Detection of large scale Lyα absorbers at large angles to the radio axis of high-redshift radio galaxies using SOAR*

M. Silva, A. Humphrey, P. Lagos, R. Guimarães, T. Scott, P. Papaderos and S.G. Morais

1Institute of Astrophysics and Space Sciences, Universidade do Porto, CAUP, Rua das Estrelas, 4150-762 Porto, Portugal.
2Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, R. Campo Alegre 687, 4169-007 Porto, Portugal.
3Centre for Space Research, North West University, Potchefstroom 2520, South Africa.
4Faculty of Medicine, Universidade Federal de Minas Gerais, Belo Horizonte, 30130-100 Minas Gerais, Brazil.

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ABSTRACT

We present an investigation of the properties of the extended Lyα halo and the large-scale H I absorbing structures associated with 5 high-redshift radio galaxies at z > 2, using the Goodman long-slit spectrograph on the SOAR telescope, with the slit placed at large angles (>45°) to the radio axis, to study regions that are unlikely to be illuminated by the active nucleus. Spatially extended Lyα emission is detected with large line widths (FWHM = 1000 – 2500 km s⁻¹), which although impacted by resonant scattering, is suggestive of turbulent motion. We find a correlation between higher blueshifts and higher FWHM, which is an indication that radial motion dominates the bulk gas dynamics perpendicular to the radio axis, although we are unable to distinguish between outflow and infall scenarios due to the resonant nature of the Lyα line. Extended, blueshifted Lyα absorption is detected in the direction perpendicular to the radio axis in three radio galaxies with minimum spatial extents ranging from ≥27 kpc to ≥35 kpc, supporting the idea that the absorbing structure covers the entire Lyα halo, consistent with being part of a giant, expanding shell of gas enveloping the galaxy and its (detected) gaseous halo.

Key words: galaxies: evolution – galaxies: high-redshift – galaxies: active – galaxies: ISM – galaxies: quasars: absorption lines – galaxies: quasars: emission lines

1 INTRODUCTION

High-redshift radio galaxies (hereafter HzRGs; z > 2) are among the most spectacular objects in the sky. Producing prodigious luminosities (e.g., L₅₀₀MH₂ > 10²⁷ W Hz⁻¹; Breuck et al. 2010 and references therein) from tiny volumes, with radiation spread over a broad range of frequencies, HzRGs are noteworthy in providing us with a unique opportunity to investigate the formation and evolution of massive galaxies and active galactic nuclei (hereafter AGN).

These galaxies are among the most massive galaxies, with stellar masses up to ~10¹² M⊙ (e.g., De Breuck et al. 2001; Seymour et al. 2007; Hatch et al. 2009; De Breuck et al. 2010; Hatch et al. 2013; Nesvadba et al. 2017b), often with evidence for significant star formation rates (up to ~1400 M⊙ yr⁻¹; Ogle et al. 2012; Seymour et al. 2012; Rocca-Volmerange et al. 2013; Hatch et al. 2013; Drouart et al. 2014). HzRGs are also commonly associated with spatially extended Lyα halos, with luminosities up to ~10⁴⁵ erg s⁻¹, which are gas rich (M_HI ~ 10⁹–11 M⊙) and extend over tens or even a few hundred kpc (Fosbury et al. 1982; di Serego Alighieri 1988; McCarthy et al. 1990b; McCarthy 1993; van Ojik et al. 1997; Pentericci et al. 1998; Francis et al. 2001; Reuland et al. 2003; Villar-Martín et al. 2003; Sánchez & Humphrey 2009; Humphrey et al. 2013a; Cantalupo et al. 2014; Swinbank et al. 2015; Borisova et al. 2016; Cai et al. 2017; Arrigoni Battaia et al. 2018). These large scale Lyα structures usually show a clumpy and irregular morphology (Reuland et al. 2003) often aligned with the radio jets (McCarthy et al. 1995) that exert significant feedback onto the surrounding intergalactic medium (hereafter IGM; Villar-Martín et al. 2003; Nesvadba et al. 2006;
Humphrey et al. 2006; Ogle et al. 2012). Generally, the halos can be divided into two distinct kinematic components: quiescent and perturbed. The quiescent component shows kinematics with full width at half maximum (hereafter FWHM) < 1000 km s\(^{-1}\) and no clear relationship with the radio jets (van Ojik et al. 1996; Villar-Martín et al. 2002, 2003; Sánchez & Humphrey 2009). This component has been reported to be a common feature of the Ly\(\alpha\) halos being detected across the full spatial extent of the halos (e.g. Villar-Martín et al. 2003). In some HzRGs, the quiescent component seems to be infalling towards the central regions of the host galaxy (e.g. Humphrey et al. 2007; Villar-Martín et al. 2007b; Humphrey et al. 2013a; Roche et al. 2014; Silva et al. 2018), which may be explained by a scenario whereby cold gas streams fall onto the dark matter halos along the cosmic web (e.g. Goerdt et al. 2010) or by an alternative scenario in which gaseous debris falls back into the host galaxy after a feedback blowout (e.g. Humphrey et al. 2013a). The perturbed component usually shows an irregular gas kinematics with FWHM > 1000 km s\(^{-1}\) (van Ojik et al. 1996; Villar-Martín et al. 2003; Humphrey et al. 2006; Silva et al. 2018). With clear spatial association with the radio structure in some HzRGs, the perturbed component provides evidence of gas that has been disturbed by the passage of the radio jets, and which may be outflowing (see Nesvadba et al. 2006, 2008a; Morais et al. 2017). As such, the Ly\(\alpha\) halos allow us to probe the evolution of massive galaxies during a phase of significant feedback, black hole growth and, in many cases, star formation. The study of the properties of these halos provides keys to understand how hosts of powerful radio galaxies form and evolve.

