



Origin of the Double-peaked Narrow Emission Lines in the Optical Spectra of X-shaped Radio Galaxies

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Abstract

We investigate X-shaped radio galaxies (XRGs) with optical double-peaked narrow emission lines (DPNELs) as potential hosts of dual or binary supermassive black holes (SMBHs). Using available optical spectra from the Sloan Digital Sky Survey and the Dark Energy Spectroscopy Instrument survey, we identify 55 DPNEL sources among a sample of 187 XRGs. We find that the occurrence of [O III] DPNELs in XRGs is $\sim 30\%$, which is substantially higher than the $\sim 1\%$ observed in the general galaxy population. Using optical (involving [O III] $\lambda 5007$, H α , H β , [N II] $\lambda 6584$, and [S II] $\lambda \lambda 6716, 6731$) and mid-infrared diagnostic diagrams, we found that both components are predominantly powered by active galactic nuclei (AGNs), implying a $\sim 95\%$ probability of hosting dual-AGN systems. In comparison, a stellar-mass-, color-, and redshift-matched control sample of non-XRG DPNEL galaxies shows a lower dual-AGN fraction, which depends strongly on radio luminosity, rising from 25% in radio-undetected galaxies to 54% in radio-detected galaxies, and reaching 95% in radio-bright XRGs and FR II radio galaxies. Interestingly, more than 30% of DPNEL XRGs have companion galaxies, supporting a merger-driven origin for these systems. Finally, we analyze parsec-scale radio structure in seven XRGs using Very Long Baseline Array (VLBA) observations at 1.4, 4.3, and 7.6 GHz, resolving the core in only one source. Nevertheless, flat radio spectral indices, AGN-like emission-line properties, and radio–optical VLBA–Gaia positional offsets found in five cases together support the interpretation that XRGs are strong dual/binary-AGN candidates.

Unified Astronomy Thesaurus concepts: Galaxies (573); Active galaxies (17); Active galactic nuclei (16); Radio jets (1347); Supermassive black holes (1663); Radio galaxies (1343)

Materials only available in the online version of record: machine-readable table

1. Introduction

In the hierarchical model of galaxy evolution, mergers are thought to play a dominant role in the final evolutionary stages (S. D. M. White & M. J. Rees 1978; G. Kauffmann & M. Haehnelt 2000). In the course of a merger, the central supermassive black holes (SMBHs) from each progenitor galaxy may form a close pair within the remnant galaxy (e.g., S. Komossa 2006). If both merging galaxies are gas-rich, substantial amounts of gas are funneled into their central regions, simultaneously triggering black hole accretion and initiating a central starburst (L. Hernquist 1989; P. F. Hopkins et al. 2006a; J. M. Comerford et al. 2015). This stage,

characterized by two SMBHs actively accreting within the same galaxy at kiloparsec-scale separations, is known as the *dual-active-galactic-nucleus* (dual-AGN) phase.

As the merger progresses, dynamical friction causes the SMBHs to lose energy, bringing them from kiloparsec- to parsec-scale separations (M. C. Begelman et al. 1980). Under favorable conditions, the two black holes enter a gravitationally bound orbital configuration (M. Volonteri et al. 2003), leading to the *binary* AGN phase. Eventually, gravitational-wave emission dominates their energy loss, culminating in coalescence—an event detectable by future space-based gravitational-wave observatories such as the Laser Interferometer Space Antenna (LISA; P. Amaro-Seoane et al. 2017).

