of the detection and our ability to put stringent constraints on the Hα kinematics. Our measurements argue for the origin of the Lyα emission being recombination radiation, suggesting the presence of high-density ionized gas. Finally, our high-resolution spectroscopic study of the Lyα emission does not show evidence of a rotating disk pattern and suggest a more complex origin for at least some parts of the Slug Nebula.

Key words: galaxies: haloes – galaxies: high-redshift – intergalactic medium – quasars: emission lines – cosmology: observations.

1 INTRODUCTION

In the standard paradigm of galaxy formation and evolution, galaxies are thought to be fueled by accreting material from their surrounding circumgalactic medium (CGM). However, the properties of this accreting material, such as the density, temperature, angular momentum and morphology, remain uncertain. Some cosmological simulations suggest that most of this material accretes in the form of relatively cold (T~10^4 K) intergalactic filaments. This has even been found to be the case for the most massive galaxies at high redshift, for which a stable hot corona should be in place (Dekel et al. 2009). On the other hand, theoretical arguments and higher resolution simulations have highlighted that such streams may not be able to survive instabilities (Nelson et al. 2013, Mandelker et al. 2016). Alternatively, such material could result from the cooling of the hot corona (Voit et al. 2015).

In order to distinguish between these two scenarios, direct imaging of the CGM and intergalactic gas is essential.

Unfortunately, the expected emission of both the cold component (due to the recombination radiation of gas ionized by the cosmic ultraviolet background) and hot component (due to X-ray bremsstrahlung) of the CGM around a typical galaxy at $z>2$ is well below current detection limits (e.g. Cantalupo et al. 2005, Gallego et al. 2017). Local ultraviolet (UV) radiation fields, such as in the vicinity of a bright active galactic nucleus (AGN), may be used to increase the detectability of Lyα emission. Indeed, in recent years, several enormous Lyα nebulae (ELANE) have been discovered at $z>2$ around bright radio-quiet quasars. ELANE are characterized by their extended Lyα emission that traces the CGM, and even intergalactic medium (IGM), out to several hundred kpc from their quasars. These detections were made using custom-made narrow-band (NB) filters on the W.M. Keck telescope (Cantalupo et al. 2014, Hennawi et al. 2015).
or by performing integral field spectroscopy using MUSE on the ESO/VLT (Borissova et al. 2016, Arrigoni Battaia et al. 2018; see Cantalupo 2017 for a review).

The largest and brightest of such Lyα emitting structures, nicknamed the “Slug Nebula”, was discovered by Cantalupo et al. (2014). The “Slug” was found near the radio-quiet quasar UM287 using a custom NB filter on the Low Resolution Imaging Spectrometer (LRIS) instrument mounted on the Keck I telescope. With a total projected size of at least 480 physical kpc, this nebula extends well beyond the virial radius of the halo of a typical bright quasar host with a mass of $\sim 10^{12.5} M_\odot$ (see da Angela et al. 2008 and Trainor & Steidel 2012). The Slug Nebula, therefore, represents the best system available to date in which to jointly study the circumgalactic and intergalactic medium in emission.

The filamentary and asymmetric morphology of the Slug Nebula is similar to the predictions of recent cosmological simulations. However, the very high surface brightness (SB) of the Lyα emission (above $10^{-17}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$) extending over hundreds of kpc presents a serious challenge to our current theoretical understanding of baryonic structure formation in the massive halos associated with quasars. As discussed in Cantalupo et al. (2014), there are at least two possible scenarios for the origin of the extended Lyα emission: i) fluorescent Lyα emission following hydrogen recombinations of the gas ionized by the quasar, and ii) Lyα “photon-pumping” or “scattering” of the quasar broad line region emission.

In the first case, the observed Lyα SB can only be explained if the recombing gas is “cold” (T<10$^4$ K) and has very large densities ($>1-10$ cm$^{-3}$) that are much higher than the typical gas densities expected at such large distances from a galaxy. However, because recombination emission scales with the density squared, a small volume filling factor or a large gas clumping factor (C>1000) below the scale of a few kpc could explain the Lyα emission as well as the much lower volume-averaged densities. Therefore, this interpretation of the data would require dense photionized “clumps” of gas within the CGM but these “clumps” must have sizes that are well below the current resolution limits of cosmological simulations (see e.g., Cantalupo et al., in prep.). In contrast with ELANs, a few detections of HeII(1640) in radio-quiet Lyα blobs (LABs, see Cantalupo 2017 for a review) have been reported (e.g., Prescott et al. 2015a), though the majority of LABs show no sign of HeII(1640) emission (Arrigoni Battaia et al. 2015a).

Though the terms LAB and ELAN are often used interchangeably, it is important to note some distinctions. ELANs are bright (Lyα $\sim 10^{44}$ erg/s) Lyα nebulae around z>2 quasars with extents $>100$ kpc (e.g. Cantalupo et al. 2014, Hennawi et al. 2015, Arrigoni Battaia et al. 2018). Though comparable in size and brightness to ELANs, LABs were historically distinguished by their apparent lack of association with an AGN or bright continuum source at the time of their discovery (e.g., Steidel et al. 2000, Matsuda et al. 2004, Dey et al. 2005, Prescott et al. 2009, Yang et al. 2009, Arrigoni Battaia et al. 2015a). However, follow-up observations of LABs often uncovered evidence of the presence of obscured AGN or massively star-forming galaxies (e.g., Chapman et al. 2001, Geach et al. 2009, Overzier et al. 2013, Prescott et al. 2015b, Hine et al. 2016). Therefore, the term LABs has started being used by some authors to refer to large Lyα nebulae with physical extents greater than $\sim 100$ kpc.

Given this broader definition of LABs, ELANs could be considered a subtype of LABs. However, since LABs encompass a wide variety of systems, it would be a mistake to blindly apply any inferences about ELAN emission mechanisms to LABs as a whole. Similarly, though very extended Lyα nebulae have been found around high redshift radio-loud galaxies with large radio jets, these more commonly exhibit extended HeII(1640) emission and broader kinematics. This could suggest that different processes are at play between radio-quiet and radio-loud systems (see, e.g., Villar-Martín 2007, Miley & De Breuck 2008, and Cantalupo 2017 for reviews).

Nevertheless, despite the different classifications and nomenclatures associated with highly extended Lyα emission discovered in the last decades, they are almost always associated with AGN or massively star forming galaxies. This suggests that the presence of a strong ionizing field,
and therefore emission produced by fluorescent recombination radiation, is likely a necessary requirement in all cases (see Cantalupo 2017 for discussion).

In this paper, we report the results of our search for extended Hα emission from the Slug Nebula using long-slit near-IR spectroscopy with the new Multi-Object Spectrometer For Infra-Red Exploration (MOSFIRE) instrument on the W.M. Keck I telescope. We also perform high-resolution Lyα spectroscopy of a similar region in the Slug Nebula with the goal of both guiding our Hα search in the velocity dimension and gaining a deeper understanding of the Lyα kinematics.

The paper is organized as follows: In §2.1, we describe the Keck I/LRIS observations taken of the brightest region of the Slug Nebula and in §2.2, discuss the data reduction process of these observations. Similarly, the two nights of deep near-infrared spectroscopy, obtained using Keck I/MOSFIRE, and their reduction, are described in §2.3 and §2.4 respectively. In §3.1 we explore the Lyα kinematics of the Slug and in §3.2 we measure the Lyα flux contained within the MOSFIRE N1 slits. §3.3 and §3.4 discuss the measurement of the Slug Nebula’s Hα flux. We also extract the 1-D spectra of two compact sources in the vicinity of the Slug Nebula (z∼22.287) from the MOSFIRE N1 and N2 observations in §3.5, and calculate their N2 and Hα fluxes. In §4.1 we examine the implications of the Lyα kinematics for the Nebula’s gas distribution. In §4.2, we compute the Lyα to Hα flux ratio and compare it to predictions from case B recombination radiation. In §4.3, we constrain the origin of the compact source “C” and “D” emission (AGN vs star-formation vs QSO A fluorescence). Finally, in §5, we summarize our results.