In addition, studies have shown that some HzRGs show spatially resolved H\(\text{I}\) absorption features in their Ly\(\alpha\) emission line profiles (e.g. Röttgering et al. 1995; van Ojik et al. 1997; Binette et al. 2000; Jarvis et al. 2003; Binette et al. 2006; Humphrey et al. 2008b, 2013b; Moyano et al. 2015; Swinbank et al. 2015; Gullberg et al. 2016; Silva et al. 2018), which are thought to be produced by a giant shell of H\(\text{I}\) gas enveloping the Ly\(\alpha\) emitting region, and which appears to be expanding or outflowing due to feedback activity (see Binette et al. 2006; Humphrey et al. 2008b; Swinbank et al. 2015; Silva et al. 2018). For example, in the case of the main extended absorber associated with MRC 0943-242 (z = 2.92), Silva et al. (2018) found a significant radial evolution in the H\(\text{I}\) absorber’s line of sight velocity which they argued is consistent with it being an expanding shell with a radius of at least several tens of kpc. With H\(\text{I}\) column densities in the range \(\sim 10^{14} - 10^{20}\) \(\text{cm}^{-2}\), observations with the slit placed along the radio axis have shown that strong absorbers (\(N(\text{H}\(\text{I}\)) > 10^{18}\) \(\text{cm}^{-2}\)) extend over the full spatial extent of the Ly\(\alpha\) emission, although the properties of the absorption does not always remain constant over the full spatial extent (van Ojik et al. 1997; Binette et al. 2006). Although the precise nature and origins of these large scale absorbing structures are not well understood, they are clearly relevant for understanding issues such as feedback, the dispersion of metals through the interstellar medium (hereafter ISM) of massive galaxies and into the surrounding IGM, as well as the escape of Ly\(\alpha\) and ionizing photons from HzRGs.

Previous studies of the Ly\(\alpha\) halos and H\(\text{I}\) absorbers associated with HzRGs have focused mainly on the relatively high surface brightness emission regions aligned with the radio jet axis, where the jet-gas interactions and the ionizing radiation of the AGN are expected to have their greatest impact (e.g. Rush et al. 1997; De Breuck et al. 2000a; Taniguchi et al. 2001; De Breuck et al. 2001; Villar-Martín et al. 2003; Nesvadba et al. 2006; Humphrey et al. 2006, 2008a, 2009; Nesvadba et al. 2017a,b). By studying the extended Ly\(\alpha\) emission regions that are located significantly away from the radio jet axis, it may be possible to obtain a more complete picture of the extended gaseous environment of HzRGs (e.g. Gullberg et al. 2016; Morais et al. 2017; Vermet et al. 2017; Silva et al. 2018), allowing us to investigate questions such as what produces the Ly\(\alpha\) emission when it is not illuminated by the AGN, and whether the impact of radio mode feedback is global or instead confined to the radio axis. Likewise, the 2-dimensional spatial distribution of the H\(\text{I}\) absorbers is also poorly known, with spatial information predominantly coming from long slit spectra where the slit was placed along the radio axis (e.g. van Ojik et al. 1997). A handful of H\(\text{I}\) absorbers have now been studied using IFU spectroscopy (e.g. Humphrey et al. 2008b; Swinbank et al. 2015; Silva et al. 2018), in each case showing that the absorber is also extended perpendicularly to the radio axis, consistent with the idea that the absorbing gas is part of a giant shell enveloping the Ly\(\alpha\) emitting region. However, similar observations of a larger number of HzRGs are needed to confirm that this is a general property of this class of absorbers.

This paper aims to characterize the properties of the extended Ly\(\alpha\) halos and the large-scale H\(\text{I}\) absorbing structures in the direction perpendicular to the radio axis of HzRGs, adding new information about the global properties of the extended ionized gas and extended absorbers associated with HzRGs. The paper is organized as follows. In \S 2, we describe the sample selection, observations and data reduction. In \S 3, we discuss our data analysis methods. In \S 4, we present the results of our study. In \S 5, we discuss the gas dynamics of the extended Ly\(\alpha\) halo and the nature of the extended H\(\text{I}\) absorbers. In \S 6, we give a brief summary concluding our results. Throughout this paper we assume \(\Omega_\Lambda = 0.713, \Omega_m = 0.287\) and \(H_0 = 69.3\) km s\(^{-1}\) Mpc\(^{-1}\) (Hinshaw et al. 2013).

2 SAMPLE SELECTION AND SOAR OBSERVATIONS

We selected 5 Ly\(\alpha\)-bright, steep spectrum HzRGs from the list of De Breuck et al. (2000b) within a redshift range of 2.16 < z < 2.76. This redshift range ensured that Ly\(\alpha\), C\(\text{IV}\) 1549 and He\(\text{II}\) 1640 fell within the wavelength coverage of the spectrograph. Our sample (see Table 1) is characterized by galaxies with relatively bright Ly\(\alpha\) emission (1.95\times10^{43} to 2.91\times10^{44} erg s\(^{-1}\), measured through a long slit aligned along the radio axis) of powerful radio sources (log\((P_{200M})\) ranging from 35.48 to 36.46 erg s\(^{-1}\) Hz\(^{-1}\)), and covers a large range in radio source diameter (< 2.5 to 196 kpc: De Breuck et al. 2000b and references therein).

The observations were performed on 2014 September and on 2015 April, using the Goodman High Throughput Spectrograph (GTHS; Clemens et al. 2004) on the Southern Astrophysical Research (SOAR) 4.1 m telescope during the commissioning of the instrument under the program...
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3 DATA ANALYSIS

3.1 Line profile fitting

We created a PYTHON routine to fit the emission and absorption line parameters, with Gaussian and Voigt profiles being used to model the emission and absorption lines, respectively. The routine minimizes the sum of the squares of the difference between the model and data using the LMFIT algorithm (Newville et al. 2014). The analysis was applied first to a 3′′ aperture centred on the HzRG, and then applied to the 2D spectrum at each position (pixel) along the slit, where the signal to noise ratio (S/N) of the emission line profile (based on the total flux) is $\geq 7$.

The Lyo profile was parametrized using a single emission (Gaussian) kinematic component for those HzRGs which show no $\text{H}_\text{i}$ absorption features (i.e. MRC 0030-219 and 4C-00.54), with a single absorption Voigt profile added for the three HzRGs which show clear $\text{H}_\text{i}$ absorption (i.e. MRC 0406-244, TN 0920-0712 and PKS 1138-262).

For the emission doublets, two Gaussians were used, with the two double components constrained to have equal FWHM, fixed wavelength separation and a fixed flux ratio (e.g., $R_{\text{F}} \times F_{\text{1216}} / F_{\text{1239}} = 2.0$ and $R_{\text{CIV}} \times F_{\text{1548}} / F_{\text{1550}} = 2.0$). No significant C IV absorption features were detected in our data, but the S/N and spectral resolution are insufficient to place scientifically useful upper limits on the column density of C IV.

