



# Lighting Up the Circumgalactic Medium: Strong, Jet-aligned $H\alpha$ Emission around Radio Galaxies

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## Abstract

A primary question is how active galactic nuclei (AGN) feedback modifies the circumgalactic medium (CGM). We present a search for faint  $H\alpha$  emission from the cool ionized CGM ( $T \sim 10^4$  K) around radio galaxies by stacking background-quasar spectra from Dark Energy Spectroscopic Instrument (DESI) sight lines. We take into account the projected distance and position angle of each quasar sight line relative to the radio-jet axis, and test whether jet–CGM coupling is anisotropic. We detect a strong  $H\alpha$  excess at  $>5\sigma$  along the collimated radio-jet axis ( $\theta < 20^\circ$ ) with a mean integrated flux of  $1.19 \times 10^{-17}$  erg cm $^{-2}$  s $^{-1}$ . In contrast, the azimuthally averaged stack over all 324 sight-line angles yields no detection ( $<2\sigma$ ), indicating that this excess emission is very localized along the radio jet. We also find that the jet-aligned  $H\alpha$  signal is radially structured, where the strongest emission occurs near the host galaxy just outside the optical half-light radius, and rising again near the projected radio-lobe region. The jet-aligned stacks reveal  $H\alpha$  signal that is roughly 100 times brighter than normal halos. In the same sight lines however, Mg II absorption shows no difference in incidence between jet-aligned and off-axis directions, with broadly similar equivalent widths, column densities, and line widths. This striking contrast shows that while Mg II traces the ambient, clumpy cool CGM reservoir, the  $H\alpha$  emission directly captures localized, low-covering-fraction clouds whose density, pressure, or ionization level has been dramatically boosted by the propagating jet. These results deliver clear evidence of localized jet–CGM interaction in radio-jetted AGNs.

*Unified Astronomy Thesaurus concepts:* Galaxy evolution (594); Active galactic nuclei (16); Radio galaxies (1343); Circumgalactic medium (1879)

## 1. Introduction

The circumgalactic medium (CGM) is the baryon reservoir that regulates the long-term growth of galaxies. It supplies gas for future star formation, receives recycled and outflowing material, and mediates the exchange of mass, metals, momentum, and energy between galaxies and the intergalactic medium (e.g., J. Tumlinson et al. 2013, 2017; S. Borthakur et al. 2015, 2016; M. Donahue & G. M. Voit 2022). A full accounting of these baryons, and understanding how they are heated, cooled, ejected, or reaccreted, remains a longstanding goal of galaxy evolution studies. This is especially important for massive quenched galaxies, where cool halo gas can survive long after active star formation has shut down (C. Thom et al. 2012). Since massive galaxies maintain quiescence over gigayear timescales, a long-lived heating source is necessary to prevent that gas from cooling too efficiently and preventing the rejuvenation of star formation (L. L. Cowie & J. Binney 1977; A. J. Benson et al. 2003; R. G. Bower et al. 2006).

There is now significant evidence that feedback from active galactic nuclei (AGNs) plays a crucial role in this regard, and relativistic radio jets from the central supermassive black holes provide one of the clearest mechanical channels through which black holes can deliver energy beyond the nucleus (A. C. Fabian & P. E. J. Nulsen 1977; D. J. Croton et al. 2006; L. C. Ho 2008; A. C. Fabian 2012; B. R. McNamara &

P. E. J. Nulsen 2012; R. Kondapally et al. 2023). In galaxy clusters, radio jets inflate cavities, drive shocks, and redistribute energy through the hot X-ray-emitting atmosphere, demonstrating that radio-mode feedback can couple to halo gas on large scales (e.g., H. Boehringer et al. 1993; A. C. Fabian et al. 2003, 2012; B. R. McNamara et al. 2005; L. Birzan et al. 2008; M. Gitti et al. 2012; B. R. McNamara & P. E. J. Nulsen 2012; T. M. Heckman & P. N. Best 2014; M. J. Hardcastle & J. H. Croston 2020). However, this direct evidence primarily traces hot gas with  $T \gtrsim 10^6$  K in massive group and cluster environments. How jet energy is deposited into the cooler,  $T \sim 10^4$  K CGM around the more common population of lower-mass radio galaxies ( $\log M_\star < 11.5$ ) is much less understood.

Existing observations suggest that jets can indeed kinematically affect the cool gas in the interstellar medium (ISM) and inner-ISM–CGM boundary. In powerful radio galaxies at  $z > 2$ , optical and near-infrared integral-field spectroscopy revealed broad, turbulent ionized gas components that are spatially aligned with the radio lobes, with line widths reaching FWHM  $\sim 1000$  km s $^{-1}$  on kiloparsec to tens of kiloparsec scales (e.g., N. P. H. Nesvadba et al. 2006, 2008, 2017; N. Roy et al. 2024, 2026; A. Saxena et al. 2024). At larger radii, extended Ly $\alpha$  and  $H\alpha$  halos have been observed in a handful of high-redshift jetted AGNs sitting in massive halos at spatial scales often exceeding 100 kpc from the nucleus (e.g., P. J. McCarthy 1993; R. van Ojik et al. 1997; M. Villar-Martín et al. 2003; G. Miley & C. De Breuck 2008). These systems show that cool and warm gas can coexist with powerful radio activity, but the prevalence of such jet–CGM coupling in more typical lower-redshift radio galaxies remains largely



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unconstrained because the CGM emission is extremely faint. Although the mechanical energy budget of radio jets is sufficient to affect the host galaxy (e.g., G. V. Bicknell 1995; B. R. McNamara et al. 2005; L. Birzan et al. 2008; B. R. McNamara & P. E. J. Nulsen 2012; N. Roy et al. 2021, 2024, 2026), where and how this energy is deposited into the cool CGM remains an open question.

In this Letter, we overcome this limitation by stacking optical spectra of background quasars from the large spectroscopic dataset obtained by the Dark Energy Spectroscopic Instrument (DESI) survey (DESI Collaboration et al. 2024, 2026). We identify background-quasar sight lines that pass through the projected halos of foreground radio galaxies from the LOFAR Two-meter Sky Survey (LoTSS; T. W. Shimwell et al. 2017, 2022; M. J. Hardcastle et al. 2023). This sample allows us to search for faint emission and absorption CGM tracers in sight lines close to the large-scale radio jets. Using the statistical power of a large sample, we can detect extremely faint hydrogen recombination emission ( $H\alpha$ ) from cool ionized gas along with magnesium resonance doublet absorption (Mg II) in galaxy halos, extending the measurements well into the CGM at  $>200$  kpc projected distances (H. Zhang et al. 2016; Y.-L. Chang et al. 2024).

Our technique to isolate sight lines close to the radio axis is crucial to derive the impact of jets on the ambient medium, and significantly differs from previous studies (Y.-L. Chang et al. 2024). If radio jets couple to the cool CGM anisotropically, then the emission features should be enhanced preferentially along the radio lobes, while an azimuthally averaged stack may show little or no excess. This provides a direct statistical test of whether the CGM around radio galaxies behaves as a passive reservoir of gas or as a medium that records where mechanical feedback energy has been deposited.

Throughout this Letter, we adopt a flat  $\Lambda$ CDM cosmology with  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_m = 0.3$ , and  $\Omega_\Lambda = 0.7$ . Projected distances are physical unless otherwise stated.

## 2. Sample and Stacking Method

### 2.1. Data: DESI Quasar Survey and Radio Catalogs

We construct a foreground–background sample by cross-matching spectroscopically confirmed background quasars from the DESI Data Release 1 (E. Chaussidon et al. 2023; DESI Collaboration et al. 2024, 2026) with foreground radio galaxies from the LoTSS Data Release 2 (DR2) value-added AGN catalog (T. W. Shimwell et al. 2022; M. J. Hardcastle et al. 2023). DESI is a highly multiplexed optical spectroscopic survey on the Mayall 4 m telescope, with 5000 fibers and a wavelength coverage of approximately 3600–9800 Å at a spectral resolution of  $R \sim 2000$ –5000 (DESI Collaboration et al. 2016; J. Guy et al. 2023; J. H. Silber et al. 2023). The broad wavelength coverage makes DESI optimally suited for searching faint foreground  $H\alpha$  emission and Mg II absorption in the background-quasar spectra in and around the gaseous halos of radio galaxies. Due to the optical wavelength cutoff of DESI ( $\approx 3600$  Å), Mg II  $\lambda\lambda 2796, 2803$  absorption is accessible only for systems at  $z \geq 0.30$ . The Mg II analysis is therefore conducted on a subsample of pairs ( $0.30 \leq z \leq 0.49$ , median  $z = 0.38$ ). For each background sight line, we extract the final recommended quasar redshift from the value-added catalog  $z_{\text{QSO}}$ , observed-frame wavelength, flux-density, and inverse-variance arrays.

