

CO line emission in the halo of a radio galaxy at $z = 2.6$ [★]

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ABSTRACT

We report the detection of luminous CO(3–2) line emission in the halo of the $z = 2.6$ radio galaxy (HzRG) TXS0828+193, which has no detected counterpart at optical to mid-infrared wavelengths implying a stellar mass $\lesssim \text{few} \times 10^9 M_{\odot}$ and relatively low star formation rates. With the IRAM Plateau de Bure Interferometer (PdBI), we find two CO emission-line components at the same position at ~ 80 kpc distance from the HzRG along the axis of the radio jet, with different blueshifts of few 100 km s^{-1} relative to the HzRG and a total luminosity of $\sim 2 \times 10^{10} \text{ K km s}^{-1} \text{ pc}^2$ detected at a total significance of $\sim 8\sigma$. HzRGs have significant galaxy overdensities and extended haloes of metal-enriched gas often with embedded clouds or filaments of denser material, and likely trace very massive dark matter haloes. The CO emission may be associated with a gas-rich, low-mass satellite galaxy with very little ongoing star formation, in contrast to all previous CO detections of galaxies at similar redshifts. Alternatively, the CO may be related to a gas cloud or filament and perhaps jet-induced gas cooling in the outer halo, somewhat in analogy with extended CO emission found in low-redshift galaxy clusters.

Key words: galaxies: high-redshift – galaxies: individual: TXS0828+193 – radio lines: galaxies.

1 INTRODUCTION

The most vigorous starbursts in the Universe occurred in massive galaxies during the most active phase of galaxy evolution and active galactic nuclei (AGN) activity, at redshifts $z \sim 2$ – 3 . These galaxies formed most of their stellar mass of a few $\times 10^{10-11} M_{\odot}$ in short bursts of few $\times 100$ Myr with star formation rates of several $100 M_{\odot} \text{ yr}^{-1}$ (e.g. Archibald et al. 2001; Smail et al. 2002; Reuland et al. 2004). Luminous CO emission observed at millimetre wavelengths is typically viewed as the most direct sign of the immense reservoirs of cold molecular gas necessary to fuel these starbursts (e.g. Greve et al. 2005).

Powerful high-redshift radio galaxies (HzRGs) may host the most extreme starbursts at high redshift (e.g. Seymour et al. 2008), seen in a short, but critical phase of their evolution dominated by strong

AGN feedback (Nesvadba et al. 2006, 2007, 2008). Bright K -band magnitudes suggest HzRGs are among the most massive galaxies at all cosmic epochs (e.g. De Breuck et al. 2002), a conclusion recently confirmed through rest-frame near-infrared photometry. Seymour et al. (2007) find stellar masses of several $10^{11} M_{\odot}$, factors of a few larger than typical masses of submillimetre galaxies at similar redshifts ($10^{10.5} M_{\odot}$, Smail et al. 2004). Luminous CO emission has been found in several HzRGs (e.g. Papadopoulos et al. 2000; De Breuck et al. 2005; Klamer et al. 2005), and recently also in a satellite galaxy of a HzRG (Ivison et al. 2008).

HzRGs reside in particularly rich environments, and are often surrounded by several 10 s of companion galaxies (e.g. Le Fevre et al. 1996; Kurk et al. 2004; Venemans et al. 2007) as well as extended haloes of ionized and neutral gas. Faint, diffuse $\text{Ly}\alpha$ emission extends to radii well beyond the inner halo, where the gas is strongly disturbed by the radio jet. Villar-Martín et al. (2002, 2003) trace ionized gas out to radii of > 100 kpc with relatively quiescent kinematics and C IV emission-line ratios implying near-solar metallicity out to large radii. Deep $\text{Ly}\alpha$ absorption troughs reveal neutral gas, likely in clouds or filaments (e.g. van Ojik et al. 1997).

[★]Based on observations collected at the IRAM Plateau de Bure Interferometer (PdBI).

