Are we seeing accretion flows in a 250kpc-sized Lyα halo at z=3?*

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ABSTRACT

Using MUSE on the ESO-VLT, we obtained a 4 hour exposure of the z=3.12 radio galaxy MRC 0316-257. We detect features down to ~10^{-19} erg s^{-1} cm^{-2} arcsec^{-2} with the highest surface brightness regions reaching more than a factor of 100 higher. We find Lyα emission out to ~250 kpc in projection from the active galactic nucleus (AGN). The emission shows arc-like morphologies arising at 150-250 kpc from the nucleus in projection with the connected filamentary structures reaching down into the circum-nuclear region. The most distant arc is offset by ~700 km s^{-1} relative to circum-nuclear HeII 1640 emission, which we assume to be at the systemic velocity. As we probe emission closer to the nucleus, the filamentary emission narrows in projection on the sky, the relative velocity decreases to ~250 km s^{-1}, and line full-width at half maximum range from ~300-700 km s^{-1}. From UV line ratios, the emission on scales of 10s of kpc from the nucleus along a wide angle in the direction of the radio jets is clearly excited by the radio jets and ionizing radiation of the AGN. Assuming ionization equilibrium, the more extended emission outside of the axis of the jet direction would require 100% or more illumination to explain the observed surface brightness. High speed (>300 km s^{-1}) shocks into rare gas would provide sufficiently high surface brightness. We discuss the possibility that the arcs of Lyα emission represent accretion shocks and the filamentary emission represent gas flows into the halo, and compare our results with gas accretion simulations.

Key words. Galaxies: evolution – Galaxies: high redshift – Galaxies: active – Galaxies: ISM – Galaxies: halos

1. Introduction

High-redshift radio galaxies, quasars (Heckman et al. 1991a,b), QSOs (Christensen et al. 2006), and “Lyα blobs” (Steidel et al. 2000) exhibit large, extended Lyα emission. High-redshift radio galaxies play a central role in our evolving understanding of the association between massive galaxies, their clustered environments, and halo gas. In fact, the first galaxies at high redshift, z>2, where halo gas was detected in Lyα emission over scales of 10-100s kpc, were radio galaxies (Chambers et al. 1990). These Lyα halos are generally aligned with the radio jets but extend well beyond the radio lobes (Villar-Martín et al. 2003). It is not clear what the association is between the active galactic nuclei (AGN) and the extended Lyα emission. In the circum-galactic environment within the radius subtended by the radio lobes, the Lyα kinematics are complex, while outside the radio emission, the gas is relatively quiescent (Villar-Martín et al. 2003).

The energy sources of Lyα nebulae are not well-constrained (Cantalupo et al. 2016). All processes that excite the Lyα emission depend on the distribution of the emission line gas, the type of objects within the nebula, and how far the emission is from sources of ionizing photons. While ionizing photons from galaxies embedded within the Lyα emission is plausible (Overzier et al. 2013), other sources powering the Lyα emission include ionization by the meta-galactic flux, mechanical heating, dissipation of potential energy as the gas falls into the halo, and resonance scattering of Lyα and UV continuum photons. The mechanisms powering the emission are inextricably linked with the origin of the gas. If the emission is related to outflows, the excitation of the gas might be due to shocks and ionization by stars or AGN (Swinbank et al. 2015). If the gas extends >100 kpc, it may be accreting from the cosmic web or gas instabilities in the halo (Maller & Bullock 2004). In that case, we expect the emission to be due to mechanical heating associated with accretion shocks (Birnboim & Dekel 2003) or from dissipation of potential energy the flows gain as they fall into the potential.