2 OBSERVATIONS

2.1 LRIS Spectroscopy

On UT September 09, 2015, we used the blue camera of the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck I 10m telescope to observe the Lyα emission of the UM287 nebula (also referred to as the “Slug Nebula” or “Slug”). The spectra were obtained with a 1″ slit as part of a multi-object slit mask. The slit was oriented with a position angle (PA) of 322°, to match the PA of the MOSFIRE Night 2 (N2) mask (see Figure 1). In order to cover the Lyα emission of the Slug, we used the D460 dichroic and the 1200 lines mm⁻¹ grism blazed at 3400Å, which covers ∼3300–4200Å. The measured full-width at half-max (FWHM) was found to be ∼1″. We acquired 9×1800s science exposures, for a total exposure time of 4.5 hrs. In between each exposure, we dithered ∼1″ along the slit. In addition to the science exposures, we took bias frames, arcs, as well as slitless and slitted twilight flats which were used in the data reduction process. All exposures were readout with 1x1 CCD binning.

2.2 LRIS Calibrations and Data Reduction

The LRIS blue camera data were reduced using the publicly available LowRedux package, distributed within XIDL (Prochaska et al. 2017) producing nine calibrated, unfluxed 2D spectra. This pipeline performs standard data reduction steps, including overscan and bias subtraction, flat fielding, and wavelength calibration.

The flat fielding procedure constructs a pixel flat used to correct for pixel sensitivity variation from the slitless twilight flats. In addition, the slitted twilight flats are utilized to correct for the non-uniform illumination of the slit. LowRedux determines a wavelength solution by fitting low order polynomials to the arc lamp spectra and is reported in air wavelengths for the 2D spectra.

We wrote custom python scripts using the Astropy (Astropy Collaboration et al. 2013), IPython (Perez & Granger 2007), Matplotlib (Hunter 2007), NumPy (Walt et al. 2011), and SciPy (Jones et al. 2001) packages, to coadd the individual reduced spectra since LowRedux does not combine 2D spectra. Due to the dithering along the slit between exposures, each image needed to be shifted, in the spatial direction, to a common frame (chosen to be that of the fifth exposure). To calculate the required shift, we fit gaussians to the spatial profile of a star in a separate slit on the mask, and determined the change in the centroid position. The applied shifts were rounded to the nearest integer pixel in order to avoid interpolation and complications in calculating the associated error. The uncertainty associated with integer shifts is at most 1/2 pixel, which corresponds to an error of 0.0675″, which is far less than the 1" seeing disk.

LRIS is known to experience significant telescope pointing position dependent flexure, which shifts the location of a fixed wavelength on the detector. LowRedux uses the known wavelengths of skylines to measure, in an extracted 1D spectrum, the wavelength solution offset caused by the flexure. We therefore used LowRedux to extract a 1D spectrum of compact source C (see Figure 2), which is located in the same slit as the Slug Nebula, and calculate the flexure-induced spectral pixel shift for each exposure. This shift of ∼11-13 unbinned pixels was then rounded to the nearest integer pixel and applied to the spectral direction of each of the 2D spectra. The rounding error of at most 1/2 pixels amounts to an uncertainty of ±0.135Å or ±10 km/s.

Once the exposures were corrected for flexure and dithering offsets, we ran each of them through the publicly distributed “dcr” package (Pych 2004, 2012) to detect and remove cosmic rays. We then coadded these nine cleaned images by summing the electron counts in each pixel and renormalizing by the total exposure time. In addition, the corresponding 2D wavelength fits file produced by LowRedux was converted from air wavelengths to vacuum wavelengths.

Lastly, we flux calibrated our coadded spectrum using the deep narrow band (NB) imaging of the UM287 field presented in Cantalupo et al. (2014). In order to do so, we applied the LRIS slit to the NB image, choosing only the pixels that contributed to the flux in our spectrum. Next, we trimmed off the outer edges of the slit, selecting only the region of the spectrum that has flux from the nebula and very good background subtraction. We then summed up the NB flux within this shortened slit, which was 4 binned pixels.
wide by 135 binned pixels long and covered 1.08" by 36.45" on the sky.

This total NB flux is compared to that of the 2D spectrum over the same wavelength range and spatial location. The equivalent flux of the 2D spectrum is calculated by first applying the filter transmission function to the spectral direction of the spectrum. We then integrate the flux, in $e^{-}/s$, over the shortened slit region and divide the total NB flux by the summed 2D spectrum flux to compute the conversion factor from $e^{-}/s$ to erg/cm$^2$/s. This conversion factor is then applied to each pixel of the LRIS spectrum to produce a fully flux-calibrated 2D spectrum.

In order to use an integer number of pixels, the width of the NB shortened slit corresponds to 1.08" which is slightly bigger than the LRIS slit width of 1". Therefore, we expect the flux-calibration of the LRIS spectrum to be biased slightly high, by approximately 8%. To estimate the systematic error on our flux calibration, we calculated the flux of the compact source, marked as “C” in Figures 1 and 2. We find that the compact source flux in the NB and spectrum differ by 20%, which will take to be our systematic uncertainty.

We observed the Slug Nebula on October 02, 2014 (Night 1 or N1) and October 03, 2014 (Night 2 or N2), using the Multi-Object Spectrometer for Infra-Red Exploration (MOSFIRE; McLean et al. 2010, 2012) on the Keck I 10m telescope. The spectra were taken using the K-band grating so as to cover the expected Hα emission ($\lambda 6562.8 \mu m$) of the nebula (z=2.283), with a total wavelength coverage of 19540-24060Å. We used a 1" slit width for both nights of observation, resulting in a spectral resolution of R $\approx$ 2500 at $\lambda = 21545.67 \mu m$.

The two masks we designed had three slitlets; the middle slitlet was centered on a region of the UM287 nebula predicted to have the highest Hα emission, while the top and bottom slitlets were aligned on two 2MASS stars (all coordinates are shown in Table 1). These 2MASS stars were included to help locate the exact position of the UM 287 coordinates are shown in Table 1). These 2MASS stars were applied to achieve the final flux calibrated UM287 nebula 2D spectrum.

For the first night, we used a slit at a position angle (PA) of 342°. We observed using an AB’BA’ dither pattern with offsets of +51", −17", +17", −51" respectively and exposure times of 119.3s for a total integration of 4.8hrs. The median seeing during Night 1 was about 0.7" for both nights but there were intermittent cirrus clouds such that the conditions were not photometric. So as to cover a larger area of the nebula, we used a different PA for Night 2 of 322°, centered on the same patch of nebula as for Night 1 (see Figure 1). We observed using the same AB’BA’ dither pattern and exposure times as for Night 1, for a total integration of 2.6 hrs. Both slit orientations are shown in Figure 1.

### 2.3 MOSFIRE Calibrations and Data Reduction

At the beginning of each night, we took neon and argon arcs through the masks as well as dome flats and thermal flats. Immediately prior to observing UM287, we took spectroscopic standards of HIP5164 with a 1" longslit on Night 1 and a 0.7" longslit on Night 2. These were used to flux calibrate our data as well as correct for telluric absorption. Since we only observed HIP5164 once in the evening, we cannot account for any changes to the telluric absorption throughout the night.

The UM287 data as well as the standard HIP5164 were reduced using the publicly available MOSFIRE Data Reduction Pipeline (version August 2016) (DRP; Steidel et al. 2014). The DRP first flat fields the images and traces the slit edges. To correct for the dome’s emission of K-band wavelength photons, the software subtracts the thermal flats from the dome flats before creating a normalized combined flat.

Next, the code combines exposures and preforms the wavelength calibration, combining an interactive fitting of the night sky lines with neon and argon arcs to correct for the faintness of the sky lines at the reddest wavelengths. The sky background is then subtracted and the images are rectified, producing a 2D spectrum for each slitlet along with their corresponding noise frames and integration time maps.