LoTSS DR2 provides 120–168 MHz imaging over 27% of the Northern sky, with continuum maps at 6'' resolution and a central frequency of 144 MHz. The DR2 source catalog contains 4,396,228 radio sources, with a median rms sensitivity of  $\approx 83 \mu\text{Jy beam}^{-1}$  (T. W. Shimwell et al. 2022). We use the LoTSS radio–optical value-added catalogs to obtain their optical counterparts, redshifts, radio luminosities, angular sizes, and radio position angles (M. J. Hardcastle et al. 2023). We retain only sources with secure spectroscopic redshifts, and exclude objects for which only photometric redshift estimates are available, because the foreground–galaxy redshift sets the rest-frame wavelength grid for the  $H\alpha$  stack and determines the projected physical separation of each quasar sight line.

### 2.2. Final Sample Selection

We select radio sources such that their radio end-to-end size ( $D_{\text{radio}}$ ) and luminosity ( $L_{144}$ ) properties are consistent with traditional FRI/FRII systems with double-sided lobes (M. J. Hardcastle & J. H. Croston 2020; N. Roy et al. 2021), satisfying

$$4.3 \leq \log_{10} \left( \frac{D_{\text{radio}}}{\text{pc}} \right) \leq 6.5, \quad (1)$$

$$23 \leq \log_{10} \left( \frac{L_{144}}{\text{W Hz}^{-1}} \right) \leq 29.5. \quad (2)$$

We also require that the radio sources have positive deconvolved major and minor axes. This requirement filters out unresolved radio point sources and ensures that the radio sources are spatially extended with jet position angles ( $\text{PA}_{\text{radio}}$ ) reliably measured. This yields an initial foreground sample of 90,228 LOFAR-detected radio AGNs with measured radio-jet-axis information. We then require the foreground–radio–galaxy host to have a spectroscopic redshift before crossmatching to the DESI quasar catalog.

For each radio galaxy, we identify the closest background DESI quasar and compute their projected separation ( $R_\perp$ , or impact parameter) using the radio–galaxy redshift  $z_{\text{RG}}$ . We retain only clean foreground–background configurations satisfying

$$z_{\text{QSO}} > z_{\text{RG}} + 0.08 \quad (3)$$

and

$$z_{\text{QSO}} - z_{\text{RG}} < 2.5. \quad (4)$$

The lower limit removes physically associated systems, and the upper limit avoids contamination from unrelated intervening spectral features and broad background-quasar rest-frame UV features such as  $\text{Ly}\alpha$ , N V, Si IV, and C IV. These features would otherwise overlap with the foreground-line windows.

To exclude host inner-ISM contamination while remaining within the projected radio-jet size, we additionally require

$$R_\perp > R_{50}, \quad (5)$$

$$R_\perp < 0.8 D_{\text{radio}} \\ < 1.6 R_{\text{radio}} \quad (6)$$

where  $R_{50}$  is the optical half-light radius of the host,  $D_{\text{radio}}$  is the projected end-to-end radio size, and  $R_{\text{radio}}$  is the corresponding radio half-size. The final catalog contains 324 radio galaxy–quasar pairs spanning  $0.05 < z_{\text{RG}} < 1.64$ ,

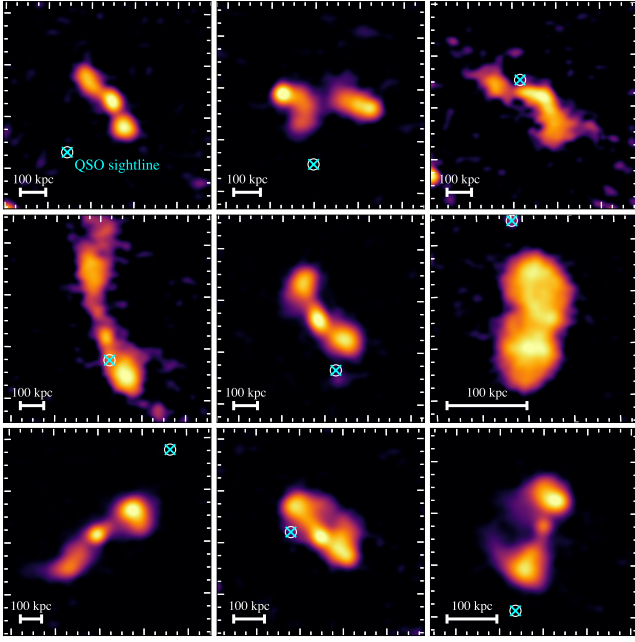


**Figure 1.** LOFAR radio images of nine example radio galaxies used in our analyses. The background-quasar sight lines from the DESI spectroscopic dataset are shown by cyan symbols.

$0.35 < z_{\text{QSO}} < 3.14$ ,  $R_{\perp} \simeq 20\text{--}800$  kpc, and  $\log_{10}(L_{144}/\text{W Hz}^{-1}) \simeq 23.06\text{--}28.17$ . Example radio images of a subset of our radio galaxy sample are shown in Figure 1.

We compute the position angle from the radio galaxy to the quasar ( $\text{PA}_{\text{RG} \rightarrow \text{QSO}}$ ) and compare it to the bidirectional LOFAR radio-jet axis ( $\text{PA}_{\text{radio}}$ ). The angular offset  $\theta$  ( $0^\circ \leq \theta \leq 90^\circ$ ) is defined as

$$\theta = |[(\text{PA}_{\text{RG} \rightarrow \text{QSO}} - \text{PA}_{\text{radio}} + 90^\circ) \bmod 180^\circ] - 90^\circ|, \quad (7)$$

where small  $\theta$  denotes sight lines near the radio axis and large  $\theta$  denotes near-transverse sight lines. The main jet-axis stack is defined by  $\theta < 20^\circ$  and contains 74 sight lines. We also use the normalized impact parameter  $R_{\perp}/D_{\text{radio}}$ , or  $R_{\perp}/R_{\text{radio}}$  to test for radial dependence of our result along the jet axis.

For each DESI quasar target ID in the final catalog, we retrieve the spectrum using SPECTRA Analysis and Retrieval Python Client (SPARCL; S. Juneau et al. 2025).<sup>4</sup> Since DESI has finite wavelength coverage, every input foreground-background pair does not contribute to every emission-line stack. Rather than imposing a separate catalog-level redshift cut for each line, the stacking algorithm rejects spectra that do not have finite, positive-inverse-variance pixels in the relevant rest-frame wavelength window. Thus, the effective number of spectra contributing to a given stack is set by the wavelength coverage and quality masks at that line.

### 2.3. Stacking and Uncertainty Estimates

We describe the full details of the continuum subtraction, masking, and noise tests in Appendix A.1. Briefly, each DESI quasar spectrum is shifted into the foreground-radio-galaxy rest frame, and we extract a  $\pm 150$  Å window around the  $\text{H}\alpha$  emission line (rest wavelength  $\lambda_0 = 6562.8$  Å). We mask strong background-quasar emission lines after projecting them

into the foreground-radio-galaxy rest frame and subtract a local second-order polynomial continuum fitted outside  $|\lambda - \lambda_{\text{H}\alpha}| < 50$  Å. The continuum-subtracted residual spectra are then interpolated onto a common rest-frame wavelength grid. Our fiducial stack is an inverse-variance-weighted mean, where we require a minimum of five contributing spectra per wavelength pixel. We measure the integrated  $\text{H}\alpha$  flux over  $|\Delta v| < 500 \text{ km s}^{-1}$  after subtracting a noise baseline (see Appendix A.2 for details) and thus avoid contamination from  $[\text{N II}]$ . Statistical uncertainties are estimated from the  $1\sigma$  scatter of the population distribution, and also from blank-region stacks randomly centered at 6800, 5500, and 4000 Å. We refer the reader to Appendices A.1 and A.2 for further details.

## 3. Results

We measure stacked  $\text{H}\alpha$  fluxes for our sample of quasar-radio-galaxy pairs, split into bins of projected angular offset from the radio axis ( $\theta$ ), the normalized position along the radio structure ( $R_{\perp}/D_{\text{radio}}$ , or  $R_{\perp}/R_{\text{radio}}$ ), and stellar mass ( $M_{\star}$ ). All stacks and figures show inverse-variance-weighted mean fluxes with their corresponding uncertainties unless otherwise mentioned.