While these general arguments motivated us to obtain deep integral-field spectroscopy of radio galaxies using MUSE on the ESO-VLT, in the specific case of MRC 0316-257, we are motivated by its striking Lyα morphology. MRC 0316-257 is well-studied, massive ∼2×10^{11} M⊙, radio galaxy (De Breuck et al. 2010), which lies in a galaxy over-density (Kuiper et al. 2012). The Lyα emission around MRC 0316-257 is filamentary on scales of ~250 kpc and has a morphology and surface brightness distribution similar to those seen in galaxy simulations. Simulations of gas accretion imply that streams will be visible via their Lyα emission if we detect down to a surface brightness of ∼10^{-19} erg s^{-1} cm^{-2} arcsec^{-2} at z~3 (Rosdahl & Blaizot 2012). It is not clear if these simulations are capturing all the physics necessary to model the emission and evolution of the accreting gas (e.g., Cornuault et al. 2016). Observational constraints are needed. Of course, one must worry about expectation bias (Jeng 2006). Do we call what we observe a “stream” because its morphology agrees with the results of simulations? While we are concerned about this bias, we think it is still instructive to compare our results with those of simulations.

2. Observations, analysis, and results

Multi Unit Spectroscopic Explorer (MUSE; Bacon et al. 2010) observations of MRC 0316-257 were obtained in service mode between UT January 2015 January 14 and 17. We used the Wide
Table 1. Characteristics of spectra of particular regions

| Id | SB $\times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ | $\Delta V$ km s$^{-1}$ | FWHM km s$^{-1}$ | Area arcsec$^2$ |
|----|---------------------------------|------------------|------------------|------------------|
| 1  | 1.3±0.2                         | 142±13           | 250±32           | 14.3             |
| 2  | 1.6±0.1                         | 220±9            | 430±21           | 46.5             |
| 3  | 1.4±0.1                         | 211±12           | 550±29           | 40.5             |
| 4  | 5.5±0.2                         | 224±5            | 410±13           | 9.3              |
| 5  | 2.8±0.1                         | 225±11           | 550±26           | 11.4             |
| 6  | 2.1±0.1                         | 230±6            | 395±16           | 43.4             |
| 7  | 0.8±0.1                         | 227±25           | 525±62           | 35.0             |
| 8  | 0.9±0.1                         | 226±28           | 670±70           | 17.2             |
| 9  | 2.6±0.2                         | 250±14           | 510±32           | 8.5              |
| 10 | 0.8±0.1                         | 290±13           | 510±32           | 74.0             |
| 11 | 1.9±0.1                         | 610±11           | 720±27           | 36.6             |

Notes. The identification numbers correspond to the regions in Fig. 2. The measured $\Delta V$ of regions 2-9 are statistically the same.

Field Mode ($1' \times 1'$ field of view) with the 2nd-order blocking filter resulting in a wavelength coverage of 480-935 nm. Our eight 900s exposures were taken at position angles of 0, 90, 180 and 270$^\circ$ with a small pointing offset to mitigate against systematic artefacts. We processed the data using MUSE pipeline version 1 (Weilbacher et al. 2012) to produce a fully-calibrated (wavelength, flux, and astrometry) sky-subtracted data cube. The measured image quality of the reconstructed white light image is $\sim 1''$. To preserve any possible extended low-surface-brightness features, we did not use sky-residual cleaning algorithms.

To remove remaining artefacts, we subtracted all continuum sources from the datacube using a linear interpolation between two 50Å wide bins on both sides of the emission line. The very extended Ly$\alpha$ emission is only marginally detected. To make the Ly$\alpha$ morphology more evident, we implemented our own version of the algorithm of Martin et al. (2014, Fig. 1). To provide the characteristics of the Ly$\alpha$ emission, we extracted and fit the Ly$\alpha$ line from several regions (Table 1, Fig. 2). The line ratios of Ly$\alpha$, CIV1548, 1551, HeII1640, and CIII]1907, 1909 of the highest surface brightness regions (3-5) imply they are ionized by the AGN. Beyond the circum-nuclear emission, $>10''$ from the AGN, the Ly$\alpha$ emitting regions are too faint to determine line ratios necessary to constrain the ionization source.