To prevent smearing out of the emission due to the mask drift across the detector over the course of our observations (see for instance, Kriek et al. 2015), we reduced our Night 1 data in 6 batches of 24 exposures (~48 mins) each (other than the last batch which only had 23 exposures). We then measured the mask drift between batches by tracking the centroids of the two 2MASS stars (see Table 1) also present in the MOSFIRE mask. We found shifts of ±1-2 pixels (0.18"-0.36") between batches which we corrected for before coadding the data. Due to the shortness of the Night 2 observations and the shifts of only about 1 pixel found in the Night 1 data over the course of ~1 hr, we did not bother correcting for mask drift in the Night 2 data.

In order to flux calibrate our UM287 nebula 2D spectrum, we used the spectrum of the A0 standard star HIP5164. The 1D spectrum of HIP5164 was derived from the 2D spectrum returned by the DRP, using a boxcar extraction that assumes a gaussian spatial profile. We then calculated the sensitivity function by comparing this 1D spectrum to a template spectrum of Vega from Bohlin (2014) that has the near-infrared emission from the debris disk removed. That spectrum was then renormalized to have the same 2MASS magnitude as HIP5164. This sensitivity function as well as a simple slit loss correction to account for the finite slit width were applied to achieve the final flux calibrated UM287 nebula 2D spectrum, shown in Figure 2.

### 3 ANALYSIS AND RESULTS

The final 2D LRIS and MOSFIRE spectra are shown in Figures 2 and 4. In this section, we first examine the kinemat-
ics of the Slug Nebula. We use the LRIS spectrum from §2.1 which will provide the kinematic structure, which we can use to measure the distribution of the gas. We will use simple moments to characterize the distribution as a way of quantifying how the material is moving with respect to the QSO we assume is illuminating the Slug. Second, we will measure the amount of flux coming from the Slug in the MOSFIRE spectra. In particular, we will measure the flux in Hα. This result will help us constrain the mechanism that produces the emission.

3.1 The Lyα kinematics

The velocity centroid and velocity dispersion as a function of spatial position for the Lyα emission around the Slug Nebula is shown in the top left and top right panels of Figure 3, respectively. To calculate these kinematic tracers, we first selected an appropriate region around the Slug Nebula. We started by running CubExtractor (Cantalupo, in prep.; see also Borisova et al. 2016 and Marino et al. 2017 for a short description) on the LRIS 2D spectrum with spatial and wavelength Gaussian smoothing of (σ = 2 pixels) and a signal to noise threshold of 3 per smoothed pixel. The resulting region is shown in the bottom left panel of Figure 3.

Next, we partitioned the spatial extent of Lyα emission into bins of 5 pixels (5.68 kpc). Note that these are not independent regions since the seeing in the spatial direction was ~10 pixels but this box size allows us to finely sample the kinematics of the transition region between the Slug Nebula and the compact source. We then calculated the flux-weighted first and second moments of the Lyα velocity distribution for each spatial bin according to equations 1 and 2.

\[ V_{\text{cent}} = \frac{\sum vF(v)}{\sum F(v)} \] (1)

\[ V_{\text{disp}} = \sqrt{\frac{\sum (v - V_{\text{cent}})^2F(v)}{\sum F(v)}} \] (2)

The velocity centroid, for each spatial bin, was determined using statistical bootstrapping and is shown as the black error bars. Since each spatial bin is about half the size of the atmospheric seeing, each of these bins are correlated. Therefore, the bootstrapped errors are likely an underestimate of the true errors.

As seen in the top left panel of Figure 3, the kinematics indicate that the Slug Nebula, the spectrum between 35 kpc and ~75 kpc, is comprised of two regions with distinct kinematics. “Region 1” is at ~50 kpc has a velocity centroid of −333 ± 12 while the “region 2” is at ~25 kpc is centered at −555±8. There is then a sharp transition around ~40 kpc marking the beginning of the compact source, which is centered at a velocity of 25±8 km/s.

The top right panel of Figure 3 shows the flux-weighted velocity dispersion of the Lyα emission as a function of the projected distance from point X. The corresponding error bars for the velocity dispersion were computed using statistical bootstrapping. As with the velocity centroid, the velocity dispersion of the Slug Nebula displays the same de-
markdations between the two regions that comprise the Slug and the compact source “C”. Their representative velocity dispersions are 217±7 km/s, 418±6 km/s, 453±9 km/s respectively.

3.2 The Lyα Flux of the Slug Nebula

We used the narrow band image (see the top panel of Figure 1) to calculate the Lyα flux of the Slug Nebula in the region defined within the MOSFIRE Night 1 slit, corresponding to where we measure the Hα emission in §3.4.1. So that comparisons to the MOSFIRE data would be as accurate as possible, we chose the same spatial width and centroid as was used to calculate the Hα flux (see §3.4.1). Though we could not precisely select the same velocity range, comparing the narrow band and continuum images shows that there are no continuum sources that could be contaminating the Lyα measurement in our region of interest. In addition, the narrow band filter covers a much larger spectral window than the velocity dispersion of the nebula (see Figure 3), ensuring that all of the Lyα velocities are included in flux measurement.

Integrating over the region encompassed by the over-plotted MOSFIRE N1 slit within the aforementioned spatial window of ~81.76 kpc, results in a total Lyα flux of \(F_{\text{Ly}\alpha} = 1.44 \pm 0.10 \times 10^{-16} \text{ erg/cm}^2/\text{s} \) (equivalent to a surface brightness of \(\text{SB}_{\text{Ly}\alpha} = 1.48 \pm 0.10 \times 10^{-17} \text{ erg/cm}^2/\text{s}/\text{arcsec}^2\)).

3.3 The Hα Emission of the Slug Nebula

3.3.1 Determining the optimal aperture for Hα detection and flux measurement

The large spatial scale (and possibly, the large velocity width) of the expected Hα emission from the Slug Nebula necessarily requires spatial and spectral binning of our original data presented in Figure 4. Moreover, we do not know a priori where the spatial and velocity center of such an aperture should be located.

In this section, we discuss how we obtained the optimal rectangular aperture for the detection of the Hα emission from the Slug. Because of the lower exposure time and higher systematic noise of the MOSFIRE Night 2 observations (see Figure 4) we will limit our search for and analysis of extended emission to the MOSFIRE Night 1 observations here and in the remainder of the paper. However, we will make use of the MOSFIRE Night 2 observations for the spectral analysis of the compact source “C”.

As discussed in this section, we find that the optimal aperture has a spatial dimension of ~81.76 kpc and is centered a distance of ~19.68 kpc from the intersection of the MOSFIRE Night 1 and Night 2 slits. The optimal spectral dimension has a width of 363 km/s centered at a velocity of -511 km/s with respect to the systemic velocity of Hα at a redshift of \(z=2.283\) (the systemic redshift of the quasar UM287 obtained from CO observation; Decarli et al, in prep.).

The spatial scale and center were chosen based on the intersection of the Night 1 slit with the Lyα NB emission. The narrow band Lyα surface brightness was first rescaled to an expected Hα surface brightness assuming a case B recombination ratio of \(\text{SB}_{\text{Ly}\alpha}/\text{SB}_{\text{H}\alpha} = 8.1\). We then calculated a 3σ contour, assuming an estimated MOSFIRE Hα surface brightness error of \(1\sigma = 3.7 \times 10^{-19} \text{ erg/cm}^2/\text{arcsec}^2\). The region within the intersections of the Night 1 slit and the 3σ contour was 9.71″ long and centered a distance of 2.34″ from the intersection of the Night 1 and Night 2 slits. Assuming a redshift of \(z=2.283\), this translates to a spatial aperture in which to calculate the Hα flux of ~81.76 kpc centered at a distance of ~19.68 kpc from the slit intersection.