As a non-resonant recombination line, He II is expected to provide a more reliable determination of the systemic velocity of a HzRG than Ly$\alpha$, NV or C IV, which can be susceptible to absorption and radiative transfer effects that can result in line broadening and velocity shifts. Following Villar-Martín et al. (2003), we use the nuclear He II to define the fiducial systemic velocity of each HzRG, with the exception of MRC 0030-219 where we instead use Ly$\alpha$ due to non-detection of He II.

The kinematic properties of the extended gas were determined using the fitting routine already mentioned, from

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1 The doublet ratio for both emission lines ranges from 2:1 in the optically thin case to 1:1 in the optically thick case. We adopted the optically thin case, but using the optically thick case did not result in significant changes to the recovered kinematic properties.
where we obtained the FWHM and the velocity offset for the emission and absorption lines, at each spatial position along the slit.

In Table 2, we show the emission lines detected for each radio galaxy along with the parameters from the best fits. In addition, in Table 3 we show the best fit parameters for the Lyα absorption. In Figures 1 to 5, we show (i) the 2-D spectra of the Lyα spectral region, which were smoothed using a Gaussian with kernel = 3.0 pixels (or 0.9″); (ii) the spatial variation of the flux of the Lyα emission line; (iii) Lyα spatial profile compared with the seeing; (iv) the 1-D spectra of the Lyα profile; (v) the spatial variation of FWHM corrected for the instrumental broadening; (vi) the spatial variation of velocity offset relative to our fiducial systemic velocity; (vii) the FWHM as a function of the velocity offset of Lyα; (viii) the spatial variation of the flux of the HeII emission line (the radio galaxy 4C-00.54 was the only one that provided a sufficient S/N at each spatial position along the slit); (ix) the Lyα/HeII flux ratio for the radio galaxy 4C-00.54; (x) the spatial variation of the velocity offset for the extended H I absorber when detected and (xi) the spatial profile of the H I column density compared with the seeing.

3.2 Spatial extent constraints using the seeing

In order to investigate whether the Lyα halos detected in our sample are spatially extended along the slit, we have compared the Lyα spatial profile with the seeing profile reconstructed from stars in images taken immediately before or after the observation of the science target (see Humphrey et al. 2015 and Villar-Martin et al. 2016 for more details of this methodology). The flux of a non-saturated star was extracted by simulating the slit width used for the spectroscopic observation of the science targets (see Table 1). The sky background was then removed from the stellar spatial profile.

In Figures 1c to 5c, we show the spatial profile of the Lyα emission along with the spatial profile of the seeing. We measured the FWHM (FWHM\textsubscript{source} ± ΔFWHM\textsubscript{source}) of the spatial profile of the Lyα line by fitting a single Gaussian. If the seeing has FWHM′ ± ΔFWHM′, we assume that the source is spatially unresolved when

\[
\text{FWHM}_{\text{source}} \leq \text{FWHM}′ + \Delta \text{FWHM}′ + \Delta \text{FWHM}_{\text{source}}.
\]

In this case, the right hand side of this inequality will be used as an upper limit for the intrinsic FWHM. For a resolved source, we estimate the intrinsic FWHM by subtracting the seeing FWHM from the observed FWHM in quadrature.
Figure 1. Radio galaxy MRC 0030–219: (a) 2-D spectrum of the Lyα spectral region, (b) Flux of the Lyα emission line, (c) Lyα spatial profile (blue circle with dashed lines) compared with the seeing (green dot dashed lines) and (d) 1-D spectrum of the Lyα spectral region extracted from the SOAR long-slit. The Lyα emission-line was extracted by summing over a 3″ region of the slit length. Spatial variations of (e) FWHM, (f) Velocity and (g) Variation of FWHM as a function of the velocity offset of Lyα with ρ and p-value representing the Spearman’s rank correlation coefficient and t-distribution, respectively.

4 RESULTS FOR INDIVIDUAL OBJECTS

4.1 MRC 0030–219

4.1.1 Previous results

In the z = 2.17 radio galaxy MRC 0030–219 the radio source consists of a single compact component with maximum angular size < 0.3″ (or < 2.5 kpc in the adopted cosmology) and has a steep radio spectrum (α ≈ -1.0; Carilli et al. 1997), as revealed by VLA observations. Optical spectroscopy observations from the Cerro Tololo 4 m Telescope revealed strong UV emission lines such as Lyα, CIV and HeII (McCarthy et al. 1990a). The Lyα emission line has a rest equivalent width \( W_{\text{rest}}^{\text{Ly}} = 174 \) Å and luminosity \( L(\text{Ly}) = 10^{43.66} \) erg s\(^{-1}\) (McCarthy et al. 1990a).
4.2.1 Previous results

Figure 1a reveals the spatially compact Ly$\alpha$ emission of MRC 0030–219. Figure 1b shows the spatial variation of the Ly$\alpha$ flux, with this emission being detected further to the NW direction. In Figure 1d, we also show the integrated 1-D spectrum of the Ly$\alpha$ profile. Figures 1e and 1f show the spatial variation of the FWHM and velocity offset of the Ly$\alpha$ emission line. The line width varies in the range FWHM = 800 – 2500 km s$^{-1}$. Within a radius of $\leq 1''$ of the nucleus, Ly$\alpha$ shows FWHM $< 1400$ km s$^{-1}$, increasing to 1600 – 2500 km s$^{-1}$ at radii of $\geq 1''$. The spatially integrated Ly$\alpha$ emission line appears blueshifted from the systemic velocity with velocity offset $-43 \pm 25$ km s$^{-1}$. In order to investigate the possible correlations between the FWHM and the velocity offset (see Fig. 2g), we use the Spearman correlation ($\rho$) and the t-distribution (p-value), which indicates a positive relationship between the FWHM and velocity curve of the Ly$\alpha$ emission with $\rho = 0.78$ and p-value $= 7.6 \times 10^{-3}$. The kinematic properties will be discussed in §5.1.