### 3.1. A Jet-aligned $\text{H}\alpha$ Excess

The left panel of Figure 2(a) shows the stacked  $\text{H}\alpha$  spectra from the background-quasar sight lines, split into three subsamples by their angular offset from the radio-jet axis:  $\theta < 20^\circ$ ,  $20^\circ < \theta < 40^\circ$ , and  $\theta > 40^\circ$ . We find that the result varies considerably for these different cases. Sight lines within  $\pm 20^\circ$  of the radio axis, shown in blue, exhibit a strong  $\text{H}\alpha$  excess centered near the systemic velocity of the foreground radio galaxies, with a mean integrated flux of  $1.19 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$ . This excess  $\text{H}\alpha$  emission is detected with a significance of  $> 5\sigma$  above the baseline average in the inverse-variance-weighted stacked spectra. The profile also appears skewed toward positive velocities ( $\Delta v \sim 900\text{--}1500 \text{ km s}^{-1}$ ), which corresponds to  $[\text{N II}]\lambda 6583$  emission associated with AGN or shock-ionized gas blended with  $\text{H}\alpha$ . In contrast, the intermediate- and large-angle stacks show no comparable  $\text{H}\alpha$  feature.

Such angular dependence of the enhanced ionized gas signature suggests that the detected emission is highly anisotropic and is linked to the radio AGN geometry. This is consistent with current theories that radio jets drive shocks, inflate overpressurized cocoons, and entrain photoionized gas preferentially along the jet propagation direction or along cocoon boundaries (M. C. Begelman & D. F. Cioffi 1989; A. Y. Wagner & G. V. Bicknell 2011; D. Mukherjee et al. 2018). In this scenario, the detected  $\text{H}\alpha$  emission in the stacked spectra traces dense, localized pockets of cool ionized CGM gas whose emissivity is directionally enhanced along the projected jet axis. However, the same parent sample gives a null detection when the spectra are averaged over all azimuthal angles. Figure 2(b) shows the stacked spectrum for all background-quasar sight lines, independent of their angle relative to the radio source. The azimuthally averaged stack does not show any statistically significant  $\text{H}\alpha$  excess. The integrated signal within the fiducial velocity window is  $< 2\sigma$  relative to the randomized noise stacks.

This nondetection is consistent with recent absorption-line stacking studies that did not find any strong isotropic

<sup>4</sup> <https://datalab.noirlab.edu/data-explorer>

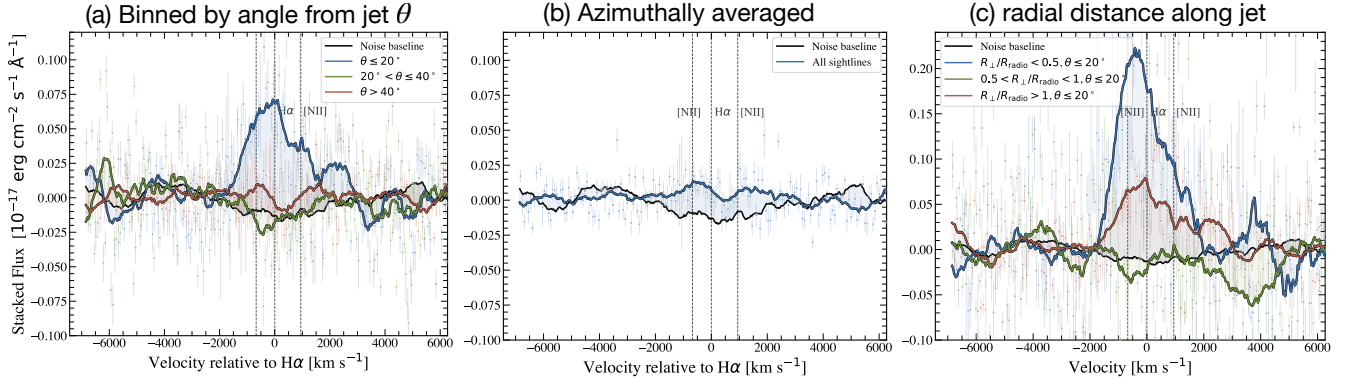


**Figure 2.** Panel (a): angle-binned stacked residual spectra. Sight lines within  $\pm 20^\circ$  of the radio axis show an  $H\alpha$  excess at the rest-frame wavelength centered at the foreground host galaxies’ systemic redshifts, but no comparable excess is seen at intermediate- or large-angle sight lines. The result indicates that the cool ionized CGM signal is strongly anisotropic and aligned with the projected radio structure. Panel (b): azimuthally averaged stacked residual DESI spectrum around foreground radio galaxies. The spectrum is shifted to the foreground-galaxy rest frame and centered on  $H\alpha$ . The all-angle stack shows no significant  $H\alpha$  excess, with an integrated significance of  $< 2\sigma$  relative to randomized blank stacks. This null result rules out a simple spherically enhanced  $H\alpha$  halo but does not test for directional jet–CGM coupling. Panel (c): integrated  $H\alpha$  signal as a function of normalized projected distance from the host galaxy for sight lines within  $\pm 20^\circ$  of the radio axis. The line excess is strongest near the galaxy and again near the projected radio-lobe/cocoon region, suggesting two preferred zones where radio jets couple to cool ionized halo gas.

enhancement of the cool CGM around radio sources relative to matched control samples (e.g., Y.-L. Chang et al. 2024). If the gas responds preferentially along the radio axis, combining all angles dilutes the signal, but it produces an excess emission signature when restricted to sight lines aligned with the projected radio source, as shown above.

We perform several checks to test whether the angular signal could be produced by a small number of outliers or by residual systematics in the quasar spectra. We find that the integrated flux changes only by  $\sim 4\%$ – $7\%$  after removing individual high-weight spectra one at a time using the jackknife method of rejection, thus retaining the detection significance to be  $> 4.7\sigma$ . The signal also cannot be reproduced artificially by stacking randomized foreground redshifts, or from any combination of nearby blank spectral regions. Our tests indicate that the detected  $H\alpha$  flux is physical and emerges from combining the true foreground redshift and the observed radio-axis geometry.

The detailed velocity shape of the stacked profile should be interpreted with some caution. We see an asymmetry in the line shape with a skewed extension on the red side, which is expected because  $[\text{N II}] \lambda 6583$  lies at  $+941 \text{ km s}^{-1}$  from  $H\alpha$  and remains blended. The broad  $> 2000 \text{ km s}^{-1}$  velocity span in the plotted stack can also arise from a combination of factors. The massive line width can be a result of object-to-object scatter in bulk velocity offsets, host-galaxy redshift uncertainties, varying motions of clouds along different orientations being averaged into one single spectrum, or physical kinematic broadening of the emission lines from jet-perturbed gas, as observed in high-redshift radio galaxies (N. Roy et al. 2024, 2026; A. Saxena et al. 2024). For this reason, all fluxes quoted here are integrated only over  $|\Delta v| < 500 \text{ km s}^{-1}$ , where the measurement is least affected by  $[\text{N II}]$  and by the noisy broad wings. A qualitatively similar directional  $H\alpha$  emission is seen in the SIMBA simulation from a representative jet-mode galaxy shown in Appendix A.3, where the area-averaged  $H\alpha$  surface brightness is largest close to the projected jet axis and decreases toward larger azimuthal angles.

### 3.2. Radial Variation of $H\alpha$ along the Radio-jet Axis

Next, we investigate how the  $H\alpha$  emission fluxes change as a function of projected radii from the center along the radio lobes. Figure 2(c) shows the inverse-variance-weighted stacked spectra measured in bins of projected radial distance of the sight line, scaled by radio half-size,  $R_\perp/R_{\text{radio}}$ , for the subsample aligned close to the jet ( $|\theta| < 20^\circ$ ). Keeping the angular offset from the radio jet to fixed and within  $\theta_{\text{jet}}$ , we split our sample into  $R_\perp/R_{\text{radio}} < 0.5$ ,  $0.5 < R_\perp/R_{\text{radio}} < 1.0$ , and  $R_\perp/R_{\text{radio}} > 1.0$ . The goal is to quantify how the flux changes as the sight line moves out from the center toward the lobe terminus. We find that stacked  $H\alpha$  is not enhanced uniformly along the radio jet on average. The emission is strongest and is detected with  $> 7\sigma$  near the central regions close to the host galaxy, where the integrated  $H\alpha$  flux =  $3.46 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$ . The mean  $H\alpha$  signal again starts to rise toward larger radii near the radio lobes, with a mean flux of  $1.31 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$ . Projected distances at intermediate radii show weaker emission or no detection. Thus, the  $H\alpha$  emission appears to be concentrated in those regions where jet–gas coupling is expected to be most effective. Near the host galaxy (but beyond  $R_{50}$  to avoid the ISM emission; see Section 2.2), the  $H\alpha$  emission likely traces gas at the transition between the dense ISM and the inner CGM, where the young jet first encounters the surrounding halo. The increased flux at higher radii where  $R_\perp/R_{\text{radio}} > 1.0$  is possibly associated with the lobe or cocoon interface, where the jet deposits mechanical energy into the ambient CGM and can compress or ionize cool gas.