We then determined the optimal spectral aperture width and central velocity. In the absence of radiative transfer effects influencing the velocity distribution of the Lyα emission, we would expect that the Hα emission to be centered close to the velocity centroid of the Lyα, found to be ~555 km/s in §3.1. However, possible asymmetries in the Lyα due to scattering effects could bias our determination of the precise Hα central velocity.

In order to allow for this possibility, we chose a “priorless” approach to determining the velocity centroid and width of the Hα emission. Rather than select the velocity centroid based on it’s expected location, we took a curve of growth approach, finding the central velocity in a wide velocity window (shown in the top panel of Figure 6), that maximized the Hα flux. We first masked out the compact source continuum emission located at ~50 kpc from the slit intersection “X”, then the Hα flux was measured assuming a narrow velocity window of 181 km/s (6 pixels) so as to finely sample the velocity range. The Hα flux peaks at a velocity centroid of -511 km/s, a result that is corroborated if we double the velocity width to 363 km/s, as shown in the top

Figure 2. The unsmoothed two-dimensional spectrum taken with Keck I LRIS (the white slit in Figure 1). The \(v = 0\) km/s corresponds to the expected Lyα emission at a redshift of \(z=2.283\), the redshift of QSO A. The projected distance corresponding to 0 kpc indicates the location of the MOSFIRE N1 and LRIS slit intersection, referred to as position “X” in Figure 1. The bright Lyα emitter around \(v \sim 300\) km/s and spatial position of ~60 kpc is the compact source “C” (see Figure 1). The Slug Nebula has a physical extent along the slit of ~150 kpc. Its Lyα emission is blue-shifted with respect to that of the compact source \((z=2.287)\) and the redshift of QSO A \((z=2.283)\).
Figure 3. The Ly$\alpha$ kinematics of the region around the Slug Nebula. The flux-weighted first moment of the velocity distribution, also referred to as the velocity centroid, is plotted as a function of position along the slit in the top-left panel. The velocity centroid was calculated according to Equation 1, within spatial bins of 5 pixels. Similarly, the flux-weighted second moment of the velocity distribution about the flux-weighted mean, which we refer to as the velocity dispersion, was calculated according to Equation 2. The velocity dispersion in spatial bins of 5 pixels is shown as a function of projected distance along the slit in the top-right panel of this figure. In both top panels, the 1$\sigma$ error bars were computed using standard bootstrapping techniques. The area of Ly$\alpha$ emission used to measure the velocity centroid and dispersion only includes pixels with a SNR $\geq$ 3, and is depicted in the bottom-left panel (the color bar matches that of Figure 2). The $v = 0$ km/s corresponds to the expected Ly$\alpha$ emission at the redshift of QSO A ($z=2.283$). The projected distance of 0 kpc indicates the location of the MOSFIRE N1 and LRIS slit intersection. Three distinct spatial regions, with different kinematic properties, are apparent in both the velocity centroid and velocity dispersion plots: the dimmer left-most region of the Nebula (“region 1”), the brighter region of the Nebula to the right (“region 2”) and the compact source “C” area in the right-most part of the figure.
panel of Figure 6. The curve-of-growth determined velocity centroid of -511 km/s is extremely close to the velocity centroid of the Lyα region 2 emission, which was measured to be -555 km/s.

Finally, we determined the spectral aperture width, which cannot simply be obtained from the breadth of the Lyα emission, since radiative effects can broaden the width of this resonant line. Instead, we varied the spectral aperture width from 181 km/s to 784 km/s and selected the width at which the measured Hα flux leveled off. As shown in the bottom panel of Figure 6, the optimal velocity aperture has a width of 363 km/s.

Since this curve of growth approach to finding the velocity centroid and width of the flux aperture seeks to maximize the Hα flux, one could be concerned that this approach would consistently bias our Hα flux towards higher values. In order to quantify this effect, we used the same methodology described above to find the peak Hα flux in several pure sky background regions. When we varied the velocity centroid and width of the flux apertures, we consistently found that the maximum Hα peaks exceeded the mean flux value in that sky background region by about $5 \times 10^{-18}$ erg/cm$^2$/s. Therefore, we conclude that this “priorless” aperture selection would inflate the Hα flux by $\lesssim 5 \times 10^{-18}$ erg/cm$^2$/s. We emphasize that our estimate is an upper limit, as it is unlikely that a statistical fluctuation would land near or on top of the detected Hα flux.

3.3.2 An empirical estimate of the sky noise

We determined an empirical noise estimate by calculating the standard deviation of the flux in “pure-sky” regions. These regions were chosen so as to avoid the expected spatial location of Slug Hα emission as well as the outer edges of the slit, which have a reduced total exposure time. We measured the flux in these background regions using the same-sized rectangular aperture and velocity centroid as when measuring the Slug Nebula flux (see §3.4.1). We found that these fluxes were dominated by a linearly varying, spatially-dependent background gradient, which we modeled and removed prior to calculating the flux scatter for the pure-sky regions. We note that the removal of this background model does not affect our measurement of the Slug’s Hα flux since the estimated background was very close to zero at that spatial position.

The “pure sky” fluxes, with the background gradient removed, are plotted in Figure 8 as unfilled blue squares. The $\pm 1\sigma$ standard deviation of the sky fluxes (our empirical noise estimate) is shown as the transparent blue shaded region. The light blue unfilled circles show the flux at spatial locations close to the expected Hα emission and were not included in the calculation of our noise estimate. The background gradient was not removed at the location of the light blue unfilled circles. The flux at the location of the Slug is represented by the larger filled blue square.

3.4 Examining the Robustness of the Slug Nebula Hα Detection

It is important to note that our chosen velocity centroid is coincident with the sky line at 20517Å. The presence of a bright, imperfectly subtracted sky line at the location of our Hα detection might cause concern that the observed Hα flux within our chosen aperture is due to variance in the sky line rather than emission from the Slug Nebula.

Figure 4 shows no clear emission at the location of the chosen aperture. However, once the spectrum is smoothed using a median filter with a 41 kpc $\times$ 363 km/s kernel, the Hα emission becomes apparent, as seen within the white rectangle in the top panel of Figure 5. In addition, this sort of line-like emission appears nowhere else along the skyline or generally in the vicinity of the expected Hα emission.

The idea that the emission within our aperture is uncharacteristic of the variance of the sky line is corroborated by the fact that the signal to noise also peaks at the same velocity centroid as the flux. The error used in the SNR was empirically calculated by taking the standard deviation of the flux in apertures along the sky line (see §3.3.2). Therefore, if the emission in our aperture was typical of the sky line, this would be reflected in the noise estimate. While the flux could be biased by the presence of a sky line, the signal to noise ratio should be much less susceptible to this effect. The velocity centroid corresponding to the peak SNR was unchanged whether we used our empirical noise estimate or a noise estimate calculated from the error array produced by the MOSFIRE DRP.

As an additional test of the validity of the Hα emission, we inserted two types of fake sources into the MOSFIRE N1 spectrum in order to verify that observed emission line is consistent with what would be predicted from the Lyα. The first fake source was created by taking the Lyα emission within region 2 of the LRIS slit and rescaling it to the Hα flux (2.62 $\times$ 10$^{-17}$ erg/cm$^2$/s). It was then inserted into it the MOSFIRE N1 spectrum at a velocity window matching that of the Lyα kinematics (centered at -718 km/s) but at a spatial location away from the expected Slug emission. The results are shown in the left panel of Figure 7, with the red rectangle denoting the fake source and the white rectangle the actual observed emission at the location of the Slug.

Since the Lyα could be broadened by radiative transfer effects that would not affect the Hα emission, the Hα could be emitted with a much more concentrated velocity distribution. The second fake source, inserted into the MOSFIRE N1 spectrum at the observed Hα velocity centroid (-511 km/s), was chosen to be a 2D gaussian with $\sigma_{vel}=181$ km/s and $\sigma_{spat}=18$ kpc and a total flux equivalent to that of the detected Hα flux.