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Using the IRAM Plateau de Bure Interferometer (PdBI), we detected luminous CO(3–2) line emission in the halo of the $z = 2.6$ HzRG TXS0828+193, with a luminosity of $2 \times 10^{10} \text{ K km s}^{-1} \text{ pc}^2$. Deep photometry from the rest-frame ultraviolet to mid-infrared including MIPS 24 μm imaging does not reveal a counterpart within the 5 arcsec beam, implying a very small associated stellar mass and low star formation rates. These are very unusual properties for a high-redshift CO emitter, and we discuss possible scenarios for its nature. Throughout the paper, we adopt a flat $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-3}$ concordance cosmology with $\Omega_\Lambda = 0.7$ and $\Omega_M = 0.3$.

2 OBSERVATIONS AND ANCILLARY DATA

We observed TXS0828+193 with the IRAM PdBI (Guilloteau et al. 1992) in the D configuration. At $z = 2.6$, CO(3–2) falls at 96.6 GHz and into the 3 mm atmospheric window. We reached a $0.3 \text{ mJy beam}^{-1}$ rms and a beam size of $5.3 \times 4.6 \text{ arcsec}^2$ ($42 \times 37 \text{ kpc}$ at $z = 2.6$). On-source integration time was 12.9 h under normal to good conditions with six antennae and system temperatures $< 150 \text{ K}$. Data were calibrated using the CLIC package and with MWC349 as flux calibrator. We combined both polarizations and rebinned the data to a resolution of 30 km s^{-1} . The PdBI receivers covered a window of $\sim 2600 \text{ km s}^{-1}$.

We also include deep Palomar WIRC K -band imaging, and *Spitzer* IRAC 3.6 μm and MIPS 24 μm photometry, as well as archival *HST* Wide Field Planetary Camera 2 *F606W* imaging. C. Carilli kindly provided his Very Large Array (VLA) 8.4 GHz A-array map of TXS0828+193 first published in Carilli et al. (1997). We detected the millimetre continuum of the radio core of TXS0828+193. Thus, we could align the PdBI data with our line-free K -band continuum image of TXS0828+193 (Nesvadba et al. 2008), assuming that the AGN is at the centre of the galaxy. The K -band data then served as a reference to align all other images.

3 CO EMISSION IN THE HALO OF A HZRG

We identify luminous CO(3–2) emission in the halo of TXS0828+193 at a distance of $\sim 10 \text{ arcsec}$ (80 kpc) south-west from the radio galaxy (Fig. 1). The 5 arcsec beam corresponds to an upper size limit of $\sim 40 \text{ kpc}$. The emission-line region is aligned with the axis of the radio jet but 2.5 arcsec (20 kpc) west-south-west in projection from the radio lobe, and hence at a larger radius from the central galaxy. Integrating over the full line, we reach 8σ significance. To further ensure the robustness of our measurement, we split the data into two subsamples with consistent results in each subset.

The integrated spectrum is shown in Fig. 2. We find two compact components, labelled TXS0828+193 SW1 and SW2, respectively. They have the same spatial position, but different blueshifts of $\Delta v_{\text{SW1}} = -200 \pm 40 \text{ km s}^{-1}$ and $\Delta v_{\text{SW2}} = -920 \pm 70 \text{ km s}^{-1}$ relative to the HzRG, respectively. The systemic velocity was estimated from rest-frame optical integral-field spectroscopy of TXS0828+193 (Nesvadba et al. 2008). SW1 and SW2 have linewidths $\text{FWHM}_{\text{SW1}} = 310 \pm 270 \text{ km s}^{-1}$ and $\text{FWHM}_{\text{SW2}} = 340 \pm 270 \text{ km s}^{-1}$, respectively. Integrated fluxes are $I_{\text{CO,SW1}} = 0.23 \pm 0.08 \text{ Jy km s}^{-1}$ and $I_{\text{CO,SW2}} = 0.24 \pm 0.06 \text{ Jy km s}^{-1}$, respectively, and correspond to luminosities of $\mathcal{L}'_{\text{CO}} = 9 \times 10^9 \text{ K km s}^{-1} \text{ pc}^2$ per component. (We assumed $\mathcal{L}'_{3-2} = \mathcal{L}'_{1-0}$ and $r_{32} = 1$).