This interpretation is consistent with resolved studies of powerful radio galaxies at higher redshift ( $z > 3.5$ ). Spatially resolved integral-field unit observations from JWST/NIRSpec have found extended nebular emission in  $H\alpha$ ,  $[\text{O III}]$ ,  $[\text{O II}]$ , and other rest-frame optical lines that are strongly aligned with their radio-jet axes (e.g., N. Roy et al. 2024, 2026; A. Saxena et al. 2024; W. Wang et al. 2024). Thus, the ionized gas emission exhibits distinct enhancements along the compact radio lobes from a few to several tens of kiloparsecs in high-redshift systems. The systems studied in this work extend this experiment to lower-redshift radio galaxies with larger and

more evolved radio structures, where lobe-to-lobe radio sizes  $D_{\text{radio}}$  reach  $\gtrsim 300$  kpc. Our stacked measurements therefore suggest that the same energy-coupling scenario seen in relatively compact high-redshift systems may persist to CGM scales in nearby radio galaxies, near the sites where radio lobes interact with the surrounding medium.

#### 4. Discussion

##### 4.1. Physical Constraints from the Stacked $H\alpha$ Signal

The detected  $H\alpha$  flux provides a direct constraint on the amount of cool ionized gas produced by jet–CGM coupling. For a characteristic background-quasar sight line passing through the foreground-radio-galaxy CGM at luminosity distance  $D_L$ , the integrated  $H\alpha$  line luminosity is

$$L_{H\alpha} = 4\pi D_L^2 F_{H\alpha}, \quad (8)$$

where  $F_{H\alpha}$  is the measured integrated flux. If we consider only the weighted mean flux from the sight lines lying along the radio-jet axis  $\theta < 20^\circ$  (irrespective of their radial distance) from Section 3.1,  $F_{H\alpha} = 1.19 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$ . Under Case B recombination, the ionized gas mass associated with the emitting phase can be written as

$$M_{\text{ion}} \simeq \frac{m_p L_{H\alpha}}{n_e \alpha_{H\alpha}^{\text{eff}} h\nu_{H\alpha}} \quad (9)$$

$$\approx 3.2 \times 10^9 \left( \frac{L_{H\alpha}}{10^{40} \text{ erg s}^{-1}} \right) \left( \frac{10^{-2} \text{ cm}^{-3}}{n_e} \right) M_\odot, \quad (10)$$

where  $n_e$  is the electron density normalized by  $10^{-2} \text{ cm}^{-3}$ ,  $m_p$  is the mass of a proton, and  $\alpha_{H\alpha}^{\text{eff}} = 1.17 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$  is the effective Case B recombination coefficient at  $T \simeq 10^4 \text{ K}$ . The normalization  $n_e = 10^{-2} \text{ cm}^{-3}$  is motivated by approximate pressure balance between the cool  $H\alpha$ -emitting phase and the surrounding hot halo. For a hot CGM phase with  $T_{\text{hot}} \sim 10^6 \text{ K}$  and  $n_{\text{hot}} \sim 10^{-4} \text{ cm}^{-3}$  (M. Fumagalli 2024), the thermal pressure is

$$\frac{P}{k_B} \simeq n_{\text{hot}} T_{\text{hot}} \sim 10^2 \text{ K cm}^{-3}. \quad (11)$$

If the  $T_{\text{cool}} \sim 10^4 \text{ K}$  ionized hydrogen clouds are in rough pressure equilibrium with this hotter ambient medium, then an order-of-magnitude cool-phase CGM density scale can be estimated as

$$n_{\text{cool}} \simeq n_{\text{hot}} \frac{T_{\text{hot}}}{T_{\text{cool}}} \sim 10^{-2} \text{ cm}^{-3}. \quad (12)$$

Thus, assuming  $n_e = 10^{-2} \text{ cm}^{-3}$ , and using the mean integrated flux  $F_{H\alpha}$  measured for the jet-aligned sight lines at  $\langle z_{\text{RG}} \rangle = 0.66$ , we obtain a characteristic luminosity  $L_{H\alpha} = 2.2 \times 10^{40} \text{ erg s}^{-1}$ . The corresponding ionized gas mass is  $7 \times 10^9 M_\odot$ . Thus, even a faint stacked  $H\alpha$  signal can correspond to a substantial cool ionized gas reservoir at plausible CGM densities.

The emission-line luminosity can be powered by several mechanisms including AGN photoionization, shock ionization along the jet axes, turbulent mixing layers, or collisional excitation in cooling gas. Our stacked measurements do not distinguish between these channels. However, the alignment with the radio axis and the radial concentration near the

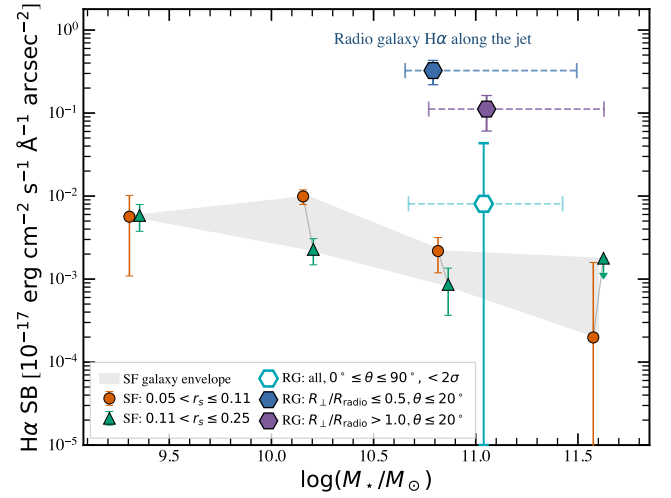


**Figure 3.**  $H\alpha$  emission surface brightness as a function of stellar mass. All measurements are expressed as rest-frame surface brightnesses after correcting for cosmological dimming by a factor of  $(1+z)^4$ . The orange circles and green triangles show star-forming galaxy measurements from H. Zhang et al. (2020) in two bins of scaled projected radius,  $r_s = r_p/R_{180}$ , where  $r_p$  is the projected distance from the galaxy center and  $R_{180}$  is the virial radius. The gray shaded region marks the corresponding range of  $H\alpha$  surface brightnesses observed from the inner to outer regions of these star-forming galaxies and groups (H. Zhang et al. 2016, 2020). The cyan hexagon shows the radio-galaxy stack including all background-quasar sight lines, independent of angular position relative to the radio axis ( $0^\circ \leq \theta \leq 90^\circ$ ). Since the  $H\alpha$  flux stacked over all azimuthal angles is a nondetection ( $< 2\sigma$ ; see Figure 2(b)), this point should be interpreted as an upper limit. This upper limit is consistent with the  $H\alpha$  surface brightness expected for normal-galaxy halos (H. Zhang et al. 2016; Y.-L. Chang et al. 2024). The blue and purple hexagons show radio-galaxy stacks restricted to sight lines within  $20^\circ$  of the projected radio axis. They are separated into inner sight lines with  $R_\perp/R_{\text{radio}} \leq 0.5$  and outer sight lines with  $R_\perp/R_{\text{radio}} > 1.0$ , which are close to the radio lobes. The  $H\alpha$  emission from jet-aligned sight lines is much stronger and is enhanced by nearly 1–2 orders of magnitude relative to the normal-galaxy baseline at similar stellar mass. This indicates that the  $H\alpha$  emissivity from cool ionized CGM is preferentially brightened along directions where radio jets interact with halo gas.

nucleus and outer radio structures point to a clear mechanical connection with the jet.

##### 4.2. Comparison with $H\alpha$ CGM Constraints in Star-forming Galaxies

Stacked recombination-line measurements have recently provided a useful baseline for the level of cool ionized gas expected around normal star-forming galaxies. Using Sloan Digital Sky Survey spectra, H. Zhang et al. (2016) detected stacked  $H\alpha + [\text{N II}]$  emission around low-redshift galaxies from projected radii of  $\sim 5$  kpc to beyond 100 kpc, with a surface-brightness profile declining approximately as  $r_p^{-1.9 \pm 0.4}$ . Extending this analysis to a larger sample of low-redshift isolated galaxies, groups, and clusters, H. Zhang et al. (2020) found that the contribution of the cool  $T \sim 10^4 \text{ K}$  CGM fraction decreases strongly with stellar and halo mass. Their measurements provide an empirical baseline for the faint, approximately halo-averaged  $H\alpha$  emission expected around normal massive, evolved galaxy systems.

Figure 3 measures the  $H\alpha$  surface brightnesses corrected by a cosmological dimming factor of  $(1+z)^4$  as a function of stellar mass, and compares the measurements for non-AGN galaxy halos from H. Zhang et al. (2020) with our radio-galaxy measurements. The comparison samples are not exactly identical because the Zhang et al. measurements are stacked

in bins of scaled projected radius,  $r_s = r_p/R_{180}$ , where  $r_p$  is the projected distance from the galaxy and  $R_{180}$  is the virial radius. On the other hand, our radio-galaxy sample is stacked in bins of normalized radial distance from the center relative to the radio-jet length,  $R_\perp/R_{\text{radio}}$ , where  $R_\perp$  is the projected distance of the sight line equivalent to the impact parameter and  $R_{\text{radio}}$  is the size of one side of the radio jet. The stacks in our sample shown here are further split by the angular offset of the sight line from the projected jet axis ( $\theta$ ). However, both measurements are expressed as stacked H $\alpha$  surface brightness and provide a direct comparison between the cool ionized CGM clouds prevalent in these systems.