The Ly$\alpha$ spatial profile with FWHM = 1.62 ± 0.07″ is dominated by a central compact source (see Fig. 1c), which appears barely resolved in the central regions compared with the seeing (1.60 ± 0.02″). Correcting for seeing broadening in quadrature, we infer FWHM$_{obs}$ = 0.54 ± 0.09″ or 4.6 ± 0.7 kpc. In addition, the variation seen in the kinematic properties of the radio galaxy (Figures 1e and 1f), in the outer parts of the Ly$\alpha$ profile at $\geq 1''$ from the centroid also suggests that it may be barely resolved. None of the other UV emission lines are found to be extended in this spectrum.

4.2 MRC 0406–244

4.2.1 Previous results

This object consists of a massive host galaxy (M$_{*} \sim 10^{11}$ M$_{\odot}$; Seymour et al. 2007; Hatch et al. 2013) with a high star-formation rate (790 ± 75 M$_{\odot}$ yr$^{-1}$; Hatch et al. 2013). Hubble Space Telescope (HST) images show spatially resolved continuum emission, with several connecting bright clumps in a figure of eight morphology elongated along the radio source of the radio galaxy (e.g. Rush et al. 1997; Pentericci et al. 2001; Hatch et al. 2013). Rush et al. (1997) concluded that the complex morphology of the spatially resolved continuum in MRC 0406–244 could be a consequence of a recent merger. On the other hand, Taniguchi et al. (2001) and Humphrey et al. (2000) argued that this morphology might be a consequence of AGN-driven winds (AGN feedback) or a superwind from a starburst event which swept up super-bubbles from the ambient ISM. Hatch et al. (2013), however argued that the continuum emission is most likely to be due to young stars or dust-scattered light from the AGN. Using VLT/SINFONI imaging spectroscopy of the rest-frame optical emission lines, Nesvadba et al. (2008b, 2017a,b) find extended emission line regions with large velocity offset in the range -600 to +600 km s$^{-1}$ and line widths in the range 500 to 1500 km s$^{-1}$ consistent with very turbulent outflowing gas. They conclude that the radio jets are the main driver of the gas kinematics. Taniguchi et al. (2001) and Humphrey et al. (2000) studied the emission line ratios of the extended gas and concluded that photoionization by the AGN is the most probable excitation mechanism of this gas. A Ly$\alpha$ image taken using the 2.5 m du Pont Telescope reveals line emission with an extent of 3″× 5″ (or 24.9 kpc × 41.5 kpc at the adopted cosmology) in which the long axis is about 130° east of north aligned with the radio source (Rush et al. 1997). In addition, using data from the 3.58 m ESO New Technology Telescope (NTT), Pentericci et al. (2001) identified a strong, extended H1 absorption feature superimposed on the bright Ly$\alpha$ emission line.

4.2.2 Results from SOAR

In our SOAR data, three emission lines were detected in the spectrum of MRC 0406–244 (see Table 2). Strong Ly$\alpha$ emission is detected in the direction perpendicular to the radio axis of the galaxy (see Fig. 2a). The Ly$\alpha$ emission shows an asymmetric spatial distribution, which is detected further in the SW direction (see Fig. 2b). C IV and H II emission lines are also detected, however they are spatially compact and also detected more in the SW direction. In Figure 2d, we show the integrated 1-D spectrum of the Ly$\alpha$ profile. Figure 2e shows the spatial variations of the FWHM of the Ly$\alpha$ nebula (1000 – 2300 km s$^{-1}$). The line width is relatively high across the full extent of the emission line, decreasing to 1000 km s$^{-1}$ in the outermost regions. The Ly$\alpha$ velocity shift relative to fiducial velocity shows the most blueshifted gas (~ 200 km s$^{-1}$) around the nuclear region of the nebula (within 1″). Towards to the outermost regions of the nebula we find velocity offset varying from -135 km s$^{-1}$ to -8 km s$^{-1}$ (see Fig. 2f). Investigating the possible correlations between the FWHM and the velocity offset (see Fig. 2g), we find a weak negative relationship with $\rho = -0.32$ and p-value = 0.23.

The Ly$\alpha$ spatial profile with FWHM = 2.86 ± 0.08″ is clearly spatially resolved compared with the seeing FWHM = 1.21 ± 0.01 (see Fig. 2c), indicative of a extended emission line. Correcting for seeing broadening, the intrinsic FWHM is 2.59 ± 0.09″ (or 22 ± 1 kpc). None of the other UV emission lines are found to be extended in this spectrum.

We detected a Ly$\alpha$ absorption feature in the spectrum of MRC 0406–244 (see Fig. 2a). The best fit to the Ly$\alpha$ profile is shown in Fig. 2d. Table 3 lists the parameters of the best fitting model together with the diameter of the absorber, and the maximum detected radius. The absorber has column density log N(H I/cm$^{-2}$) = 14.81 ± 0.03 with Doppler parameter $b = 205 \pm 11$ km s$^{-1}$. This structure is detected across the full spatial extent of the Ly$\alpha$ emission where S/N in the line is sufficient to detect an absorber with that column density. In Figure 2b, we show the line of sight velocity of the H1 absorber measured from the SOAR spectrum across its detected spatial extent. The absorbing gas appears blueshifted from the systemic velocity with line of sight velocity -184 ± 8 km s$^{-1}$. We find that the absorber is detected extending over across 4.2″ (or 35 kpc) in the direction perpendicular to the radio axis of the galaxy. In addition, the Ly$\alpha$ absorption feature detected in the spectrum of MRC 0406–244 shows a constant N(H I) along the slit, which suggests to be spatially extended when comparing the spatial profile of the H1 column density with the seeing profile (see Fig. 2i). If the Ly$\alpha$ emission is extended and the absorber is not extended, we should expect a radial decline in the strength of the absorber (e.g. N(H I)).
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Assuming that this structure is a spherically symmetric shell, its H\textsc{i} mass is given by

\[ M_{\text{H}\textsc{i}} = 4\pi R^2 N(\text{H}\textsc{i}) m_{\text{H}} \]

which simplifies to

\[ M_{\text{H}\textsc{i}} \gtrsim 5.3 \times 10^3 (R/23 \text{ kpc})^2 (N(\text{H}\textsc{i})/10^{14} \text{ cm}^{-2}) M_\odot. \]

where \( R \) is the radius of the absorption system in kpc, and \( N(\text{H}\textsc{i}) \) is the \( \text{H}\textsc{i} \) column density in cm\(^{-2}\), and \( m_{\text{H}} \) is the mass of a hydrogen atom. We estimate the mass of the absorbing shell of gas to be \( \log (M_{\text{H}\textsc{i}}/M_\odot) \gtrsim 4.5 \). If the absorbing gas is partly ionized, then its total mass (i.e. \( M(\text{H}\textsc{i}) + M(\text{H}\textsc{ii}) \)) could be substantially higher.