Molecular gas mass estimates of high-redshift galaxies depend on the assumption that the conversion factors from CO to H_2 (X factors) established at low redshift will apply. The X -factor of $X_{\text{U}} =$

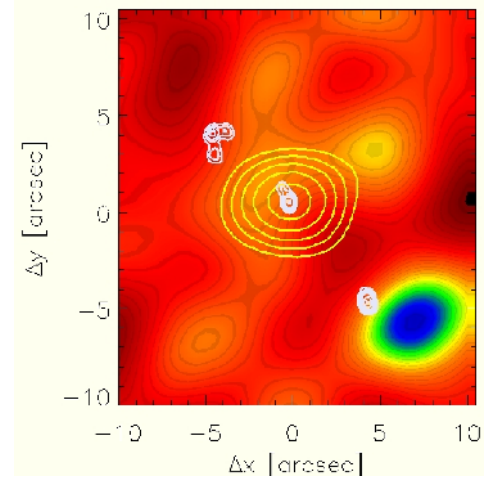


Figure 1. CO(3–2) line image, integrated over the full wavelength range of the two components. Line emission is not spatially resolved with a 5 arcsec beam. Thick yellow and thin white contours show the non-thermal continuum observed at 3 mm with the PdBI and at 8.4 GHz with the VLA, respectively.

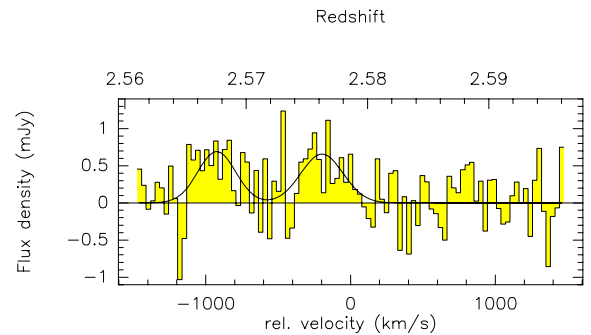


Figure 2. Integrated spectrum of the CO emitter south-west from TXS0828+193. The yellow histogram marks the data, with a Gaussian fit of two components overlaid (black line). The blueshifted and redshifted components are detected at 3σ and 4σ significance, respectively.

$0.8 \text{ M}_\odot / (\text{K km s}^{-1} \text{ pc}^2)$ appropriate for ULIRGs yields estimates $\sim 5\times$ lower than the Milky Way X -factor (Downes & Solomon 1998). With X_{U} , the $I_{\text{SW1}} \sim S_{\text{SW2}} \sim 0.25 \text{ Jy km s}^{-1}$ per component corresponds to $7 \times 10^9 \text{ M}_\odot$ in cold gas per component, or $1.4 \times 10^{10} \text{ M}_\odot$ in total.

We will now discuss two possible scenarios for the nature of the CO emission in the halo of TXS0828+193, namely, that it may be associated with a satellite galaxy or that it may be related to gas clouds or filaments within the gas-rich halo of TXS0828+193.

3.1 An extremely gas-rich satellite galaxy?

We searched for the stellar continuum of putative galaxies associated with SW1/2 in our set of images with rest-frame wavelengths between $\sim 1700 \text{ \AA}$ and $7 \mu\text{m}$ (Section 3). SW1/2 was not detected in any of the data sets (Fig. 3). This is in strong contrast to the companion of the $z = 3.8$ HzRG 4C60.07, that was detected in all bands in a similar study of Ivison et al. (2008). We use the deep K -band photometry with a 3σ limit of $K_{3\sigma} = 23.7 \text{ mag}$ in a 1 arcsec aperture and the population synthesis models of Bruzual & Charlot (2003), to place an upper limit on the stellar mass. Continuous star