Detecting dual and binary AGNs is the key to understanding the coevolution of SMBHs, the fueling of AGNs driven by galaxy mergers, and the formation of gravitational-wave sources (see A. De Rosa et al. 2019 and references therein). Cosmological and merger simulations suggest that the occurrence of dual AGNs correlates with the galaxy merger

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rate, which peaks around cosmic noon ($z \sim 1-3$), where the corresponding dual-AGN fraction is $\leq 6\%$ (C. Puerto-Sánchez et al. 2025). Further simulations indicate that for a sample of major and minor mergers hosting dual AGNs the fraction is 20%–30% and 1%–10%, respectively (P. R. Capelo et al. 2017). Despite these theoretical expectations, dual AGNs remain quite rare from an observational perspective (K. Rubinur et al. 2017; Y.-W. Zhang et al. 2021), conceivably due to challenges such as dust obscuration, AGN duty cycle, short lifetimes of the dual-AGN phase, and limitations imposed by the required resolution of microarcseconds. In the recent Big Multi-AGN Catalog (Big MAC; R. W. Pfeifle et al. 2025), a total of 156 confirmed dual-AGN systems have been identified using techniques including optical spectroscopy, radio imaging, and mid-infrared (MIR) imaging; a further 4180 dual-AGN candidates have been cataloged from the literature. In contrast, due to the requirement for parsec-scale resolution, only one confirmed binary AGN has been established (see below) (C. Rodríguez et al. 2006), while approximately 1368 candidates are listed in Big MAC. Since direct detection methods such as high-resolution imaging in the X-ray (M. Hou et al. 2019), optical (M. Imanishi & Y. Saito 2014; X. Liu et al. 2018; A. Bhattacharya et al. 2023), and radio bands (K. Rubinur et al. 2019; E. Schwartzman et al. 2024) and integral field spectroscopy (IFS; M. Perna et al. 2023; M. Scialpi et al. 2024) have a limited potential for this purpose, indirect methods like double-peaked emission lines (L. Blecha et al. 2013; A. Doan et al. 2020), periodicities in optical and radio light curves (E. Bon et al. 2012; M. J. Graham et al. 2015; S. O’Neill et al. 2022), and cross-symmetric (X, S, or Z) radio sources (X.-G. Zhang et al. 2007; P. Kharb et al. 2017; X. Yang et al. 2022) have been employed to short-list dual-AGN candidates.

In spectroscopic surveys using relatively large fibers (e.g., the 3''-diameter fibers used in the Sloan Digital Sky Survey (SDSS)), light from dual AGNs gets integrated/aggregated if the two nuclei are encompassed within the fiber. In that situation, a sufficiently high resolution optical spectrum may reveal “double-peaked” narrow emission lines (DPNELs), each peak corresponding to the narrow-line region (NLR) of one member of the AGN pair. In the past decades, this method has resulted in spectroscopic selection of hundreds of dual-AGN candidates (J.-M. Wang et al. 2009; X. Liu et al. 2010; K. L. Smith et al. 2010; R. C. McGurk et al. 2015). However, such double-peaked emission lines could also arise from other processes, such as biconical outflows of warm gas, bulk rotation of the NLR gas, and jet–cloud interactions (F. Müller-Sánchez et al. 2015; R. Nevin et al. 2016; K. Rubinur et al. 2019). In order to further investigate the origin of DPNELs, follow-up observations including high spatial resolution imaging combined with spatially resolved spectroscopy are required. In such efforts, only 5% of the known DPNEL galaxies at $z \leq 0.15$ have been followed up with subarcsecond spatial resolution imaging in optical and NIR bands (H. Fu et al. 2011; J. Shanguan et al. 2016). Among them, only about a sixth of such systems having two photometric counterparts within 3'' (less than 10 kpc) have been confirmed with spatially resolved spectroscopy (see P. Severgnini et al. 2021, and references therein). Interestingly, out of the Big MAC sample of double-peak AGNs, one parsec-scale binary SMBH, namely J0402+379 (C. Rodríguez et al. 2006), has robustly been confirmed through the detection of a

pair of compact, variable, flat-spectrum AGNs in multi-frequency Very Long Baseline Array (VLBA) observations (R. W. Pfeifle et al. 2025, and references therein). All this underscores the potential of DPNEL galaxies as the hosts of a dual/binary BH inside the galactic core.