We find Ly$\alpha$ emission, down to $\approx 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, up to $\sim 35''$ from the radio galaxy ($\sim 250$ kpc in projection). The morphology of the emission, outside of that likely excited by the AGN, is arc- and stream-like with the higher surface brightness arcs appearing at $\sim 150$-250 kpc (regions 1, 2, and 11) from the nucleus with the connected filamentary structures reaching into the circum-nuclear regions (regions 6-8). The most distant arc (region 11) has an offset velocity relative to the arc second-scale HeII1640 emission from the AGN of $\sim 700$ km s$^{-1}$. We assumed that the velocity of the HeII line represents the systemic velocity of the system. This assumption is supported by the small relative offset velocity ($\lesssim 50$ km s$^{-1}$) between circum-nuclear dense gas (from CO8(8-7)) and HeII in another radio galaxy (Gullberg et al. 2016). Closer to the nucleus, the filamentary of Ly$\alpha$ emission narrow on the sky, the redshifted offset velocity decreases to $\sim 250$ km s$^{-1}$, line full-width at half maximum remain very high, reaching up to $700$ km s$^{-1}$, $\sim 50$-100 kpc from the nucleus. All throughout the emission, the lines are broad, $\sim 300$-700 km s$^{-1}$.

Projected on to region 11, we find a z=3.1245 galaxy, which we have dubbed the “Arrow” because of its arrow-like morphology in HST/ACS F814W imaging (Fig. 2).
(red regions 6–11 in Fig. 2), it is unlikely that the AGN provides sufficient photons; young stars embedded in these regions would be an alternative. However, the remarkable uniformity of regions 6–10 suggests there is no significant local ionization by stars as observed in, e.g., MRC 0943-242 (Gullberg et al. 2016) and also argues against a central source such as an AGN ionizing the gas. **Ionization by the meta-galactic flux:** At $z \sim 3$, the intensity of ionizing photons due to the meta-galactic flux is $\approx 2 \times 10^5$ photons cm$^{-2}$ s$^{-1}$ (Haardt & Madau 1996). Assuming ionization equilibrium and the clouds are optically thick, implies that the meta-galactic ionization rate is $\sim 2$ orders-of-magnitude less than that necessary to maintain the ionization of the extended gas. So while the meta-galactic flux contributes to the ionization of the diffuse gas, it does not maintain it.

**Resonance Scattering:** If the extended gas has sufficient column of neutral HI to be optically thick at the wavelength of Lyα then resonance scattering of the Lyα and UV continuum from the AGN can contribute to its surface brightness. The line profiles of the extended Lyα emission do not mirror those of the nuclear gas – they are both narrower and have significant velocity offsets relative to the nuclear emission (Table 1). The approximately constant surface brightness of the extended emission argues against a central source exciting the emission. In addition, spectropolarimetry of MRC 0316-257 (Reuland et al. 2003) finds unpolarized (<4%) Lyα emission, arguing against any significant contribution of scattered light to the circum-nuclear emission.

**Shock heating in the outer halo:** Another possibility for exciting the Lyα emission in the halo of MRC 0316-257 is an accretion shock from inflowing gas at the halo boundary and/or shocks from cloud-cloud collisions in a multiphase stream (Cornuault et al. 2016). The morphology of the most extended emission to the west-southwest (region 11) is shell-like and certainly suggestive of compression (a “splash”). We observe a velocity shear between region 11 and that of the inner halo across regions 6–10 of $\sim 400$–500 km s$^{-1}$. In addition, over these regions, 6–11, the gas appears to be highly disturbed having FWHM of 300–700 km s$^{-1}$. These violent motions and shears make shock heating a plausible mechanism for exciting the gas.