Figure 2. Radio galaxy MRC 0406-244: (a) 2-D spectrum of the Ly\(\alpha \) spectral region, (b) Spatial variation of the flux of Ly\(\alpha \) line, (c) Ly\(\alpha \) spatial profile (blue circle with dashed lines) compared with the seeing (green dot dashed lines) and (d) 1-D spectrum of the Ly\(\alpha \) line. (e) Ly\(\alpha \) FWHM, (f) Ly\(\alpha \) Velocity, (g) Ly\(\alpha \) FWHM vs. Velocity, (h) Ly\(\alpha \) Velocity Abs., (i) Ly\(\alpha \) N(\(\text{H}\textsc{i}\)) vs. Seeing.

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4.3 4C–00.54

4.3.1 Previous results

The $z = 2.36$ radio galaxy 4C–00.54 (also known as USS 1410–001) consists of a very optically elongated host galaxy (e.g. Pentericci et al. 1999, 2001) for the UV/optical morphology. With $M_\star \sim 10^{11.4} M_\odot$ (e.g. Seymour et al. 2007) and a star formation rate $\sim 460 - 270$ $M_\odot$ yr$^{-1}$ inferred from 7.7 $\mu$m polycyclic aromatic hydrocarbon luminosity (e.g. Rawlings et al. 2013). The radio source has a double lobe morphology with total extent of 24$''$ (or 196 kpc at the adopted cosmology) and it has a misalignment of $\sim 45^\circ$ relative to the UV-optical continuum emission in the central few tens of kpc of the galaxy (e.g. Pentericci et al. 1999, 2001). Spectroscopic studies with the ESO-NTT have revealed extended Ly$\alpha$ emission ($\sim 80$ kpc) without any sign of H$\text{I}$ absorption (e.g. van Ojik et al. 1997). Long slit spectropolarimetry using Keck II has shown that the UV continuum emission along the radio axis is significantly polarized (P$\lambda = 11.7 \pm 2.7$) with contribution from the scattered AGN continuum (47 – 88 $%$), young stellar population (41 – 0 $%$) and nebular continuum (12 $%$) (e.g. Vernet et al. 2001). Using the same data, Villar-Martín et al. (2003) and Humphrey et al. (2006) concluded that the extended gas along the radio axis is part of a giant quiescent halo (FWHM $\leq 472 - 800$ km s$^{-1}$) without any evidence of jet-gas interactions. Using VLT/SINFONI imaging spectroscopy of the rest-frame optical emission lines of HzRGs, Nesvadba et al. (2017a,b) find line emission extending over an area of 2"×5.6" (or 14 kpc × 41 kpc) with the major axis going from south to north. They find line widths in the range FWHM = 400 – 1300 km s$^{-1}$ in which a small region to the north-east of the nucleus. In addition, with velocity offsets in the range -400 – +400 km s$^{-1}$, they conclude that the radio jets are the main driver of the turbulent outflowing gas. Also using rest-frame optical emission lines obtained with the VLT/ISAAC, Humphrey et al. (2008a) concluded that AGN photoionization is the dominant ionization mechanism operating in the extended emission line region possibly with a fractional contribution from shocks.

4.3.2 Results from SOAR

The Ly$\alpha$ emission detected in the direction perpendicular to the UV-optical emission of the galaxy (see Fig. 3a) shows an asymmetric spatial distribution, which is slightly more extended in the S direction (see also Fig. 3b). In addition to Ly$\alpha$ (see the I-D spectrum in Fig. 3f), we could also detect N$\text{v}$, C$\text{iv}$ and He$\text{ii}$ emission lines (see Table 2). In Figures 3g and 3h, we show the spatial variations of the FWHM and velocity of the Ly$\alpha$ emission line, respectively.  We find that the extended emission line halo shows a central region of kinematically quiescent gas with FWHM $< 1000$ km s$^{-1}$. From the nucleus towards the outermost regions we find a gradual increase in FWHM, with values reaching up to 1600 km s$^{-1}$. The velocity offset of the extended gas varies from -578 km s$^{-1}$ to 216 km s$^{-1}$. In Figure 3i, we show the correlation between the FWHM and the velocity offset of Ly$\alpha$. The diagram suggests a strong negative relationship between the parameters with $\rho = -0.60$ and $p$-value = 7.4 × 10$^{-7}$. We note that a similar anticorrelation between velocity shift and FWHM is also present in Fig. 4 of Villar-Martín et al. (2003), albeit along a different slit PA to ours.

With the slit position angle set to 90°, which is perpendicular to the UV-optical emission in the HST images, we note that the slit is at an angle of 45° to the radio axis as defined by the line running through the 2 hotspots and the radio core (see Pentericci et al. 1999, 2001). However, as Pentericci et al. (1999) suggest, the AGN axis (or the radio jet axis) might be precessing, in which case the radio axis near the nucleus might be different to what the radio axis was when the material in the hotspots was ejected from the nucleus. It does seem plausible that due to jet precession, the slit position angle used might intersect gas that has been disturbed by the radio jets. However, it seems odd since that at the nucleus and along the UV-optical axis the kinematics are more quiescent. We should expect the jets going through and perturbing gas in the nuclear region as well.

The Ly$\alpha$ spatial profile of the radio galaxy 4C–00.54 with FWHM = 2.22 ± 0.06'' shows that the emission line is spatially extended compared with the seeing FWHM = 1.08 ± 0.02'' (see Fig. 3c). In addition, the spatial profile shows an excess above the seeing disk especially obvious towards the South. Correcting for seeing broadening in quadrature, we infer the intrinsic FWHM as 1.94 ± 0.07'' or 16 ± 1 kpc. None of the other UV emission lines are found to be extended in this spectrum.

In Figure 3e, we show the spatial variation of the Ly$\alpha$/He$\text{ii}$ flux ratio along the slit. We find a significant variation in Ly$\alpha$/He$\text{ii}$, with a radial increase from 5.0 ± 0.3 near the spatial zero position, up to 16.3 ± 1.9 ($r = -0.9^\circ$) and 17.2 ± 1.3 ($r = +1.5^\circ$). The spatial variation of the Ly$\alpha$/He$\text{ii}$ shows flux ratios that are consistent with the standard photoionization models, which predict Ly$\alpha$/He$\text{ii}$ in the range 15 – 20 for HzRGs (e.g. Villar-Martín et al. 2007a). The possible reasons for such variation will be discussed in §5.2.