In addition, X-shaped radio morphologies of jets/lobes have long been linked to the presence of binary SMBHs (e.g., M. C. Begelman et al. 1980), such that gravitational interaction between the two SMBHs can induce jet precession or, ultimately, even jet reorientation (spin-flip; J. Dennett-Thorpe et al. 2002; D. Merritt & R. D. Ekers 2002; H. Rottmann 2002; A. Babul et al. 2013; A. Misra et al. 2023; A. Misra et al. 2025) in the aftermath of the SMBH coalescence (C. Zier & P. L. Biermann 2001; H. Rottmann 2002). For instance, in a multifrequency Very Large Array (VLA) observation of X-shaped radio galaxy (XRG) J0725+5835, X. Yang et al. (2022) found a double radio core with nonthermal radio emission exhibiting the signature of jet reorientation in 5 GHz high-resolution European VLBI Network observations. We also note that several other physical mechanisms, such as diversion of the synchrotron plasma streaming backward from the terminal hot spots in the two primary lobes, or jet–shell interaction, have also been invoked to explain the formation of XRGs (see reviews by Gopal-Krishna et al. 2012; G. Giri et al. 2024, and references therein). D. Merritt & R. D. Ekers (2002) have suggested that many Z- or S-shaped radio sources are associated with binary SMBHs approaching coalescence, whereas at least some of the X-shaped radio sources showing off-axis, oppositely directed radio protrusions may represent merged SMBH systems following the gravitational radiation stage (see also C. Zier & P. L. Biermann 2001; H. Rottmann 2002). In such a merger event, the active SMBH’s spin angular momentum axis would flip, and the reenergized jets would normally go off in a significantly changed direction. Thus, binary SMBHs, being the progenitors of the coalesced SMBHs, could eventually be successfully used to constrain the SMBH merger rate and the related physics. On the other hand, wing formation, a marker of X-shaped radio morphology, could even begin during the pre-coalescence stage, due to the interaction of the jet pair with the circumgalactic medium of the host elliptical galaxy, which has been set in organized rotation by the inspiraling of the secondary SMBH (hosted by a smaller galaxy) toward the primary SMBH (Gopal-Krishna et al. 2003). From all these considerations, it becomes important to try to find and investigate SMBH binaries, their rarity notwithstanding.

In this article, we examine the scenario of XRGs hosting dual/binary SMBHs, as suggested by two key indirect indicators: the XRG morphology and DPNELs, while discounting, for the moment, the aforementioned alternative possibilities for the origin of DPNELs. Simultaneously, we also probe the role of radio power output of the AGNs in this context. Some related results based on our very long baseline interferometry (VLBI) of four XRGs are also presented. This paper is structured as follows: Section 2 describes the observations and sample selection. This is followed by the analysis in Section 3 and our results and discussion in Section 4. The conclusions of this study are summarized in Section 5. Throughout we have assumed a flat Universe with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

Table 1
Samples of XRG Candidates from the Literature

Source	Sample /Overlap	Final Sample	Survey
1. C. C. Cheung (2007)	100/0	100	1.4 GHz VLA ^a
2. D. D. Proctor (2011)	156/21	135	1.4 GHz VLA ^a
3. X. Yang et al. (2019)	290/25 ^b	265	1.4 GHz VLA ^a
4. S. Bera et al. (2020)	161/21	140	1.4 GHz VLA ^a
5. D. Patra et al. (2025)	123/0	123	144 MHz LOFAR ^c
Total	830	763	

Notes.

^a R. H. Becker et al. (1995).

^b Includes 106 strong and 184 probable candidates.

^c T. W. Shimwell et al. (2022).

2. Observations and Sample Selection

To probe the possible binary black hole scenario for the formation of XRGs, we compiled a list of 763 XRGs from the literature. The sources were selected from several published works, including C. C. Cheung (2007), D. D. Proctor (2011), X. Yang et al. (2019), and S. Bera et al. (2020), primarily drawn from the images obtained in the 1.4 GHz VLA FIRST survey (R. H. Becker et al. 1995). A summary of the sample, including the catalogs used, the sample sizes (after accounting for any common sources among the catalogs), and details of the final XRG sample, is presented in columns (2) and (3) of Table 1.