Earlier, we found that when all radio-galaxy sight lines are combined over all azimuthal angles with respect to the jet ( $0^\circ \leq \theta \leq 90^\circ$ ), the stacked spectrum yields no significant H $\alpha$  detection, with an integrated significance of  $<2\sigma$  as shown in Figure 2(b). Therefore, the corresponding cosmological-dimming-corrected surface-brightness value shown by the cyan symbol in Figure 3 should be interpreted as an upper limit rather than a detection. This upper limit is consistent with the H $\alpha$  surface brightness expected for normal-galaxy halos (H. Zhang et al. 2016; Y.-L. Chang et al. 2024) and indicates that their globally averaged cool ionized CGM is possibly no different from that of actively star-forming halos. But the H $\alpha$  emission becomes drastically stronger when the stacks are restricted to sight lines aligned with the radio-jet axis. Within  $\theta \leq 20^\circ$  around the radio jets, both the inner ( $R_\perp/R_{\text{radio}} \leq 0.5$ ) and outer ( $R_\perp/R_{\text{radio}} > 1.0$ ) radial bins (blue and purple hexagons, respectively) show substantially enhanced H $\alpha$  surface brightnesses compared to the H. Zhang et al. (2020) measurements at similar stellar mass. The jet-aligned measurements are enhanced by 1–2 orders of magnitude relative to the normal-galaxy baseline at similar stellar mass. Hence, the impact of jets on the CGM is about 2 orders of magnitude stronger than the similar impact driven by star-forming galaxies.

The nondetections when averaged over all azimuthal angles do not establish a globally larger H $\alpha$ -emitting reservoir in low-redshift radio-galaxy halos. Instead, their detected enhanced H $\alpha$  emission is localized along the radio-jet axis, showing that the gas is not distributed or excited isotropically. The jet modifies the emissivity of cool CGM gas in a strongly directional manner. This directional enhancement can arise through two related physical pathways. The radio jet may encounter preexisting cool CGM clouds and increase their H $\alpha$  emissivity through compression, shock ionization, or turbulent mixing at the lobe–halo interface. Alternatively, some of the H $\alpha$ -emitting material may originate in the ISM or inner CGM and be entrained outward by the outflow. These two scenarios may not be mutually exclusive from each other. Since recombination-line emissivity scales approximately as  $n_e^2$ , locally compressed or more highly ionized clouds can become dramatically brighter in H $\alpha$  without requiring an increase in the total cool-gas mass averaged over the halo. The comparison with normal galaxies clarifies the role of radio-mode feedback in these systems. The enhanced H $\alpha$  emission close to the radio axis, detected both near the host and toward the outer lobes, provides direct evidence that radio jets affect the surrounding ISM and CGM in a strongly anisotropic manner.

### 4.3. Energetics Estimates

The rest-frame 1.4 GHz radio luminosities in our sample range between  $\log(L_{1.4\text{ GHz}}/\text{erg s}^{-1}) \simeq 39\text{--}43$ , corresponding to inferred jet mechanical powers of  $\log(P_{\text{jet}}/\text{erg s}^{-1}) \simeq 42.2\text{--}45.5$ . For a mean  $\langle \log P_{\text{jet}}/\text{erg s}^{-1} \rangle \simeq 43.5$  (N. Roy et al. 2026), the available mechanical power is at least 1 order of magnitude larger than the characteristic mechanical energy injection from stellar feedback in normal star-forming galaxies. For supernovae and stellar winds, the characteristic energy deposition rate is recorded to be  $\dot{E}_{\text{SF}} \sim 7 \times 10^{41} (\text{SFR}/1 M_\odot \text{ yr}^{-1}) \text{ erg s}^{-1}$  (e.g., C. Leitherer et al. 1999; S. Veilleux et al. 2005). Thus, the factor of 1–2 orders of magnitude enhancement in jet-aligned H $\alpha$  surface brightness relative to the star-forming-galaxy halo baseline is energetically feasible.

Using the observed jet-aligned luminosity,  $L_{\text{H}\alpha} \simeq 2 \times 10^{40} \text{ erg s}^{-1}$ , we find

$$\frac{L_{\text{H}\alpha}}{\langle P_{\text{jet}} \rangle} \simeq 6 \times 10^{-4} \simeq 0.06\%. \quad (13)$$

Thus, only of order  $10^{-3}$  of the available jet mechanical power needs to emit as H $\alpha$  radiation from the cool ionized phase to account for the observed enhancement in H $\alpha$  emission. This ratio is likely only a small fraction of the total coupling efficiency of the jet to the CGM, as H $\alpha$  traces gas only at a temperature of  $T \sim 10^4 \text{ K}$  gas. This low required energy coupling efficiency is also consistent with a representative jet-mode AGN from the SIMBA cosmological simulation demonstrated in Appendix A.3. Additional energy from the jet may be deposited as kinetic or thermal energy in other temperature and gas phases, most predominantly in the shock-heated, X-ray-emitting gas with  $T \gtrsim 10^6 \text{ K}$  (B. R. McNamara & P. E. J. Nulsen 2007, 2012; A. C. Fabian 2012; M. Gitti et al. 2012).

### 4.4. The Origin of the H $\alpha$ Ionized Gas: Insights from Mg II Absorption Profiles

The previous sections show that the azimuthally averaged H $\alpha$  stack is not significantly detected, while the same sample shows a strong H $\alpha$  excess when restricted to sight lines close to the projected radio axis. This raises a key question: Does the jet-aligned H $\alpha$  excess reflect an intrinsically larger amount of cool gas along the radio-jet axis, or does the jet locally brighten a more broadly distributed cool-gas reservoir?

To address this, we search for Mg II  $\lambda\lambda 2796, 2803$  absorption in the same DESI background-quasar sight lines. Mg II provides a complementary probe because it is sensitive to the presence and column density of cool, metal-enriched clouds, rather than to the  $n_e^2$  emissivity that governs recombination emission. We fit the Mg II  $\lambda\lambda 2796, \lambda 2803$  doublet together using a two-component Gaussian absorption-doublet model, fixing the wavelength separation and requiring both lines to fall at the same foreground-galaxy velocity. The equivalent width and apparent-optical-depth column density are then measured from the continuum-normalized spectrum.

We adopt the Mg II detection threshold as a rest-frame equivalent width  $W_r(2796) \geq 0.3 \text{ \AA}$  at  $\geq 3\sigma$  significance. We measure a Mg II covering fraction of  $f_c = 21.6^{+5.2}_{-4.6}\%$  along jet-aligned sight lines ( $\theta < 20^\circ$ ), compared to  $f_c = 16.0^{+2.6}_{-2.3}\%$  (40/250) for off-axis sight lines ( $20^\circ \leq \theta \leq 90^\circ$ ). Here, the uncertainties denote 68% confidence intervals. We perform a