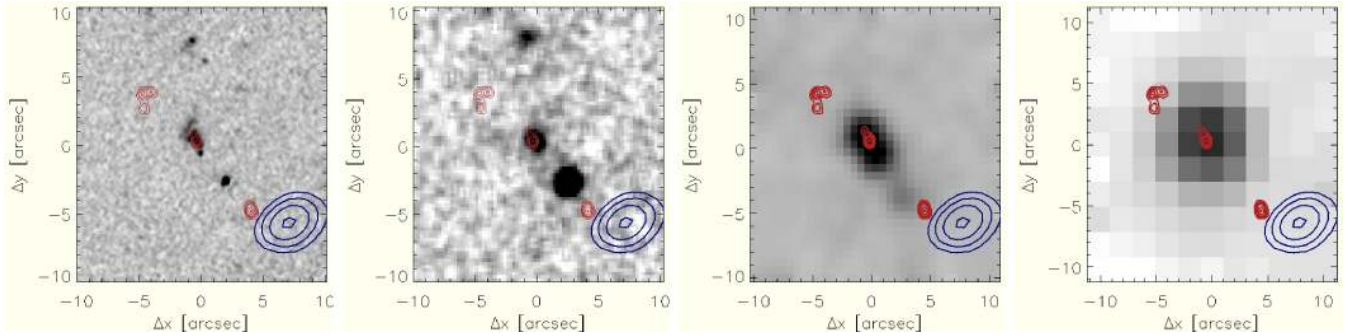


Figure 3. Left- to right-hand panel: *HST* WPC2 F606W, Palomar *K* band, *Spitzer* IRAC 3.6 μm and MIPS 24 μm photometry of TXS0828+193. Thick blue contours show the position of the SW1/SW2, thin red contours mark radio jets. SW1/SW2 is undetected in all bands.

formation histories with ages between 5×10^7 and 2×10^9 yr (implying a formation at $z \lesssim 10$), and extinctions $A_V = 1\text{--}5$ mag correspond to a maximum of $\sim 3 \times 10^9 M_\odot$ in stellar mass. This covers more than the range of extinctions found for dusty submillimetre galaxies (SMGs) at $z \geq 2$ and low-redshift ULIRGs typically associated with strong CO emission ($A_V \lesssim 2$ mag Scoville et al. 2000; Smail et al. 2004). These extinctions are derived from the integrated photometry of the galaxies, as appropriate for our purposes. Extinctions along individual sightlines and into a starburst may be significantly higher.

The rms of $\sim 100 \mu\text{Jy}$ in our MIPS 24 μm image is well below the fluxes measured by Pope et al. (2008) for submillimetre galaxies at similar redshifts, which are in the range 200–500 μJy . This allows us to set constraints on the star formation, because the filter covers the 6.2 μm polycyclic aromatic hydrocarbon (PAH) band, and more than half of the 7.7 μm band at the redshift of SW1/2. With the MIPS non-detection, it appears unlikely that SW1/2 is forming stars at the prodigious rates of several $100 M_\odot$ typically observed in SMGs.