4.4 TN J0920–0712

4.4.1 Previous results

VLA observations of the HzRG TN J0920–0712 at $z = 2.76$ revealed a radio source consisting of a single component with a maximum angular size of 1.4'' (11 kpc in the adopted cosmology), and spectral index $\alpha = -1.51$ (e.g. De Breuck et al. 2000a, 2001). Using the Faint Object Spectrograph and Camera (EFOSC1) on the ESO 3.6 m telescope at La Silla, De Breuck et al. (2001) found extended Ly$\alpha$ emission with FWHM = 2050 ± 150 km s$^{-1}$ and a large equivalent width (W$^\text{rest}_\lambda$ = 350 ± 60 A). Additionally, they also detected Si$\text{iv}$ + O$\text{iv}$, C$\text{iv}$ and He$\text{ii}$ emission lines. They also reported the detection of an extended H$\text{I}$ absorber on the blue side of the Ly$\alpha$ line although it has not been explored. De Breuck et al. (2000b) compared the UV line ratios of this HzRG, and found that photoionization by the central AGN offers a plausible explanation for the excitation of the line emitting gas, with potential for a significant additional contribution from shock ionization.
Figure 3. Radio galaxy 4C–00.54: (a) 2-D spectrum of the Lyα spectral region, (b) Spatial variation of the flux of Lyα line, (c) Lyα spatial profile (blue circle with dashed lines) compared with the seeing (green dot dashed lines), (d) Spatial variation of the flux of Heii line, (e) the Lyα/Heii line ratio and (f) 1-D spectrum of the Lyα spectral region extracted from the SOAR long-slit. The Lyα emission-line was extracted by summing over a 3′ region of the slit length. Spatial variations of (g) FWHM, (h) Velocity, (i) Variation of FWHM as a function of the velocity offset of Lyα with ρ and p-value representing the Spearman’s rank correlation coefficient and t-distribution, respectively. The black arrows seen in the Lyα/Heii line ratio diagram represent the 3σ lower limit of the line ratios.

4.4.2 Results from SOAR

The Lyα nebula shows an elongated and symmetric spatial distribution (see the 2-D spectrum of the Lyα spectral region in Fig. 4a, and also Fig. 4b). In Figure 4d, we show the integrated 1-D spectrum of the Lyα extracted from the SOAR long-slit, with the Gaussian emission component plus absorption model overlaid. Together with Lyα, we also detected the emission lines such as Ovi + CII, NV, CIV and Heii (see Table 2). The spatial variation of the FWHM shows a smooth transition from SW to the NE during which the line width varies from 1220 km s\(^{-1}\) to 2400 km s\(^{-1}\) across the entire nebula (see Fig. 4e). The velocity shift varies from -242 km s\(^{-1}\) to 208 km s\(^{-1}\) (see Fig. 4f). We find a correlation between the FWHM and the velocity offset of Lyα, such that regions with higher FWHM also tend to have a
higher blueshift (see Fig. 4g). The result indicates that there is a relationship between the parameters with $\rho = -0.70$ and p-value $= 5.4 \times 10^{-4}$.

The Ly$\alpha$ spatial profile with FWHM $= 1.78 \pm 0.03''$ shows that the emission line is spatially extended compared with the seeing FWHM $= 1.08 \pm 0.02''$ (see Fig. 4c). In addition, the spatial profile shows excess of emission above the seeing wings at both sides of the central source showing that the Ly$\alpha$ halo is extended. We infer the intrinsic FWHM to be $1.42 \pm 0.04''$ (or $11.4 \pm 0.3$ kpc). None of the other UV emission lines are found to be extended in this spectrum.

Like De Breuck et al. (2001), we also detect a spatially
extended Lyα absorption feature on the blue side of the Lyα emission in the spectrum of TN J0920–0712 (see Fig. 4a).

The best fit to the Lyα is shown in Fig. 4d. Table 3 lists the parameters of the best fitting model together with the diameter of the absorber, and the maximum detected radius. We obtain a column density log N(H\textsc{i})/cm\textsuperscript{−2} = 14.23 ± 0.03 with Doppler parameter $b = 185 ± 10$ km s\textsuperscript{−1}, and velocity offset of the absorber -232 ± 6 km s\textsuperscript{−1}. In Figure 4h, we show the line of sight velocity of the H\textsc{i} absorber measured from the SOAR spectrum across its detected spatial extent, which shows that the absorbing gas appears blueshifted from the systemic velocity. This absorber is detected across the full spatial extent of the Lyα emission where the S/N of the line is sufficient to detect an absorber with that column density, i.e., 3.3′′ or 27 kpc. This absorption is clearly spatially extended compared to the the seeing profile (see Fig. 4i).

Assuming that the absorbing gas is a spherically symmetric shell, using the expression 3 we estimate log (M\textsc{Hi}/M\odot) ≥ 3.7.

4.5 PKS 1138–262

4.5.1 Previous results

VLA observations of the z = 2.16 radio galaxy PKS 1138–262 (Spiderweb galaxy) shows that the radio source consists of multiple hotspots in the eastern lobe, which shows a double bend towards south (e.g. Carilli et al. 1997; Pentericci et al. 1997). The radio source has a maximum angular size of 11.4′′ (97 kpc in the adopted cosmology) and spectral index $α = -1.3$ (e.g. Carilli et al. 1997; Pentericci et al. 1997). The rest-frame near-infrared (near-IR) light and the K-band luminosity indicate that the host galaxy is very massive (e.g. Carilli et al. 1997; Pentericci et al. 1997). The spatial profile of the radio galaxy PKS 1138–262 (FWHM = 4.81 ± 0.31′′) is spatially resolved compared with the seeing disk FWHM = 1.76 ± 0.02. The emission line shows an excess above the seeing disk at ≤ 5.4′′, which is particularly obvious towards the East (see Fig. 4c), confirming that Lyα is dominated by extended emission. The intrinsic FWHM for Lyα will be 4.48 ± 0.33′′ or 38 ± 3 kpc. None of the other UV emission lines are found to be extended in this spectrum.