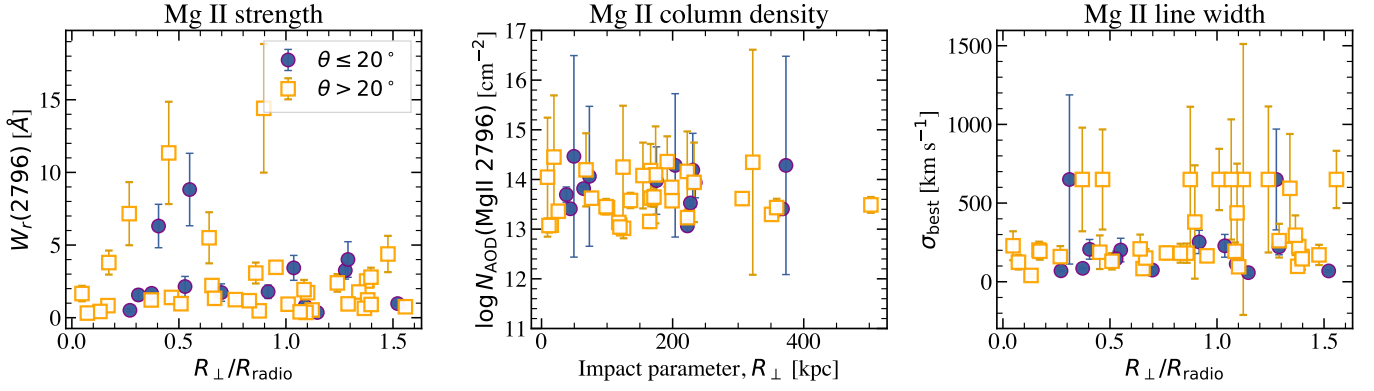


**Figure 4.** Mg II absorption properties for individual radio-galaxy sight lines for the individually detected absorbers. Blue filled circles show absorbers along jet-aligned sight lines with  $\theta \leq 20^\circ$ , while orange open squares show absorbers at  $\theta > 20^\circ$ . Left: Mg II  $\lambda 2796$  rest-frame equivalent width as a function of normalized projected distance,  $R_\perp/R_{\text{radio}}$ . Center: apparent-optical-depth Mg II  $\lambda 2796$  column density as a function of projected impact parameter,  $R_\perp$ . Right: fitted velocity dispersion ( $\sigma$ ) determined from a two-component Gaussian profile fit to the Mg II  $\lambda \lambda 2796, 2803$  absorption doublet, as a function of  $R_\perp/R_{\text{radio}}$ . Note that only confirmed Mg II detections are displayed across all panels. The jet-aligned and off-axis absorbers span similar ranges in equivalent width, column density, and line width, indicating that the Mg II-bearing cool clouds are not strongly enhanced or kinematically distinct along the radio-jet direction. This contrasts with the strongly jet-aligned H $\alpha$  emission, suggesting that radio jets primarily brighten or ionize a subset of a more broadly distributed cool CGM reservoir.

two-sided proportion test that gives  $p = 0.24$  and  $z = 1.17$ , indicating that this difference in the covering fractions is not statistically significant. Figure 4 demonstrates that the Mg II equivalent widths (left panel), apparent-optical-depth column densities (middle panel), and fitted line widths (right panel) are broadly similar for jet-aligned sight lines ( $\theta \leq 20^\circ$ ; blue circles) and off-axis sight lines ( $\theta > 20^\circ$ ; yellow squares). These quantities also show no clear systematic trend with normalized distance along the radio source for our sample. Thus, unlike H $\alpha$ , the Mg II clouds appear to be distributed over a broad range of azimuthal angles and do not show any strong evidence for being preferentially concentrated along the projected jet axis.

This result is consistent with previous absorption-line work showing that massive quiescent galaxies can retain substantial cool CGM reservoirs. For example, the COS-Halos survey detected cool, largely bound H I-bearing gas around passive early-type galaxies, with inferred cool CGM masses of  $10^9$ – $10^{11} M_\odot$  (C. Thom et al. 2012). Mg II absorption has also been detected statistically around luminous red galaxies (LRGs) and other massive halos (G. Zhu et al. 2014; T.-W. Lan & H. Mo 2018). In our sample, Figure 5 shows that individual Mg II absorbers, shown in red symbols, are found to large projected distances, often beyond  $\sim 100$  kpc, and in some cases above the average LRG profiles from T.-W. Lan & H. Mo (2018). Sight lines without individual Mg II detections are not shown as separate points in Figure 5, but they are included in the radial stacked measurements. Hence, the stacked Mg II signals shown in blue squares are weaker, and several radial bins yield only upper limits. The combined evidence points to an extended, clumpy cool phase with low covering fraction, rather than a smooth, high-covering-fraction reservoir.

This contrast between the nature of H $\alpha$  emission and Mg II absorption can occur if radio jets propagate through an extended population of isotropically distributed cool clouds and locally alter their physical state. Jet-driven cocoons can create overpressured regions relative to the ambient medium (M. C. Begelman & D. F. Cioffi 1989), and simulations of jets propagating through clumpy multiphase gas show that the expanding jet-driven cocoon and backflow can compress cool clouds, drive shocks and turbulence, and increase the

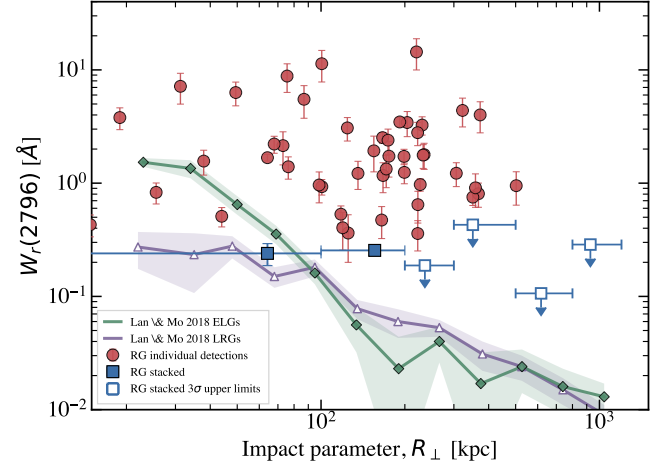


**Figure 5.** Mg II  $\lambda 2796$  rest-frame equivalent width as a function of projected impact parameter,  $R_\perp$ . Red circles show individual Mg II detections associated with the radio-galaxy sight lines in this work. Nondetections are not shown as individual points in this panel; however, they are included in the stacked measurements and they contribute to the low mean equivalent widths in the radial bins. Filled blue squares show the measurements from stacked profiles, while open blue squares indicate  $3\sigma$  upper limits from stacks without individual detections. For comparison, the green and purple curves show the average Mg II absorption profiles around emission-line galaxies and luminous red galaxies from T.-W. Lan & H. Mo (2018), respectively, with shaded regions indicating the reported uncertainties. Individual radio-galaxy absorbers are detected over a broad range of projected radii, including beyond  $\sim 100$  kpc, and several lie above the average LRG profile. However, the stacked signal is weak and several radial bins yield only upper limits, indicating that the cool Mg II-bearing gas around radio galaxies is extended and clumpy, with a low covering fraction rather than a smooth, high-covering-fraction halo component.

temperature and ionization state of the gas along the jet path (R. S. Sutherland & G. V. Bicknell 2007; A. Y. Wagner et al. 2012; D. Mukherjee et al. 2016, 2018; R. Dutta et al. 2024). Since H $\alpha$  emissivity scales approximately as  $j_{\text{H}\alpha} \propto n_e^2$ , even a modest density enhancement in a small subset of clouds can produce a large increase in recombination emission without a comparable increase in the Mg II covering fraction. This causes a large enhancement of H $\alpha$  signal in the jet direction, but no dependence of the Mg II signal on azimuthal angle. Another possibility is gas being entrained along the jet, as shown by powerful high-redshift radio galaxies on tens of

kiloparsec scales (e.g., N. Roy et al. 2024, 2026). We indeed observe preliminary signatures of a significantly broadened, stacked  $H\alpha$  line that spans  $>2000 \text{ km s}^{-1}$  and may suggest kinematic disturbance of the gas due to the jet. However, as discussed before in Section 3.1, the broad profile can also arise from stacking a superposition of the  $H\alpha + [\text{N II}]$  complex, convolved with line-of-sight velocity scatter among the different sight lines and host-galaxy redshift uncertainties. The detailed kinematic characterization needs a more extensive follow-up study.

However, the above findings favor a picture in which Mg II-bearing clouds provide an extended, clumpy cool-gas reservoir from which at least part of the  $H\alpha$  emission arises. The radio jet then increases the density, pressure, and ionization state of the subset of clouds along its path, making them disproportionately bright in  $H\alpha$ . Some entrainment from the ISM or inner CGM may also occur, but the lack of an enhanced Mg II velocity width or velocity offset for jet-aligned sight lines suggests that the dominant effect is local brightening or ionization of preexisting CGM clouds.

## 5. Conclusions

We have presented a statistical search for faint  $H\alpha$  emission from the cool ionized CGM around radio galaxies by stacking DESI background-quasar spectra at the redshifts of foreground LoTSS radio galaxies. The key feature of our experiment is that we preserve the projected geometry of each sight line relative to the radio axis, allowing us to test whether radio jets affect the cool CGM anisotropically rather than only in an azimuthally averaged sense. Our main results are as follows:

1. The  $H\alpha$  signal is strongly dependent on projected radio-jet alignment. Sight lines within  $\theta < 20^\circ$  of the radio axis show a clear  $H\alpha$  excess centered near the systemic velocity of the foreground radio galaxies, with a mean integrated flux of  $F_{H\alpha} = 1.19 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$  and a detection significance of  $>5\sigma$ . In contrast, intermediate- and large-angle sight lines show no comparable emission feature. The azimuthally averaged radio-galaxy stack also does not show a significant  $H\alpha$  detection. When all sight lines are combined over  $0^\circ \leq \theta \leq 90^\circ$ , the integrated signal is  $<2\sigma$  relative to the noise/control stacks. Thus, the  $H\alpha$ -emitting clouds are clumpy and distributed anisotropically, and lie preferentially enhanced along the projected radio axis.
2. The jet-aligned  $H\alpha$  emission is also radially structured. For sight lines within  $\theta < 20^\circ$ , the strongest emission occurs close to the host galaxy at the ISM–CGM boundary, beyond the optical half-light radius, with  $F_{H\alpha} = 3.46 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$ . The signal weakens at intermediate normalized radius and rises again near the outer radio-lobe region, with  $F_{H\alpha} = 1.31 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$ . This suggests two preferred zones of jet–gas coupling: near the ISM–CGM transition and near the radio lobe–CGM interface.
3. Compared with stacked  $H\alpha$  measurements around normal star-forming galaxies and galaxy systems from H. Zhang et al. (2016, 2020), the radio-galaxy spectra stacked over all angles with respect to the jet lie within the expected massive-halo baseline, while the jet-aligned stacks are elevated by almost 2 orders of magnitude. This

contrast shows that the radio-galaxy halos are not globally richer in  $H\alpha$ , but radio jets locally enhance the  $H\alpha$  emissivity of cool CGM material along preferred directions.