As seen in the right panel of Figure 7, the observed Hα emission (white rectangle) looks similar to the compact 2D gaussian fake source (red rectangle). As this exercise was purely for illustrative purposes, the fact that the observed emission looks similar to a reasonable expectation of the Hα emission supports that the observed Hα emission is not simply due to the underlying sky line. In addition, the apparent compact size of the Hα as compared with the expected size seen in Lyα could suggest that the Lyα emission is broadened by radiative transfer effects.

3.4.1 The Hα flux and the Lyα to Hα ratio

We measured the Hα flux of the observed portion of the Slug Nebula in the region of the MOSFIRE N1 slit using the rectangular aperture obtained as discussed above. This
aperture has a spatial dimension of 81.76 kpc and spectral dimension of 363 km/s and it is spatially centered at a distance of 19.68 kpc from the intersection of the Night 1 and Night 2 slits (point “X” in Figure 1). The velocity centroid of the aperture is -511 km/s. The region in which the Hα flux was measured is over-plotted as a white rectangle in the top panel of Figure 4 and both panels of Figure 5.

We find an Hα flux within our aperture of F_{Hα} = 2.62 ± 0.47 × 10^{-17} erg/cm^2/s (equivalent to a surface brightness of SB_{Hα} = 2.70 ± 0.48 × 10^{-18} erg/cm^2/s/arcsec^2), where the error is calculated from the standard deviation of the fluxes in “pure sky” regions as described in §3.3.1. Considering the Lyα flux in the same spatial region obtained from the NB image (found to be F_{Lyα} = 1.44 ± 0.10 × 10^{-16} erg/cm^2/s in §3.2), the Lyα to Hα flux ratio in this region of the Slug is 5.5±1.1. If, as discussed in §3.3.1, we take into account that the Hα flux might be biased high by up to 5 × 10^{-18} erg/cm^2/s, the Lyα to Hα flux ratio would instead be around 6.9. We will discuss the possible implications of this flux ratio with respect to the physical emission mechanism and Lyα escape fraction in §4.2.2.

### 3.5 The Compact Sources in the MOSFIRE Data

Two line emitters were also observed in our MOSFIRE spectra. These sources were originally detected in the LRIS NB and V band data and were dubbed compact source “D” and compact source “C”. The sources are shown and labeled in Figure 1 and correspond to the MOSFIRE N1 and MOSFIRE N2 slits respectively. Note that emitter “C” is the same redshift of \(z_\approx≈2\) each compact source. We find that both sources are at the same redshift of \(z_\approx≈2\). This corresponds to a velocity \(\approx-333\) km/s -3 compared to it’s corresponding Lyα emission: 1) a purely ex-situ production of the Lyα in the broad-line region of QSO A that is then scattered and reemitted by neutral hydrogen in the nebula and 2) a significant contribution of in-situ fluorescent Lyα emission produced by case B recombination of the Slug’s hydrogen gas.

Finally, we also examine the origin of the Hα emission of compact sources “C” and “D”. In §4.3, we use the ratio of their N\textsc{ii}/Hα flux to place these galaxies on a BPT diagram and determine whether these galaxies are star-forming or have a central AGN. In addition, we also explore the possibility of a contribution of fluorescent emission due to QSO A.

#### 4.1 The Lyα kinematics of the Nebula

We can gain insight into the physical structure of the gas by examining the Lyα kinematics. In their work, Martin et al. (2015) claimed that the brightest region of the Slug Nebula is an extended rotating hydrogen disk contained within an \(\approx 10^{13} M_\odot\) dark matter halo. However, the kinematics shown in Figure 3 belies the idea that the Slug Nebula is a simple monolithic structure like a disk.

As discussed in §3.1, the velocity centroid as a function of spatial position (the upper-left panel of Figure 3) reveals three clearly distinguishable regions with distinct velocity centroids. These same regions are clearly recognizable in the plot of velocity dispersion as a function of spatial position and are marked by very sharp transitions at \(\sim -35\) kpc and \(\sim 45\) kpc.

The two left-most regions comprise the Slug Nebula. The dimmer “region 1” is centered at \(\sim -50\) kpc with a characteristic velocity centroid of \(-333\) km/s while the brighter “region 2” is located at \(\sim 25\) kpc with a velocity centroid of \(-555\) km/s. The Lyα emission of the Slug is separated from that of compact source “C” by a very narrow transition region \(\sim 10\) kpc. We also see that the velocity dispersion has sharp transitions at the same location where we see sharp changes in the mean velocity, lending further credence to our interpretation that these are kinematically distinct regions.

Although it is difficult to disentangle velocity effects from distances along the line of sight, these sharp transitions may suggest that the Slug Nebula could be composed of several structures. This is not unexpected from our theoretical understanding of cosmic structure formation: the most massive filaments of the cosmic web are composed of both diffuse material and more massive haloes containing denser gas. If the Lyα emission is produced by recombination radiation and therefore scales with the gas density squared, our observations would be most sensitive to detecting the densest knots and structures within the filaments.

This interpretation of the Slug’s physical structure is inconsistent with the giant disk argued for by Martin et al. (2015), despite the fact that Martin et al.’s pseudo-slit largely overlaps with our LRIS slit. We believe that the lower spatial and spectral resolution of the pseudo slit observations may have smoothed out the sharp transitions that we re-
solved, making the distribution of velocity centroids resemble that of a giant disk.

Instead, our observation reveals a very abrupt cutoff, seen in Figure 2, of the Lyα flux at a spatial position of ~ 50 kpc. It is currently unclear whether this sharp edge to the Lyα emission is due to an absence of cold gas or whether the Lyα emission is instead being absorbed along the line of sight. The cutoff location is tantalizingly close to compact source “C”. However, compact source “C” located several hundred km/s on the red side of this feature and therefore we do not think that the compact source and its environment are the origin of a possible absorption feature. It is also interesting to note that the Lyα emission cutoff is adjacent to the brightest region of the nebular emission. Deeper integral field observations with Keck/KCWI and MUSE for both Lyα and other emission lines (Cantalupo et al, in prep.) could be useful to disentangle whether this may be due to a lack of quasar illumination in a particular direction (i.e., a “shadow” of some absorber that is associated with the quasar) or suggestive of a possible different physical origin for this emission (e.g., shocks).

4.2 Constraining the Emission Mechanism of the Slug Nebula

Cantalupo et al. (2014) presents two possible mechanisms that could power the Lyα emission of the Slug Nebula. In the first case, Lyman continuum photons produced by the nearby QSO A ionize the gas of the nebula, producing Lyα photons as the hydrogen atoms recombine. In the so-called “case A”, the gas is optically thin to ionizing radiation, while α near QSO A ionize the gas of the nebula, producing Lyman continuum photons produced by the ionization of the gas. In the opposite optically thick situation is usually referred to as “case B”. In the absence of dust, for reasonable nebular temperatures of $5 \times 10^4 - 2 \times 10^5$ K and electron densities $n_e < 10^4$ cm$^{-3}$ the expected integrated Lyα/Hα ratio for case B recombination should range between 8.1−11.6 (Hummer & Storey 1987). In order to remain consistent with the broader literature, we use the conventional case B ratio of 8.7 set by Hu et al. (1998) (for further discussion, see Henry et al. 2015, Hayes 2015, Trainor et al. 2015).

Note that this ratio assumes spatially integrated measurements with apertures large enough to capture the full Lyα flux as the Lyα can scatter and spatially diffuse while Hα cannot. If the spatial aperture does not encompass all the Lyα, the measured Lyα/Hα may be considered to be a lower limit to the true value.

In the second case, the Lyα emission is produced as mostly neutral hydrogen gas absorbs Lyα and doppler-shifted Balmer continuum photons (“photon-pumping”) from the broad line region of QSO A and re-emits them as Lyα photons into our line of sight. In this scenario, we would expect little to no Hα to be produced, i.e., we would expect to obtain only a lower limit on the Lyα/Hα ratio. If such a lower limit is at least 12 or so, this scenario could then be distinguished from the recombination case.