In particular, sample 3 (X. Yang et al. 2019) contains 290 XRGs, comprising 106 classified as “strong” candidates and 184 classified as “probable” candidates. Both strong and probable candidates have been included in our sample. Additionally, we have included the 123 new XRGs from D. Patra et al. (2025), picked out of the LOFAR Two-meter Sky Survey DR2 (T. W. Shimwell et al. 2022), resulting in the final sample of 763 XRGs (see Table 1).

2.1. Optical: Spectral

We first searched for the optical spectra in the SDSS DR18 (A. Almeida et al. 2023) and the Dark Energy Spectroscopy Instrument (DESI) Data Release 1 (DESI Collaboration et al. 2026). For 487 of the 763 XRGs, spectra could be found, and these span a redshift range $0.0054 \leq z \leq 4.25$. We then primarily used the prominent [O III] $\lambda 5007$ nebular emission line to designate a source as a DPNEL galaxy. To characterize the double-peak nature, we estimated the equivalent width of the [O III] $\lambda 5007$ emission line and selected a subset of 275 sources for which the [O III] $\lambda 5007$ equivalent width is $\geq 3 \text{ \AA}$ (R. Cid Fernandes et al. 2010; S. J. Penny et al. 2015; D. Koziel-Wierzbowska et al. 2017; S. Zhou et al. 2025) (see Section 3). Finally, in order to be able to determine the AGN fraction among the selected DPNEL sources, based on the locations of individual sources in the Baldwin, Phillips, & Terlevich (BPT; J. A. Baldwin et al. 1981) emission-line diagnostic map, a prerequisite was that the [N II] $\lambda 6548$, 6584 and H α emission lines are covered within the SDSS and DESI spectral wavelength ranges of 3600–10400 $\text{\AA}$ and 3600–9800 $\text{\AA}$, respectively. These requirements imposed together limited our XRG samples to $z \leq 0.58$ and $z \leq 0.49$, respectively. Following the aforementioned selection criteria, a total of 187 XRGs became available to us for emission-line fitting.

2.2. VLBA Observations

To address whether the galaxies exhibiting the X-shaped morphology and double-peaked [O III] $\lambda 5007$ nebular emission line harbor binary SMBHs, we have carried out VLBA observations on a small set of four XRGs that exhibit a prominent double-peaked [O III] $\lambda 5007$ nebular emission line. Among the four proposed XRGs from the sample of 187 sources, 3C 223.1 and J1430+5217 were selected from the XRG catalogs of C. C. Cheung (2007), while TXS 1244+200 was selected from X. Yang et al. (2019). In addition, we observed a radio galaxy, J2315+1027 (D. Patra et al. 2025), with a hint of a radio spur as a possible XRG with double-peaked emission lines.

The VLBA 1.5 GHz (*L*-band) data for these four double-peaked XRGs were acquired using either nine (BJ095A and BJ095D) or 10 (BJ095B and BJ095C) antennas of the VLBA in phase-referencing mode, between 2019 March 8 and June 3 (Proposal ID: BJ095; PI: R. Joshi). The observations were conducted with an antenna recording rate of 2 Gbps, using two 128 MHz basebands in both left and right circular polarizations, yielding a total recording bandwidth of 512 MHz. The calibrators 3C 286, OQ 208, 3C 48, and 3C 84 were used as fringe finders and bandpass calibrators. The following combos of target – calibrator were used as phase-referencing observations: TXS 1244+200 – J1248+2022, J2315+1027 – J2310+1055, 3C 223.1 – J0934+3926, and J1437+5112 – J1430+5217. A standard “nodding” phase-referencing strategy was employed, consisting of 4 minutes on the target source followed by 1 minute on the phase calibrator. The observation information can be found in Table 2.