4. The inferred mass and energetics are consistent with a jet-powered origin for the enhanced  $H\alpha$  emission. For the characteristic jet-aligned luminosity,  $L_{H\alpha} \simeq 2.2 \times 10^{40} \text{ erg s}^{-1}$ , the implied ionized gas mass is  $\sim 7 \times 10^9 (10^{-2} \text{ cm}^{-3}/n_e) M_\odot$ , where the assumed density is motivated by pressure balance between  $T \sim 10^4 \text{ K}$  clouds and a  $T \sim 10^6 \text{ K}$  hot halo. The required  $H\alpha$  luminosity is only  $\sim 6 \times 10^{-4}$  of the mean inferred jet mechanical power. Thus, a very small fraction of the available jet energy is sufficient to produce the observed  $H\alpha$  excess in the cool ionized CGM.
5. Mg II absorption provides a complementary view of the cool CGM. Candidate Mg II absorbers are found along  $\simeq 22\%$  of jet-aligned sight lines and  $\simeq 16\%$  of off-axis sight lines, with no strong difference in equivalent width, column density, velocity offset, or line width. Individual Mg II absorbers can extend beyond  $\sim 100 \text{ kpc}$ , but the stacked signal is weak, indicating a clumpy, low-covering-fraction cool phase. The contrast between broadly distributed Mg II absorption and strongly jet-aligned  $H\alpha$  emission suggests that jets do not create all of the cool gas, but instead brighten, ionize, compress, or perturb a subset of preexisting cool CGM clouds.

In summary, our stacking analysis provides clear statistical evidence that radio jets couple to the cool ( $T \sim 10^4 \text{ K}$ ) CGM in a strongly anisotropic manner. The significant  $H\alpha$  excess along the jet-axis sight lines with an isotropic distribution of Mg II absorbers suggest that radio jets locally compress, ionize, or perturb preexisting halo gas along their propagation path. A qualitatively similar behavior is observed in the cosmological large-volume simulation SIMBA in a jet-mode AGN host galaxy, as discussed in Appendix A.3. Future simulation–observation comparisons that forward-model DESI-like sight lines through statistically matched samples of jet-mode galaxies will be essential for turning this qualitative agreement into quantitative constraints on where, when, and how radio jets deposit energy into cool halo gas.

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## Appendix

### A.1. Continuum Subtraction of DESI Quasar Spectra and Detailed Stacking Procedure

We describe the details of continuum subtraction of our quasar sight-line spectra from DESI, their stacking analyses, and the determination of the noise baseline shown in Figure 2. First, we search for H $\alpha$  line emission (rest wavelength  $\lambda_0 = 6562.8$  Å) at the redshift of the foreground radio galaxy by shifting each background-quasar spectrum into the foreground rest frame. We extract a local window of half-width  $\Delta\lambda = 150$  Å around the target line in the foreground rest frame. Within this window, we keep only pixels with finite flux and positive inverse variance. Since the background sources are quasars themselves, their own broad or narrow emission features can fall into the same observed-frame spectral region as the foreground line of interest. We therefore mask common quasar rest-frame optical emission lines after

projecting them into the radio-galaxy rest frame. For each sight line, a background-quasar line with rest wavelength  $\lambda_{\text{QSO}}$  appears in the foreground-radio-galaxy rest frame at

$$\lambda_{\text{QSO} \rightarrow \text{RG}} = \lambda_{\text{QSO}} \frac{1 + z_{\text{QSO}}}{1 + z_{\text{RG}}}. \quad (\text{A1})$$

We mask pixels within  $\pm 900$  km s $^{-1}$  of the projected positions of primarily strong nebular lines, particularly [O II]  $\lambda 3727$ , H $\beta$ , [O III]  $\lambda 4959$ , 5007, [N II]  $\lambda 6548$ , 6583, H $\alpha$ , and [S II]  $\lambda 6717$ , 6731, whenever those projected lines fall within the local stacking window. Masked pixels are assigned an inverse-variance weight of zero ( $w_i(\lambda) = 0$ ), effectively removing them from the stacked mean calculation.

We subtract the local continuum  $f_{\text{cont},i}(\lambda)$  independently for each foreground-background pair. The continuum is modeled with a second-order polynomial in the foreground rest-frame wavelength after excluding the emission-line region  $|\lambda_{\text{rest}} - \lambda_0| < 50$  Å. To ensure a robust continuum fit, we require at least five unmasked continuum pixels in the local window  $|\lambda - \lambda_0| \in [50, 150]$  Å. In rare cases ( $< 1\%$  of the sample) where quasar-line masking removes almost all the pixels such that fewer than five valid continuum pixels remain, we omit the emission-line mask for that spectrum and apply a simple median baseline subtraction instead. The continuum-subtracted spectrum  $f_{\text{cs},i}(\lambda)$  is then

$$f_{\text{cs},i}(\lambda) = f_i(\lambda) - f_{\text{cont},i}(\lambda). \quad (\text{A2})$$

After continuum subtraction, each spectrum is interpolated onto a common rest-frame wavelength grid. The grid spacing is inferred from the median pixel spacing of the first spectrum with valid wavelength coverage in the target-line window. For each pixel in the common grid, the inverse-variance weight ( $w_i(\lambda)$ ) is obtained by interpolating the original variance array and using

$$w_i(\lambda) = \frac{1}{\sigma_i^2(\lambda)}. \quad (\text{A3})$$

The fiducial stacked spectrum is the inverse-variance-weighted mean:

$$\langle f_\lambda(\lambda) \rangle = \frac{\sum_i w_i(\lambda) f_{\text{cs},i}(\lambda)}{\sum_i w_i(\lambda)}. \quad (\text{A4})$$

We require each retained object to have at least five finite pixels in the full stacking window. For the fiducial H $\alpha$  stacks, we additionally require at least five finite pixels within  $\pm 50$  Å of the target line and at least five contributing spectra per wavelength pixel. Pixels failing the latter criterion are set to NaN. These cuts prevent noisy spectra and sparsely sampled wavelength regions from driving the result.

We measure the integrated H $\alpha$  flux by summing the continuum-subtracted stacked spectrum over a fixed velocity window centered on  $\lambda_{\text{H}\alpha} = 6562.8$  Å. We adopt  $|\Delta v| < 500$  km s $^{-1}$ , corresponding to  $\Delta\lambda = \lambda_{\text{H}\alpha} \Delta v / c \simeq 10.9$  Å, to avoid including the contribution of [N II] in our measurements. The integrated flux is therefore

$$F_{\text{H}\alpha} = \int_{\lambda_{\text{H}\alpha} - \Delta\lambda}^{\lambda_{\text{H}\alpha} + \Delta\lambda} [y(\lambda) - y_{\text{base}}] d\lambda,$$

where  $y(\lambda)$  is the stacked flux density in units of  $10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ , and  $y_{\text{base}}$  is the residual baseline estimated from adjacent line-free sidebands.

### A.2. Noise Estimation and Control Stacks

We estimate the statistical uncertainty in two ways. First, for each stack we compute the empirical dispersion of the individual continuum-subtracted spectra contributing to each wavelength pixel. The standard error on the stacked spectrum is

$$\sigma_{\text{stack}}(\lambda) = \frac{\text{std}[f_{\text{cs},i}(\lambda)]}{\sqrt{N_{\text{contrib}}(\lambda)}}, \quad (\text{A5})$$

where  $N_{\text{contrib}}(\lambda)$  is the number of spectra with finite continuum-subtracted flux at that pixel. This uncertainty captures object-to-object scatter and wavelength-dependent variations in the number of contributing spectra.