To test this possibility, we compare our measured surface brightness with those predicted for high velocity shocks. The models of Allen et al. (2008) imply that even in relatively low density, low metallicity, gas (> fewx$10^{-3}$ cm$^{-3}$), the surface brightness produced by shocks is sufficient to explain our observations for the relative velocities we observe in the data,
4. Lyα structures as accretion streams

Comparing the relative velocities of galaxies surrounding MRC 0316-257 with those from cosmological simulations, Kuiper et al. (2012) suggest that it is a result of the on-going merger of two massive, ~10^{14} M_\odot, proto-clusters. Finding that the surface brightness of the gas in the outer halo is consistent with being shocked heated, its arc- or shell-like and filamentary morphology, large line widths, redshifted velocities, and relatively smooth change in velocity as a function of distance from the AGN suggests this may be gas accreting from the cosmic web (Rosdahl & Blaizot 2012). Goerdt et al. (2015). If we make this assumption, then what do our results tell us about gas accretion into massive halos and do they agree with those from cosmological simulations?

For this comparison, we focus exclusively on the filamentary structure to the west-southwest of the AGN (regions 6–11). We limit ourselves to these regions because none of the low surface brightness emission shows obvious evidence for being ionized by the AGN, they do not lie along the direction of the radio jets (which trace the direction of the ionization cone and the ionization cones have opening angles ~45°), suggesting these regions lie outside; Drouart et al. (2012), and they extend rather contin- uously in emission from the outer halo into the circum-nuclear region. As already noted in the introduction, these regions have surface brightnesses consistent with estimates from simulations (Rosdahl & Blaizot 2012). The “Arrow” lies in this structure which is seen in simulated filaments (Gheller et al. 2016 Fig.[2]). These observations form the basis for us assuming these regions are part of an accretion stream.

The surface brightness of the distant arc can be explained via shock heating. Assuming such shock occurs at the virial radius, simple scaling relations imply radii of ~150 and 330 kpc for 10^{13} and 10^{14} M_\odot halos respectively. Similarly, the virial velocities for halos with these masses are 500 and 1100 km s^{-1}. We do not necessarily expect the velocities of the streams to be equal to the virial velocity but can be as low as half (Goerdt & Ceverino 2015). Both the distance of the outermost shell from the nucleus and the velocities we observe are consistent with virial expectations. We observe projected distances and velocities (and the projection of the velocity could change with position), not true positions and velocities, so this comparison is, by necessity, only order-of-magnitude. Simulations do show broad lines in Lyα of the same order (~100k ms^{-1}) as we observe (Goerdt et al. 2010).

Gas accretion through a stream, while able to make up most of the total accretion rate, can also vary substantially within a filament. Goerdt et al. (2015) found accretion rates of ~50-5000 M_\odot yr^{-1} through filaments for a halo mass of ~10^{12}. Scaling up these rates per sr by the virial mass as is appropriate for total mass accretion rates (M \propto M^{2/3}, Goerdt et al 2015), we estimate rates 15 to 300\times higher for 10 to 100\times higher halo masses. A rough estimate suggests the shock sub-tends ~1% of the spherical surface area at 250 kpc and using the mass flow rate (\alpha), implies an accretion rate per unit solid angle ~2\times 10^{-5} M_\odot yr^{-1} sr^{-1} -- a value consistent with simulations.

Many properties of the Lyα emission we observed in the circum-galactic medium of MRC 0316-257 are broadly consistent with the results of simulations of gas accretion streams. However, we view aspects of this agreement as fortuitous. Simulations generally lack the spatial and temporal resolution necessary to capture thermal and dynamical instabilities, resolve high Mach shock fronts, fragmentation of the post-shock gas, and turbulence that naturally occur in astrophysical gas flows (Kritsuk & Norman 2002, Cornuault et al. 2016). It is not clear if simulations show conspicuously large shock fronts and strong post-shock cooling at approximately the halo boundary as we have suggested. Such fronts, if real, are important for establishing many properties of the gas on its inward journey deeper into the potential well (fragmenting the gas and inducing turbulence). Until simulations reach the necessary resolutions and input physics to resolve shock fronts and fragmentation, it is fair to say that our theoretical understanding of these flows is limited. Observational constraints, such as those provided here, are crucial for obtaining a deeper understanding of how galaxies get their gas through gas accretion flows.

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