Unlike Pentericci et al. (1997), only a single absorption feature is detected in the spectrum of PKS 1138–262 (FWHM = 1700 – 3890 km s\textsuperscript{−1}) to Lyα nebula emission. The extended emission line shows line widths in the range FWHM = 1700 – 3890 km s\textsuperscript{−1} while the velocity offset is ranging from -670 km s\textsuperscript{−1} to 292 km s\textsuperscript{−1}. As in the previous objects, we find a correlation between the FWHM and the velocity offset of Lyα, such that regions with higher FWHM also tend to have a larger blueshift (see Fig. 5g).

The result indicates that there is a negative relationship between the parameters with $ρ = 0.60$ and p-value = 1.9 × 10\textsuperscript{−2}.

The spatial profile of the radio galaxy PKS 1138–262 (FWHM = 1700 – 3890 km s\textsuperscript{−1}) is extended from the slit approximately along the radio axis, Pentericci et al. (1997) report the detection of several H\textsc{i} absorbers at a similar redshift to the HzRG. They find column densities of the order log N(H\textsc{i}/cm\textsuperscript{−2}) = 15 – 16 and Doppler parameters between 40 and 100 km s\textsuperscript{−1}. In addition, studying optical images of the extended Lyα halo obtained with FORS1 at the 8.2m VLT Antu, Kurk (2003) identified the presence of H\textsc{i} absorption associated with the Lyα emission line. Simulating 3 slits placed in different regions of the Lyα halo, Kurk could identify up to two absorption troughs in the Lyα line with column density in the range log N(H\textsc{i}/cm\textsuperscript{−2}) = 14.2 – 14.8 and Doppler parameters between 140 and 430 km s\textsuperscript{−1}.

4.5.2 Results from SOAR

In the direction perpendicular to the radio axis, we detect the Lyα emission showing an asymmetric spatial distribution, being more extended towards the E (see the 2-D spectrum of the Lyα spectral region in Fig. 5a, see also the spatial variation of the Lyα flux in Fig. 5b). In Figure 5d, we show the integrated 1-D spectrum of the Lyα profile. In addition to Lyα, we also detected the C\textsc{iv} and He\textsc{ii} emission lines (see Table 2). In Figures 5e and 5f, we show the spatial variations of FWHM and velocity of the extended Lyα nebula emission. The extended emission line shows line widths in the range FWHM = 1700 – 3890 km s\textsuperscript{−1} while the velocity offset is ranging from -670 km s\textsuperscript{−1} to 292 km s\textsuperscript{−1}. As in the previous objects, we find a correlation between the FWHM and the velocity offset of Lyα, such that regions with higher FWHM also tend to have a larger blueshift (see Fig. 5g).

The result indicates that there is a negative relationship between the parameters with $ρ = 0.60$ and p-value = 1.9 × 10\textsuperscript{−2}.

Using VLT/SPITFI IFU (SPectrometer for Infrared FaintField Imaging) of the rest-frame optical emission line, Nesvadba et al. (2006) conclude that the kinematic properties and energy arguments favor the AGN as the plausible mechanism that efficiently power the outflowing gas. Furthermore, using VLT/SINFONI imaging spectroscopy of the rest-frame optical emission line of the warm ionized gas, Nesvadba et al. (2017a) find that the kinetic energy and momentum injection rates from the radio jets seem to be the most efficient mechanism powering the outflowing gas.

Investigating the Lyα emission line using medium resolution spectroscopy (instrumental FWHM = 2.8 A) with
Figure 5. Radio galaxy PKS 1138–262: (a) 2-D spectrum of the Lyα spectral region, (b) Spatial variation of the flux of the Lyα line, (c) Lyα spatial profile (blue circle with dashed lines) compared with the seeing (green dot dashed lines) and (d) 1-D spectrum of the Lyα spectral region extracted from the SOAR long-slit. The Lyα emission-line was extracted by summing over a 3″ region of the slit length. Spatial variations of (e) FWHM, (f) Velocity, (g) Variation of FWHM as a function of the velocity offset of Lyα with ρ and p-value representing the Spearman’s rank correlation coefficient and t-distribution, respectively, (h) Velocity of the Hα absorber and (i) Spatial profile of the H α column density (blue circle points) compared the seeing (red dot dashed lines), both on a logarithmic scale. In addition, the seeing profile has been normalised and shifted in order to allow the comparison.

5 DISCUSSION

5.1 Gas Dynamics
Several scenarios have been suggested in order to explain the observed kinematic properties of the giant nebulae associated with HzRGs, including outflows resulting from jet-gas interactions, AGN or starburst driven super-winds (e.g. Villar-Martín et al. 1999, 2000; Jarvis et al. 2003; Humphrey et al. 2006, 2008b; Nesvadba et al. 2006, 2008b; Swinbank et al. 2015; Cai et al. 2017; Nesvadba et al. 2017a), gas infalling/inflow (e.g. Humphrey et al. 2007; Villar-Martín et al. 2007b; Humphrey et al. 2013a; Roche et al. 2014; Silva et al. 2015b; Humphrey et al. 2007b; Villar-Martín et al. 2007b; Humphrey et al. 2013a; Roche et al. 2014; Silva et al. 2015b).
the other hand, if the jets are not responsible for the high FWHM we suggest this might be a result of scattering of Lyα photons that were originally produced along the radio axis or within the ionization cones, by neutral gas in regions that are predominantly neutral due to not being illuminated by the AGN. In this scenario, the emergent velocity profile of the scattered Lyα would have a velocity profile that has been artificially broadened as a result of the kinematic diversity of the Lo emitting regions in the radio galaxy’s extended gas halo. Another possibility might be that Lyα emitted by highly turbulent gas associated with jet-gas interactions is being preferentially scattered by neutral hydrogen within the extended regions in our slit. However, detailed numerical modeling of Lyα radiative transfer within the gas halo would be needed to explore this possible effect in more detail. The radio galaxy MRC 0030-219 has a single and compact radio source, which is much less extended than the Lyα emission line gas detected. Given the sizes involved between the radio source and the emission line gas, we suggest that jets seem unlikely to be responsible for such turbulence. However, we are unable to definitely say what kind of motion is dominating the gas (i.e. infall, outflow or rotation) or if the observed properties observed are a consequence of the resonant scattering within the nebula.