Second, we construct blank-region noise stacks centered on randomly selected rest-frame wavelengths where no foreground  $\text{H}\alpha$  or any other emission lines are expected. We use the same background-quasar spectra, foreground redshifts, wavelength window, masking, continuum fitting, and inverse-variance stacking procedure to keep the entire analysis method consistent. We construct several blank stacks centered at 6800, 5500, and 4000  $\text{\AA}$  with the same  $\pm 150 \text{ \AA}$  window used during  $\text{H}\alpha$  stacking. The blank stacks serve as a noise baseline for the  $\text{H}\alpha$  measurement, as shown in Figure 2. Since these are processed through the identical continuum-subtraction, quasar-line-masking, bad-pixel-cleaning, interpolation, and analysis steps, they capture residual systematics in the most robust way possible. Hence, in the main analysis, we evaluate whether the  $\text{H}\alpha$  stacks show excess flux relative to this noise baseline.

### A.3. A Simulated $\text{H}\alpha$ View of Jet-mode Feedback from the SIMBA Simulation

To complement the observed results with a physical picture of the cool circumgalactic gas around a radio-jet host, we construct a mock  $\text{H}\alpha$  surface-brightness map of a representative galaxy with a jet-mode AGN chosen from the SIMBA cosmological hydrodynamic simulation (R. Davé et al. 2019). We use SIMBA’s high-resolution  $25 h^{-1} \text{ Mpc}$  volume, with  $2 \times 512^3$  resolution elements, at  $z = 0$ . The galaxy is selected from the jet-active sample of T. Yang et al. (2024). We follow that work for the jet-mode selection criteria and for the definition of the jet axis. The selected central galaxy has host-galaxy properties matched with our sample, with  $\log(M_*/M_\odot) = 10.6$ ,  $\log(M_{\text{BH}}/M_\odot) = 7.6$ ,  $f_{\text{Edd}} \simeq 5 \times 10^{-3}$ , and  $R_{200c} = 208 \text{ kpc}$ . For each gas resolution element, we assign an  $\text{H}\alpha$  volume emissivity:

$$\varepsilon_{\text{H}\alpha,i} = \varepsilon_{\text{H}\alpha}(n_{\text{H},i}, T_i, Z_i), \quad (\text{A6})$$

from a CLOUDY v23.01 (M. Chatzikos et al. 2023) photoionization-plus-recombination grid computed under the F. Haardt & P. Madau (2012) ultraviolet background. We integrate the emissivity along the line of sight with YT (M. J. Turk et al. 2011) to obtain the intrinsic  $\text{H}\alpha$  intensity:

$$I_{\text{H}\alpha}(\mathbf{X}) = \int \varepsilon_{\text{H}\alpha} d\ell, \quad (\text{A7})$$

where  $\mathbf{X}$  is the projected sky position. Assuming isotropic emission, the intrinsic, rest-frame surface brightness is

$$\text{SB}_{\text{H}\alpha}(\mathbf{X}) = \frac{I_{\text{H}\alpha}(\mathbf{X})}{4\pi} \left( \frac{1 \text{ sr}}{4.255 \times 10^{10} \text{ arcsec}^2} \right), \quad (\text{A8})$$

in units of  $\text{erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$ . The galaxy is viewed edge-on to the jet, with an integration depth of  $\pm R_{200c}$ . To isolate the diffuse CGM, we measure the area-averaged (stacked)  $\text{H}\alpha$  surface brightness within  $R_\perp < R_{200c}$  after masking the disk emission and removing the contribution from three compact star-forming clumps, which may not be associated with the main galaxy. The remaining emission is measured in three azimuthal bins from the projected jet axis:  $\varphi < 20^\circ$ ,  $20^\circ < \varphi < 40^\circ$ , and  $\varphi > 40^\circ$ , matching the angular bins used for the observed stacks.

In this representative galaxy with an active jet-mode AGN, the diffuse  $\text{H}\alpha$  surface brightness is clearly anisotropic. Figure A1 shows that the brightest  $\text{H}\alpha$ -emitting structures are preferentially located near the projected jet axis. The area-averaged surface brightness exhibits the largest mean surface brightness value close to the jet axis in the  $\varphi < 20^\circ$  angular bin and declines with increasing angle from the jet toward the disk plane, with  $\text{SB} \simeq 2.5, 2.2$ , and  $1.6 \times 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$  in the three azimuthal bins, respectively (Figure A1, middle panel). The trend is qualitatively consistent with our observed stacks of  $\text{H}\alpha$  from the DESI spectra, where the detected  $\text{H}\alpha$  signal is strongest for sight lines closest to the projected radio axis. Interestingly, the surface-brightness distribution per pixel, shown in the right panel, is broad and highly skewed for every angular bin. This indicates that the  $\text{H}\alpha$ -emitting gas clouds associated with the jet are not produced by a smooth, uniformly filling halo. The mean values are possibly driven by a small number of bright, dense, and highly ionized clumps embedded within a more diffuse, low-surface-brightness CGM component. This is consistent with our observations, and explains why we measure a  $>5\sigma$  detection in mean  $\text{H}\alpha$  stacks along the radio axis, where some sight lines intersect these bright clumps. However, the azimuthally averaged signal and median-like statistics remain weak or undetected because the emitting gas has a low covering fraction. Note, however, that the amplitudes or the absolute values of the  $\text{H}\alpha$  surface brightness are lower by approximately 3 orders of magnitude compared to our observational data. This discrepancy indicates that photoionization by the metagalactic background alone is far too feeble to power the observed emission, and implies a substantial energetic boost driven by the impact of the radio source. The simulation therefore supports a multiphase picture in which radio jets propagate through an extended, clumpy cool CGM reservoir, similar to the broadly distributed Mg II-absorbing clouds observed in our DESI sight lines. Mg II absorption traces the presence of this cool gas over a wide range of azimuthal angles, whereas  $\text{H}\alpha$  emission identifies the subset of clouds whose density, pressure, or ionization state has been enhanced by the jet or cocoon. Although this single SIMBA galaxy is an example rather than a one-to-one detailed model comparison to our sample, it demonstrates that jet-mode feedback can produce the qualitative signature inferred from the observations. Future comparisons with larger samples of simulated jet-mode galaxies, matched in stellar mass, radio power, halo mass, viewing angle, and jet age, will be essential for turning this qualitative agreement into quantitative constraints on how radio jets deposit energy into cool circumgalactic gas.

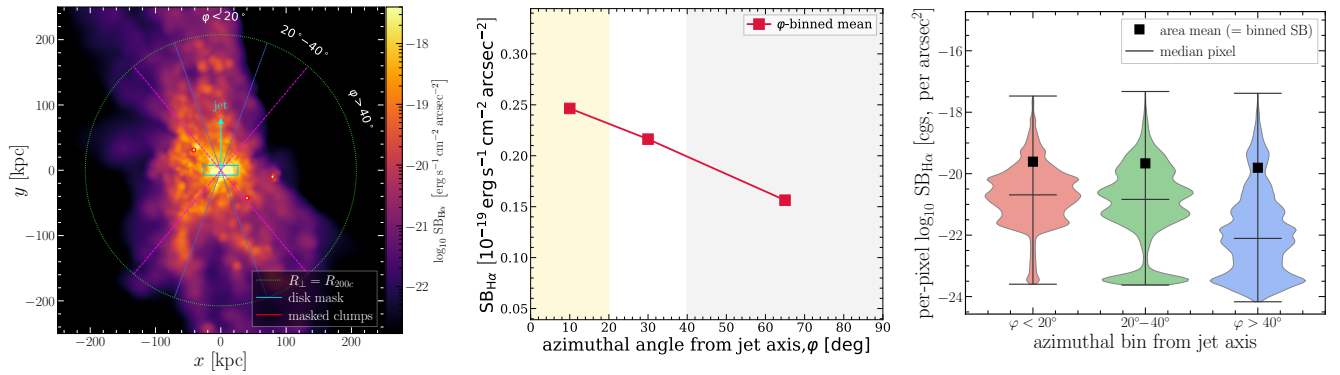


**Figure A1.** Intrinsic H $\alpha$  surface-brightness diagnostics of a jet-mode galaxy (g54 in m25n512) from the SIMBA simulation, viewed edge-on to the jet. Left: H $\alpha$  surface-brightness map over a  $\pm 250$  kpc field. The cyan arrow marks the projected jet axis, the green dotted circle marks the  $R_{\perp} = R_{200c}$  aperture, the blue rectangle marks the masked edge-on disk, and the red circles mark masked compact star-forming clumps. The blue and magenta radial lines show the three azimuthal bins measured from the jet axis:  $\varphi < 20^\circ$ ,  $20^\circ < \varphi < 40^\circ$ , and  $\varphi > 40^\circ$ . Middle: stacked H $\alpha$  surface brightness as a function of azimuthal angle  $\varphi$ . Red squares show the mean surface brightness in the three coarse azimuthal bins, matching the angular bins used for the observed H $\alpha$  stacks. Right: per-pixel  $\log_{10}$  H $\alpha$  surface-brightness distributions in the same three azimuthal bins. Black squares show the area-averaged surface brightness, and horizontal black lines show the median pixel value. The means lie above the medians, indicating that the azimuthally binned signal is dominated by a relatively small number of bright pixels.

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