We will now estimate a dynamical mass for SW1/2. With a beam size of 40 kpc, we do not know whether the CO line emission may be associated with one or with two galaxies. If SW1/2 represents a double-horned profile of a single, roughly virialized, rotating galaxy (as often assumed for SMGs), we can estimate a mass by setting $M_{\text{dyn}} = (v/\sin i)^2 R_{1\text{kpc}}/G$ with circular velocity $v = 350 \text{ km s}^{-1}$, inclination i , radius $R_{1\text{kpc}}$ and gravitational constant, G . The radius R is given in kpc. Tacconi et al. (2008) use radii $\sim 2\text{--}5$ kpc for their mass estimates, which would imply $M_{\text{dyn}} \sim 0.6\text{--}1.5 \times 10^{11} M_\odot$ for an edge-on disc and, perhaps more realistically, two to three times higher masses for a more average inclination. Thus, SW1/2 would have a mass in the typical range of submillimetre galaxies or powerful radio galaxies, which are $K \sim 20$ mag or brighter (De Breuck et al. 2002; Smail et al. 2004). This would also significantly exceed the baryonic (gas and stellar) mass of few $\times 10^{10} M_\odot$. If alternatively, we assume that SW1 and SW2 are associated with two different galaxies in the halo of TXS0828+193 (a plausible assumption given the 40 kpc covered by the beam), then, following Neri et al. (2003), we estimate a dynamical mass of $M_{\text{dyn}} = 4 \times 10^9 R_{1\text{kpc}} M_\odot$ per galaxy for a full width at half-maximum (FWHM) = 300 km s^{-1} linewidth of each component. Assuming a radius of a few kpc, the dynamical mass estimate will be lower than the molecular gas mass by factors of a few, except if we assume that both galaxies are seen within a few degrees from being face-on, which does not appear very likely. Each of these estimates relies on the assumption that the gas is approximately virialized. This is a common assumption in CO emission-line studies at high redshift, but whether it is justified has yet to be proven. In

Section 3.2, we discuss a scenario where the virial assumption would not apply. Likewise Ivison et al. (2008) raised doubts as to whether this assumption is always justified in the context of high-redshift galaxies.

In these ‘galaxy’ scenarios, we also need a mechanism to suppress star formation in the cold gas traced by the CO. If the CO line emission arises from a disc with a few kpc in radius, then the observed gas mass of $1.4 \times 10^{10} M_\odot$ corresponds to a surface mass density of few $\times 1000 M_\odot \text{ pc}^{-2}$. Following the Schmidt–Kennicutt relation (Kennicutt 1998) between gas surface density and star formation intensity (SFI), we expect $\text{SFI} = \text{few} \times 10 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$. Averaging over the size of the disc, this corresponds to a total star formation rate of several $100 M_\odot \text{ yr}^{-1}$. This is in the typical range of submillimetre galaxies, but in contradiction with our non-detection at 24 μm . Likewise, with star formation rates of few $\times 100 M_\odot$ a stellar mass of few $\times 10^9 M_\odot$ would be built in few $\times 10^7$ yr, so that SW1/2 would have to be in a very special, very young stage of the starburst if it was a galaxy.

Papadopoulos et al. (2008) recently found luminous, but excited CO line emission in a nearby radio galaxy, 3C293, which does not seem associated with a starburst. The same is suggested by *Spitzer* observations of a small number of nearby galaxies with strongly enhanced, mid-infrared H_2 line emission (e.g. Ogle et al. 2007). Guillard et al. (2009) argue that this gas may be heated through the dissipation of kinetic energy. In these cases, it is likely that the energy was injected by an external mechanism (a merger or AGN). We will in the following propose a somewhat related scenario, where the nearby radio lobe may have induced the collapse of gas within the halo of TXS0828+193.

3.2 Cold gas in the halo?

TXS0828+193 was the first HzRG where an outer halo was found (Villar-Martín et al. 2002), which extends beyond the turbulent, luminous inner emission-line region that is likely powered by energy released from the powerful AGN (e.g. Villar-Martín et al. 1999; Nesvadba et al. 2008). Diffuse gas in the outer halo is fainter, and has more moderate velocity gradients and linewidths, which may indicate rotation in the potential of the underlying dark matter halo (Villar-Martín et al. 2003, 2006), or perhaps gas infall (Humphrey et al. 2007). Villar-Martín et al. (2002) find C iv emission in the outer halo of TXS0828+193 and suspect that metallicities may be up to nearly solar, perhaps representing gas that has previously been driven out from the central galaxy.