4.2.1 Evidence for a detection of the Slug Nebula’s Hα emission

In order to differentiate between these two production mechanisms, it is important to ensure that our Hα detection in the MOSFIRE N1 spectrum originated from the Slug Nebula. As mentioned in §3.4, despite of the presence of a bright, imperfectly subtracted sky line at the location of our Hα detection there are several points that help support the idea that the measured Hα flux is indeed emission from the Slug.

(i) There is a significant Hα emission: The Hα flux we measured corresponds to a 5.6σ detection if we use our empirical sky noise estimator. If we instead use the error file from the MOSFIRE DRP to estimate the noise, the SNR doubles. In either case, the detection is significant despite being on top of a sky line. Though the Hα flux we measure is not clearly visible in the unsmoothed 2D MOSFIRE spectrum shown in Figure 4, once the spectrum is smoothed, as shown in Figure 5, the emission line becomes evident.

(ii) The Hα emission is located where it is expected: When determining the aperture in which to measure the Hα flux, we determined the spatial centroid and width solely from the NB image. It is therefore notable that the only significant emission besides QSO A and compact source “D” in the region is located within these independently derived spatial constraints. In addition, it is striking that despite our priorless search for the velocity centroid of the Hα emission, it coincides so well with the velocity centroid of the Lyα emission that we derived from the LRIS slit.

Note that while the LRIS slit does not match the orientation of the MOSFIRE N1 slit, they do have an overlap region at point “X”, where the velocity centroid of the Lyα and Hα are very closely matched. In addition, the LRIS kinematics shown in Figure 3 indicate a constant velocity centroid within each region. Since the MOSFIRE N1 slit goes squarely through region 2 of the Nebula, it is unlikely that the Lyα velocity centroid within a MOSFIRE N1-like slit would differ much from our observed LRIS kinematics.

(iii) The Hα emission looks like what we would expect from the Lyα: In order to verify that our observed Hα emission looked reasonably similar to what we would expect from the Slug Nebula, we visually compared it to two simple emission prediction models based on the LRIS Lyα emission and an assumption of case B recombination radiation.

As described in §3.4 and shown in Figure 7, we found that our observed Hα detection is visually consistent with a compact 2D gaussian emission model (σ$_{\text{rel}}$=181 km/s and σ$_{\text{spat}}$=18 kpc) with a total flux that is the same as our observed Hα flux.

Thus, there is significant Hα emission at a location consistent with that of the Lyα emission of the Slug Nebula and that it looks similar to what would be expected assuming a relatively narrow Hα velocity distribution produced by recombination emission. These facts together indicate that our MOSFIRE Hα flux is very likely a true detection of the Slug Nebula Hα emission. However, the only way to definitively confirm the Hα detection at much higher significance level would require observations that are not affected by sky-lines, i.e. from space using the James Webb Space Telescope.

4.2.2 The Fluorescent Nature of the Slug Nebula’s Emission

The ratio of the Lyα flux, measured in §3.2, to the corresponding Hα flux, calculated in §3.4.1, allows us to deter-
mine which mechanism is primarily responsible for powering the Slug Nebula emission. We find a ratio of:

\[
\frac{F_{\text{Ly}\alpha}}{F_{\text{H}\alpha}} = 5.5 \pm 1.1
\]  

(3)

Despite the large uncertainties and the limitations of our current observations, our measured value of \( F_{\text{Ly}\alpha}/F_{\text{H}\alpha} \) is clearly much lower than the expected ratio of \( F_{\text{Ly}\alpha}/F_{\text{H}\alpha} > 12 \) if the Ly\( \alpha \) emission of the Slug Nebula were primarily being produced via “photon-pumping” or scattering of the quasar broad line region. Rather, it is remarkably close to the “standard” case B recombination ratio of 8.7. If, as discussed in \S 3.3.1 and \S 3.4.1, the H\( \alpha \) flux is biased slightly high due to our aperture selection, the flux ratio could be as large as 6.9 \pm 1.1, driving it even closer to the canonical 8.7 value. Observing Ly\( \alpha \) to H\( \alpha \) emission ratios that are so close to those expected for case B recombination, implies that the gas in the Slug Nebula must be mostly ionized, presumably by QSO A, optically thick to Ly\( \alpha \) photons, and producing the fluorescent Ly\( \alpha \) corresponding H\( \alpha \) emission in-situ as the gas recombines. Of course, some small contribution due to “photon-pumping” or scattering from the quasar broad line region cannot be excluded.

In studies of Ly\( \alpha \) emitting galaxies, it is customary to interpret this ratio in terms of the Ly\( \alpha \) escape fraction \( f_{\text{esc}} \). The Ly\( \alpha \) escape fraction compares the ratio of observed \( F_{\text{Ly}\alpha}/F_{\text{H}\alpha} \) (where \( F_{\text{H}\alpha} \) is generally dust corrected) to the ideal case B recombination value of 8.7 (see i.e. equation 2 of Atek et al. 2009). If we convert our measurement of the \( F_{\text{Ly}\alpha}/F_{\text{H}\alpha} \) ratio from equation 3 into a Ly\( \alpha \) escape fraction, it would correspond to \( f_{\text{esc}} \sim 63\% \). This value is in keeping with the escape fractions found for Ly\( \alpha \) selected galaxies at redshifts of \( z \sim 2 \) – 3, which range from a few percent to over 100%, but are typically \( \sim 30\% \) (e.g. Hayes et al. 2010, Steidel et al. 2011, Erb et al. 2014, Trairinor et al. 2015, Mattei et al. 2016). The presence of dust is often used to explain escape fractions that are below 100%, since dust preferentially destroys Ly\( \alpha \) as compared to H\( \alpha \). Hayes et al. (2010), Steidel et al. (2011), and to a lesser extent Mattei et al. (2016), all observe that \( f_{\text{esc}} \) is anti-correlated with dust attenuation.

However, it is very important to remember that the Slug Nebula is not a Ly\( \alpha \) galaxy. Rather, it is a very massive reservoir of cool gas that spans over 450 kpc, has no detected stellar continuum component, and as discussed in \S 4.1, has kinematics that are inconsistent with being a massive rotating disk. Therefore, as discussed in Cantalupo et al. (2014), the Slug Nebula is likely a filamentary structure in the IGM, and we do not expect significant amounts of dust to be present on these intergalactic scales. Indeed, the non-detection of metal emission, from C\( IV \) (Arrigoni Battaia et al. 2015b) suggests that the metallicity of the Slug is not as high as in the ISM of high-redshift galaxies.

Another explanation for the \( f_{\text{esc}} \) \(< 100\% \) observed in Ly\( \alpha \) emitting galaxies was proposed by Steidel et al. (2011). As they point out, it is not necessary to destroy Ly\( \alpha \) photons to affect the Ly\( \alpha \) flux measurement. Notably, resonant scattering causes the Ly\( \alpha \) photons to diffuse spatially outwards while leaving the non-resonant H\( \alpha \) unaffected. Therefore, an aperture that encompasses all of the H\( \alpha \) emission will likely be missing a significant amount of the Ly\( \alpha \), leading to measured escape fractions that are less than 100%.

This scattering of Ly\( \alpha \) photons to larger spatial scales is probably the dominant effect contributing to why our measured Ly\( \alpha \) flux is below what we would expect for case B recombination. Since we are measuring the Ly\( \alpha \) flux corresponding to the Night 1 slit by integrating the Ly\( \alpha \) flux within a pseudo-slit region of the NB image, we are likely missing a significant fraction of the Ly\( \alpha \) photons produced in this bright region, particularly those that are scattered by more than the 1” slit width. This explanation is further supported by the fact that we see possible radiative transfer effects playing a role in producing a Ly\( \alpha \) spectral width that is broadened compared to that of the H\( \alpha \). In this case, we would expect higher Ly\( \alpha \) to H\( \alpha \) ratios in the outer, fainter regions of the Slug Nebula that are currently not covered by our spectroscopic slit, which was centered on the brightest emission. Deep H\( \alpha \) narrow-band or integral field spectroscopic observations would be needed to confirm this scenario.