Lyα is particularly sensitive to radiative transfer effects. Given this nature, the best way to avoid any possible uncertainty on this issue would be to compare the kinematic properties of Lyα with lines that are not affected by radiative transfer effects, such as HeII λ 1640 or optical forbidden lines such as [OIII] λλ 4959,5007. Although we can not neglect the contribution from radiative transfer effects, without other emission lines we are not able to say whether the high FWHM of Lyα is dominated by these effects or is instead due to extreme motions in the extended gas.

5.2 The radial gradient of Lyα/HeII in 4C–00.54

Previous investigations using long-slit spectroscopy along the radio axis or perpendicular to the radio axis of other HzRGs have shown that line ratios involving Lyα emission line can vary significantly (e.g. Humphrey et al. 2008a; Morais et al. 2017).

We find a significant variation in Lyα/HeII flux ratio (see Fig. 3e). The ratio shows a radial increase from 5.0 ± 0.3 near the spatial axis origin, up to 16.3 ± 1.9 (r = -0.9°) and 17.2 ± 1.3 (r = +1.5°). Such a variation suggests

Table 3. Lyα absorption features best fit parameters. Column (1) gives the object name. Column (2) gives the redshift for the Lyα emission Gaussian. Column (3) gives the redshift for the Lyα absorption. Column (4) gives the column density (N(HI)). Column (5) gives the Doppler width b. Column (6) gives the velocity shift of the absorber with respect to HeII emission line. Column (7) gives the maximum diameter detected of the absorbers. Column (8) gives the maximum radius of the absorbers. We note that the radius over which we detect the absorber only gives us a lower limit to the radius of the shell because the absorption feature can not be detected where the background Lyα emission is weak or absent. In addition, without information on the ionization fraction of hydrogen, the HI column density only gives a lower limit on the total hydrogen column density. Moreover, because of the degeneracy discussed by Silva et al. (2018) we also note that our column density estimate is likely a lower limit of the true column. Thus, our mass estimates are lower limits.
evidence for some process in which the Lyα is depressed in the centre with this effect becoming less important when moving far from the centre. As it moves out from the centre, we note that the flux ratio reaches values that are typically seen in other HzRGs (\(\text{Ly} \alpha/\text{He} \text{II} = 15 – 20; \) Villar-Martín et al. 2007a).

Using only the Lyα/He\text{II} flux ratio, it is not easy to discriminate what kind of effects might be responsible for the large variation observed. However, we suggest that it may be a consequence of effects such as (i) absorption of Lyα, presumably by H\text{I} or interstellar dust (see Röttgering et al. 1997; van Ojik et al. 1997), (ii) resonant scattering of Lyα photons (see Dijkstra & Loeb 2008; Hayes et al. 2011; Steidel et al. 2011) and (iii) enhanced emission of Lyα, which can be produced by a low ionization parameter, a relatively soft ionizing spectral energy distribution (SED) or a low gas metallicity (see Villar-Martín et al. 2007a; Humphrey et al. 2018).

Interestingly, higher FWHM are one of the possible signatures of Lyα resonance scattering. If this is true, then the observed Lyα might be a result of resonant scattering strongly affecting the regions across the nebula.

5.3 The nature of the H\text{I} Absorbers

A new perspective about the gaseous environment of HzRGs was opened up by Röttgering et al. (1995) and van Ojik et al. (1997) with the discovery of associated, spatially extended H\text{I} absorbers. With the slit positioned along the radio axis, a number of investigations have shown that the H\text{I} absorbers are typically detected with column densities between log N(H\text{I}/cm\text{−2}) = 13 – 19 and Doppler width \(b = 20 – 874\) km s\text{−1} (e.g. Röttgering et al. 1995; van Ojik et al. 1997; Binette et al. 2000; Jarvis et al. 2003; Wilman et al. 2004). In addition, previous work has shown that the absorbers are extended over tens or even a few hundred kpc, leading to H\text{I} mass estimates of up to \(\log (M_{\text{H}\text{I}}/M_{\odot}) \sim 9\). In addition, it has been argued that the extended absorbers are (i) in outflow; (ii) partly ionized based on detection of C\text{IV} and other lines in a few cases; (iii) probably located outside the Lyα halo based on covering factor \(\sim 1\) and the fact that the absorbers appear to completely cover the (detected) extended Lyα emission (e.g. Binette et al. 2000). Based on these properties, it has been argued that the absorbing gas is part of an expanding shell that surrounds the HzRG and its Lyα halo, produced by feedback activity (e.g. Binette et al. 2000).

However, single-slit observations did not provide information about the two-dimensional distribution of the absorbing gas, leaving open the possibility that the absorbers do not cover the entire Lyα halo, and are only present along regions that are expected to have little influence from the radiation field of the active nucleus or the radio jets, to examine the global properties of these two gaseous components.

We find spatially extended gas with high line widths (FWHM = 1000 – 2500 km s\text{−1}), suggestive of turbulent motion. In addition, we find a correlation between the FWHM and the velocity offset of Lyα, such that regions with higher FWHM are more blueshifted. Based on this result, we conclude that an outflowing gas or an infalling gas are the two scenarios consistent with the kinematic properties of the radio galaxies, depending on the level of resonant scattering of the Lyα photons within the nebula but also on the gas geometry, H\text{I} distribution and column density.

Studying the H\text{I} absorbers of 3 HzRGs with the long slit placed at a large angle to the radio axis (\(>45°\)), we have detected the H\text{I} absorber across the full spatial extent of the Lyα emission. In all three cases, the absorber is blueshifted relative to the systemic velocity across its full detected extent. Our new results show that the extended H\text{I} absorbers associated with HzRGs, when present, cover the entire Lyα halo, which is consistent with previous IFU results and also consistent with the absorbing gas being part of a giant, expanding shell of gas enveloping the HzRG and its Lyα halo.

Finally, we comment that our work shows the potential capability of the Goodman Spectrograph on the SOAR 4.1 m telescope to observe objects at high-redshift \((z > 2)\).

6 CONCLUSIONS

Making use of the Goodman long-slit on the SOAR telescope, we have studied the properties of the extended Lyα halo and the large-scale H\text{I} absorbers structures of 5 HzRGs, in regions that are expected to have little influence from the radiation field of the active nucleus or the radio jets, to examine the global properties of these two gaseous components.

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