Fig. 4 shows the relative velocity and radial distance of SW1 and SW2 from TXS0828+193 relative to the two-dimensional Ly α

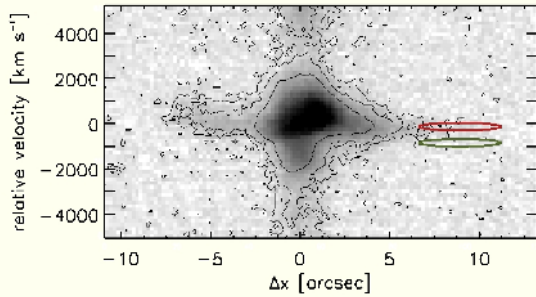


Figure 4. $\text{Ly}\alpha$ spectrum of TXS0828+193, graciously provided by M. Villar-Martín with the CO(3–2) components SW1 and SW2 shown as red and green ellipses, respectively. Positions and sizes correspond to the distance from the HzRG and beam size, and to the relative redshift and FWHM linewidth of the two components, respectively.

longslit spectrum of Villar-Martín et al. (2002). The slit of the $\text{Ly}\alpha$ spectrum falls near the CO position, but since the slit width, 1 arcsec, is significantly smaller than the beam of 5 arcsec, we cannot infer whether it covers the position of the CO emitter. $\text{Ly}\alpha$ emission is traced almost out to the 24 kpc radial distance of SW1/2 from the HzRG.

SW1 and SW2 are blueshifted relative to the radio galaxy, and are also on the side of the radio galaxy where the diffuse $\text{Ly}\alpha$ halo is blueshifted (the luminous inner halo is redshifted). The kinematic properties of SW1 (FWHM = $310 \pm 270 \text{ km s}^{-1}$, $z = 2.5761 \pm 0.0008$) are very similar to those of the diffuse ionized gas (FWHM = $590 \pm 60 \text{ km s}^{-1}$, $z = 2.5741 \pm 0.0008$), with a relative blueshift of SW1 relative to the $\text{Ly}\alpha$ emission of $170 \pm 60 \text{ km s}^{-1}$. SW2 (FWHM = $340 \pm 270 \text{ km s}^{-1}$, $z = 2.5678 \pm 0.0007$) is blueshifted by 890 km s^{-1} relative to the diffuse $\text{Ly}\alpha$ emission, but has a similar linewidth within large uncertainties. Given the low stellar mass possibly associated with the CO line emission (Section 3.1), this may suggest that the CO emission originates from clouds or filaments in the diffuse halo gas of TXS0828+193, which has metallicities of up to about solar (Villar-Martín et al. 2002). De Breuck, Neri & Omont (2003) detected CO emission at the redshift of a $\text{Ly}\alpha$ absorber near the $z = 3.1$ HzRG B2 2330+3927, and proposed a similar scenario, but did not have the spatial resolution to directly measure positional offsets between the radio galaxy and CO emission.

Several mechanisms may plausibly influence the halo gas including minor or major mergers, or powerful outflows from starbursts and AGN. Each of these mechanisms may sweep up and accelerate halo gas over time-scales of a few $\times 10^8 \text{ yr}$ similar to those suggested by the relative velocity of the CO and distance to the radio galaxy. The close proximity of the emitters to the radio hotspot and alignment with the jet axis is, however, suspicious. The emitters are very close to the jet axis, and within a projected area of $\sim 300 \text{ kpc}^2$ from the hotspot, whereas our data have a half-power beamwidth covering a total of $135\,000 \text{ kpc}^2$. If this is not due to mere projection effects, then weak shocks produced by the expanding radio source may play a role in compressing and exciting the gas (the radio hotspot is only about 2.5 arcsec or 20 kpc away, and we may not detect the low surface brightness radio plasma). In turn, the interaction with dense gas may be enhancing or even triggering the radio hotspot.

Extended cold molecular gas is found in some massive cooling-flow clusters at low redshift (e.g. Edge 2001; Salomé & Combes 2004), where molecular gas forms along the edges of X-ray cavities

inflated by the radio jet and outside the volume filled by the radio plasma. Similarly, CO line emission in the haloes of HzRGs may trace the edges of cavities inflated by the radio lobes. Within the large uncertainties, the $\sim 300 \text{ km s}^{-1}$ FWHM of SW1/2 are not very different from the linewidths in the diffuse CO in the Perseus cluster (Salomé et al. 2008).