As discussed in Borisova et al. (2016), another conceivable contribution to the lower than expected Ly\( \alpha \) flux could be “filter-loss” effects. These filter losses occur when a portion of the broad Ly\( \alpha \) emission falls outside of the peak transmission of the NB filter. However, if we compare the measured transmission curve of the NB filter in the laboratory to the Ly\( \alpha \) kinematics from our LRIS spectrum, assuming that these kinematics are similar to those that would have been observed using the N2 slit, we find that the Ly\( \alpha \) emission coincides well with the NB filter peak transmission and that any filter-losses would be too small to explain the lower than expected Ly\( \alpha \) to H\( \alpha \) ratio.

The recombination nature of the Slug Nebula’s emission has important implications for the conditions of the gas on intergalactic and circumgalactic scales around quasars. As discussed in detail in Cantalupo et al. (2014) and Arrigoni Battaia et al. (2015b) (also see Cantalupo 2017 for a review) the large Ly\( \alpha \) (and H\( \alpha \)) SB of the Slug in the recombination case would imply very high gas densities \( n > 1 \text{ cm}^{-3} \) that can only be explained by large clumping factors \( (C \sim 1000) \), and therefore small volume filling factors) given the large intergalactic scales associated with the emission. In addition, the indications that Ly\( \alpha \) is being radiatively broadened due to radiative transfer effects, suggest that the gas is highly ionised but not completely optically thin to Ly\( \alpha \) radiation produced by recombination. This would imply a neutral hydrogen column density significantly above \( 10^{14} \text{ cm}^{-2} \) and will help future studies to further constrain the ionisation parameter, total column densities, and volume densities of the gas.

### 4.3 Elucidating the Nature of Compact Sources “C” and “D”

In \S 3.5, we calculated the H\( \alpha \) and N\([\text{II}]\) fluxes for compact galaxies “C” and “D”, which we can use to surmise the origin of the H\( \alpha \) emission. Cantalupo et al., (in prep.) modeled the UV continuum emission of compact source “C” using Starburst99 (Leitherer et al. 1999) and found that the galaxy was consistent with having little to no dust and a star formation rate (SFR) of \( \approx 2 \) – 3 \( M_\odot/\text{yr} \). We can convert this star formation rate into a predicted H\( \alpha \) flux by using the classic conversion of SFR to H\( \alpha \) luminosity from Kennicutt (1998). In this way, we can calculate that a SFR of \( 3 M_\odot/\text{yr} \) corresponds to an expected H\( \alpha \) flux of \( F_{\text{H}\alpha,\text{expected}} = 9.0 \times 10^{-18} \).
erg/cm²/s. Comparing this expected flux to the observed $H\alpha$ flux measured in §3.5, we find that the observed flux is 4.8 times higher than what would be predicted from star formation alone when using the Kennicutt (1998) relation.

We can perform a similar analysis on compact source “D”. Since we do not have a UV spectrum of compact source “D”, we cannot do the full modeling of its UV continuum emission, as we did for compact source “C”. Instead, we can attempt to rescale the SFR we computed for compact source “C” by comparing their UV continuum fluxes as determined from the V-band photometry (see Figure 1). We find that $F_{UV,C}/F_{UV,D} \approx 2.9$, suggesting a SFR for compact source “D” of $\sim 4.8$ times higher than what would be predicted from star formation (see Figure 1). We find that a tail of star-forming systems with small $N_{II}$ for low-redshift systems, Brinchmann et al. (2008a,b) find a ratio of $N_{II}/H\alpha$ to $O\beta/\beta$ when examining this relation for low-redshift systems, Brinchmann et al. (2008a,b) find a tail of star-forming systems with small $N_{II}/H\alpha$ and high $O\beta/\beta$, generally with high specific star-formation rates ($10^{7} - 10^{8}$ years$^{-1}$). Such galaxies are common in surveys of star-forming systems at $z \sim 2$, yielding a N2-BPT diagram populated with extreme ratios of $N_{II}/H\alpha$ (Nakajima et al. 2013, Maseda et al. 2013, Steidel et al. 2014, Shapley et al. 2015, Holden et al. 2016, Trainor et al. 2016, Strom et al. 2017). To produce these extreme ratios requires a much higher ionizing flux than typically produced star-forming regions in, for example, the Milky Way. One method of producing these would be the nearby QSO, but the frequency of these galaxies outside of the neighborhoods of QSO points to different conditions of star-formation such as is discussed in, for example, Kewley et al. (2013), Steidel et al. (2016), and Eldridge et al. (2017).

5 CONCLUSIONS

The recent discovery of Enormous Lyα Nebulae (ELAN) also referred to as Giant Lyα Nebulae) around quasars has opened up a new observational window to study intergalactic gas in emission on scales of several hundred kpc around massive galaxies at high redshift (see e.g., Cantalupo 2017 for a review). The Slug Nebula is one of the largest and most luminous among the ELAN discovered to date, extending over 450 physical kpc around the bright quasar UM287 at z=2.283 (Cantalupo et al. 2014) with a very high Lyα surface brightness. Depending on the Lyα emission mechanism, these high SB values would imply either a “clumpy” and mostly ionised medium (in the case of recombination radiation) or large column densities of neutral gas (in the case of “photon-pumping” or scattering radiation from the quasar broad line region emission), as discussed in Cantalupo et al. (2014).

In order to clearly distinguish between these two scenarios, we searched for the non-resonant hydrogen $H\alpha$ emission from the brightest part of the Slug by means of deep Keck/MOSFIRE long-slit spectroscopic observations. In addition, we obtained a deep, moderately high-resolution Lyα Keck/LRIS spectrum in order to guide our $H\alpha$ emission search in the spectral direction and to study the detailed kinematics of the Nebula.

(i) Compared to previous lower-resolution and lower signal-to-noise Lyα spectral studies, our LRIS observation of Lyα emission revealed a more complex kinematic pattern than a simple, giant rotating disk (Martin et al. 2015). Instead, as presented in §3.1 and discussed in §4.1, these kinematics seem more consistent with the presence of at least two structures that are clearly separated in velocity space.

(ii) We then independently analyzed the $H\alpha$ spectrum obtained by Keck/MOSFIRE. By optimizing the spectral aperture size and velocity centroid using a curve-of-growth approach, we found an $H\alpha$ detection of $F_{H\alpha} = 2.62 \pm 0.47 \times 10^{-17}$ erg/cm²/s with a significance of $\sim 5.6\sigma$, at a velocity of -511 km/s from the systemic redshift of the quasar UM287 (z=2.283) (see §3.3 for more details). Such a detection is exactly at the expected velocity and spatial location obtained from the Lyα LRIS spectrum and NB image, respectively, reinforcing the reliability of the detected emission.

(iii) The observed $H\alpha$ signal overlaps with residuals from a relatively bright IR sky line, reducing the overall signal-to-noise ratio and hampering the possibility of a detailed kinematic analysis of this emission. However, our curve-of-growth analysis in §3.3.1 suggests that the $H\alpha$ emission could be significantly more narrow (181 km/s) than its Lyα counterpart (418 km/s). This possible broadening of the Lyα emission as compared to the $H\alpha$ emission would naturally be produced by resonant scattering of Lyα photons if the Nebula were optically thick to the Lyα radiation, thus implying $N_{HI} > 10^{14}$ cm$^{-2}$.

(iv) The most important result from our observations is the direct measurement of the Lyα to $H\alpha$ ratio in the region covered by our MOSFIRE N1 slit. We found the ratio $F_{Ly\alpha}/F_{H\alpha}$ to be $5.5 \pm 1.1$ $\pm 1.4$ (sys), see §3.3.1 for a discussion of the systematic error. Since “photon-pumping” or scattering emission from the quasar broad line region contribute Lyα photons without producing any corresponding $H\alpha$ photons, we would expect these emission mechanisms to result in very high values of $F_{Ly\alpha}/F_{H\alpha}$ that would be well above the expected case B recombination (8.7 for total integrated emission or slightly lower for a slit observation like our own).

Therefore, the fact that the observed Lyα to $H\alpha$ is this close to the expected case B recombination value suggests that any contribution to the Lyα emission from these alternate emission mechanisms should be negligible and that the dominant source of Lyα emission for the Slug Nebula is recombination radiation. As derived in Cantalupo et al. (2014), $H\alpha$ column densities above $N_{HI} \sim 10^{19}$ cm$^{-2}$ are expected to have a significant Lyα flux contribution due to “photon-pumping” or scattering from the quasar broad line
region. Thus, our Lyα to Hα flux ratio places an upper limit on the H1 column density of N(H1) < 10^{19} cm^{-2}.

Taken as a whole, the above conclusions imply that the emission from the Slug Nebula is powered by recombination with minimal contributions due to scattering of ex-situ Lyα photons. Thus, the intergalactic and circumgalactic medium around UM287 must be highly ionized, with an H1 column density between 10^{14} cm^{-2} to 10^{19} cm^{-2}. Considering the work of Cantalupo et al. (2014) and Arrigoni Battaia et al. (2015b), this suggests that the Slug Nebula emission requires the presence of high density gas structures (“clumps”) with a small volume filling factor. Though the exact gas density distribution is not well constrained, these “clumps” could be the high density tail of a very broad gas distribution (Cantalupo et al, in prep.).

Despite the technical challenges and limitations of extended, faint emission spectroscopy in the IR, our result demonstrate the potential of Hα intergalactic fluorescent observations at high-redshift. Future surveys from space-based observatories such as JWST that do not suffer from the presence of sky-lines would be necessary for a significant step forward for the Hα study of the Slug Nebula and for other enormous Lyα nebulae at high redshift.

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Figure 4. The top panel shows the unsmoothed two-dimensional spectrum taken with Keck I/MOSFIRE (4.8 hrs) using the N1 slit orientation (the red slit in Figure 1). The $v = 0$ km/s corresponds to the expected H$_\alpha$ emission at a redshift of $z=2.283$, the redshift of QSOA. The spatial offset of 0 kpc indicates the location of the MOSFIRE N1 and LRIS slit intersection, referred to as position “X” in Figure 1. The white rectangle indicates the region in which the H$_\alpha$ flux of the Slug was measured (see §3.3.1 for a description of how the dimensions and location of the rectangle were chosen). Note that the flux measurement aperture overlaps with the continuum emission from compact source “D”. This contaminant is masked out when we perform any analyses or measure fluxes. The bright continuum source around $\sim 150$ kpc is QSO B. The H$_\alpha$ and N$_\text{II}$ [6583] emission lines of compact source “D” ($z=2.287$) are visible at a spatial position of $\sim 50$ kpc and spectral positions of $\sim 400$ km/s and $\sim 1200$ km/s respectively. The bottom panel shows the unsmoothed two-dimensional spectrum taken with Keck I/MOSFIRE (2.6 hrs) using the N2 slit orientation (the green slit in Figure 1). The spectral and spatial axes match those of the N1 spectrum and their zero-points are defined in the same way as in the top panel. The emission line at $\sim 400$km/s and $\sim 50$pc is the H$\alpha$ line of compact source “C” ($z=2.287$).
Figure 5. The smoothed MOSFIRE N1 2D spectrum produced using a median filter with a smoothing kernel of 41 kpc (27 pixels) in the spatial direction and 363 km/s (12 pixels) in the spectral direction. These dimensions correspond to half the size of the white rectangular aperture that was used to measure the Hα flux. Prior to smoothing, the continuum and line emission from compact source “D” as well as QSO B were masked out. Since the median-smoothing filter does not conserve flux, this figure is meant to be purely illustrative and was not used for any of the measurements in the analysis. Though the Hα detection lies on top of a relatively bright sky line, we argue in §4.2.1 that the emission is produced by the Slug Nebula rather than high variance pixels in the sky line residual.

Figure 6. Though the spatial aperture size and centroid can be determined empirically from the narrow-band Lyα image (see Figure 1), radiative transfer effects can modify the kinematics of the Lyα such that it cannot be used to inform the expected wavelength of the Hα emission. To determine the most likely velocity centroid, we calculated the flux as a function of velocity position within a narrow velocity window (6 pixels/181 km/s), as shown in green in the top panel of this figure. The velocity that maximized the flux, −511 km/s, was chosen as the centroid position. Note that doubling the velocity window does not change the location of the peak (shown in blue). We used a flux curve of growth approach to determine the optimal spectral window size. The flux within the MOSFIRE aperture (centered at the velocity centroid of −511 km/s) is shown in the bottom panel as a function of velocity aperture width. At a spectral width of 363 km/s, the Hα flux starts to level off. We therefore choose this as the size of the velocity width of our aperture when calculating the Slug’s Hα flux. The flux within these aperture dimensions result in a SNR of \( \sim 5.6\sigma \).
Figure 7. This figure presents a visual verification that our observed Hα flux (in the white rectangle) resembles a reasonable model of the Hα emission of the Slug. The injected fake sources represent two extremes of the possible Hα velocity distributions: a) the Hα emission is assumed to have a broad velocity distribution that matches that of the LRIS Lyα spectrum (left panel) and b) the Hα line is assumed to have been emitted at a much more narrow range of velocities and the Lyα was broadened by radiative transfer effects (right panel). The left panel shows the median-smoothed image of the MOSFIRE N1 spectrum (using a kernel of 41 kpc × 363 km/s) with an injected fake source that was modeled by taking the Lyα flux from “region 2” in the LRIS spectrum and rescaling it to match the Hα flux. Thus, this Hα emission model keeps the velocity distribution of the Lyα emission intact and is centered at a spatial position of 188 kpc and at a velocity of -718 km/s. We find that the brightest region of the injected source (expected location shown as the red rectangle) appears less significant than the observed emission (in the white rectangle). Similarly, in the right panel we show the MOSFIRE N1 spectrum median-smoothed with the same kernel of 41 kpc × 363 km/s that was applied in Figure 5. The injected fake source, centered at 188 kpc and a velocity centroid that matches the observed Hα emission, was modeled as a 2D-Gaussian. The fake emission had a standard deviation in the spatial direction of 18 kpc and of 181 km/s in the spectral direction and a total flux of $2.62 \times 10^{-17} \text{erg/s/cm}^2$ that matches the observed Hα flux. This emission model (visible within the red rectangle) better resembles the observed Hα emission (at the location of the white rectangle), suggesting that the Hα emission of the Slug has different kinematics than the Lyα and is emitted at a narrower range of velocities.
Figure 8. The Hα flux computed within rectangular apertures of size 81.76 kpc by 363 km/s, measured as a function of spatial position along the MOSFIRE N1 slit. For all these flux calculations, the apertures were centered at a velocity of -511 km/s. The bigger filled blue square point marks the flux at the expected location of the Slug Nebula (see Figure 4). The light blue points with much higher flux values (~75 kpc to ~75 kpc) are associated with the QSOB emission. The small darker blue unfilled squares correspond to regions far enough away from the expected location of the Slug Nebula to be considered “pure sky”. The error on the measurement of the Slug Nebula flux was calculated using the standard deviation of the flux in these “pure sky” apertures. We note here that the “pure sky” regions have a background gradient removed but the rest of data do not, see §3.3.2 for details. The ±1σ error is shown as the transparent blue region as well as the blue error bars associated with the Slug Nebula flux (large blue square). The flux at the location of the Slug Nebula (the dark blue square) corresponds to a ~ 5.6σ detection.

Figure 9. The 1D spectra of compact sources “C” (top panel) and “D” (bottom panel) derived from the 2D MOSFIRE N2 and N1 spectra, respectively, using a simple box extraction. The flux is shown in blue, the error array is plotted in purple, while the green and red vertical lines shows the expected wavelength of Hα and NII[6583] respectively, given the redshift of z=2.287 for each source.