We can use the observed surface brightness of the faint $\text{Ly}\alpha$ emission in the halo of TXS0828+193 and the observed CO luminosity to investigate whether TXS0828+193 falls near the correlation between the luminosity of the molecular and ionized gas found in local cooling-flow clusters (Edge 2001). Adopting a flux conversion $\mathcal{L}_{\text{Ly}\alpha} = 13 \times \mathcal{L}_{\text{H}\alpha}$ between $\text{Ly}\alpha$ and $\text{H}\alpha$ luminosity (where we neglect extinction), we find a strict upper limit on the $\text{Ly}\alpha$ luminosity of $\mathcal{L}_{\text{Ly}\alpha} = 1.4 \times 10^{42} \text{ erg s}^{-1} \text{ cm}^{-2}$ within the $20''$ arcsec area of the beam. Translating the CO gas mass of Edge (2001) into a CO luminosity, we find that the halo of TXS0828+193 falls only factors of a few below the expected value found in local cooling-flow clusters. Allowing for different physical conditions, gas distributions and AGN properties (HzRGs host powerful AGN), we may well be seeing a fundamentally similar phenomenon.

However, the brightness temperatures and spatial distribution of the extended CO emission in low-redshift clusters are significantly different. Low brightness temperatures suggest low-gas filling factors, and much of the gas is concentrated towards the central radio galaxy. This may arise from different properties of the diffuse cluster gas at high and low redshift, which is cold for HzRGs (with embedded filaments or clouds of few $\times 10^9 M_{\odot}$ and more in dense neutral gas van Ojik et al. 1997) and hot and rarefied in low-redshift clusters. In fact, in HzRGs at $z \sim 2\text{--}3$, we may be witnessing the processes that led to the rapid heating and entropy enhancement of cluster gas through AGN feedback, which seem necessary to explain the temperature profiles of massive X-ray clusters at low redshift (Nath & Roychowdhury 2002; McCarthy et al. 2008). Interestingly, $\text{Ly}\alpha$ absorbers are only found in the haloes of HzRGs with relatively small, and likely rather young, radio sources. This suggests that large amounts of cold, dense gas (and perhaps dust) may be present in the halo at radii that are not yet affected by mechanical heating from the radio source, and perhaps represent gas falling into the massive dark-matter halo. The approaching radio jet of TXS0828+193 may have contributed to triggering the collapse and forming SW1/2. Similar processes may ultimately lead to positive AGN feedback and jet-triggered star formation in some cases, if the cold molecular gas will relax and form stars over sufficiently short time-scales.

4 SUMMARY AND CONCLUSIONS

We discuss the nature of luminous CO(3–2) line emission in the halo of the radio galaxy TXS0828+193 at $z = 2.6$. The CO emission resembles that of submillimetre galaxies, but we do not detect continuum emission from SW1/2, including $24 \mu\text{m}$ MIPS imaging, which covers the PAH bands at $z = 2.6$. For a gas disc in a galaxy, we would expect strong star formation if the Schmidt–Kennicutt law roughly applies.

Alternatively, SW1/2 may represent a cloud or filament in the halo, maybe related to neutral, dense $\text{Ly}\alpha$ absorbers observed near some HzRGs. The approaching radio jet of TXS0828+193 may have contributed to triggering the collapse and exciting the gas. This is somewhat in analogy with diffuse CO emission in low-redshift clusters, but the ambient gas properties will likely be very different at $z = 2.6$. In either case, SW1/2 does not appear to be an ‘ordinary’ high-redshift CO emitter, and further observations are necessary

to differentiate between the two scenarios. This suggests that CO observations of the high-redshift Universe with the refurbished PdBI and soon with ALMA, will reveal a rich and multifaceted picture of the early Universe.

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