The observational data from each station were then transferred to the VLBA correlation center in Socorro (New Mexico, USA) for correlation at the Distributed FX (DiFX) correlator (A. T. Deller et al. 2011) with 2 s integration time. Then, we used the AIPS (Astronomical Image Processing System) software from the US National Radio Astronomy Observatory (NRAO; E. W. Greisen 2003) to perform data calibration following the standard calibration procedure.¹³

The amplitude scale was established using station-specific system temperature measurements and gain curves. We accounted for Earth orientation parameters (EOPs) using the US Naval Observatory database and corrected for ionospheric dispersive delays using Global Positioning System (GPS)-derived total electron content (TEC) maps.¹⁴ Additional corrections for atmospheric opacity and parallactic angle variations were applied using the auxiliary metadata provided with the datasets. Instrumental delays and bandpass responses were calibrated using observations of fringe-finder calibrators within each session. Visibility phases were determined via phase referencing; specifically, we performed a global fringe-fitting search on the phase-reference calibrator, incorporating its structural model to solve for residual phase delays. These solutions were then interpolated and applied to the target source. The fully calibrated visibilities were exported to Difmap (M. C. Shepherd 1997) for imaging and model fitting. Due to the moderate flux density of the target source, self-calibration was not implemented.

¹³ See Appendix C of the AIPS Cookbook in <http://www.aips.nrao.edu/cook.html>.

¹⁴ <https://cdsis.nasa.gov>

Table 2
The VLBA Observations

Code	Date	Target: XRG	Phase Calibrator	ToS	Telescopes ^a
(1)	(YYYY/MM/DD)	(J2000)	(J2000)	(h)	
(1)	(2)	(3)	(4)	(5)	(6)
bj095a	2019/04/27	TXS 1244+200	J1248+2022	7.2	BR,FD,HN,KP,LA,MK,NL,OV,PT
bj095b	2019/03/08	J2315+1027	J2310+1055	3.6	BR,FD,HN,KP,LA,MK,NL,OV,PT,SC
bj095c	2019/03/13	3C 223.1	J0934+3926	3.6	BR,FD,HN,KP,LA,MK,NL,OV,PT,SC
bj095d	2019/03/22	J1430+5217	J1437+5112	3.6	BR,FD,HN,LA,MK,NL,OV,PT,SC

Note. Column (1): observation code of VLBA sessions. Column (2): observation date. Column (3): the target of the observation session. Column (4): phase calibrator of the phase-referencing session. Column (5): time on the target source of the session. Column (6): telescopes participating in the VLBA observation.

^a VLBA telescopes participating in the observations: BR (Brewster), FD (Fort Davis), HN (Hancock), KP (Kitt Peak), LA (Los Alamos), MK (Maunakea), NL (North Liberty), OV (Owens Valley), PT (Pie Town), SC (Saint Croix).

3. Analysis

In this section, we model the spectra to characterize the double-peak [O III] $\lambda 5007$ emission line. At first, we dereddened the SDSS spectra by applying the galactic dust maps with a Milky Way extinction curve from E. L. Fitzpatrick (1999). We employed the publicly available spectral fitting code PyQSOFit (H. Guo et al. 2018; W. Ren et al. 2024) only for stellar continuum fitting, which uses two independent sets of eigenspectra—pure galaxy and pure quasar—to decompose the spectrum into host galaxy and quasar continuum. The quasar continuum is modeled by a combination of power law and [Fe II] blend, whereas the Balmer continuum due to the underlying stellar population is modeled with the penalized pixel-fitting (pPXF) routine (M. Cappellari 2023) within PyQSOFit. In brief, the pPXF masks the emission lines and models the spectrum using simple stellar population templates from MILES (A. Vazdekis et al. 2010), which cover a broad metallicity range (M/H from -2.32 to $+0.22$) and age ranging between 63 Myr and 17 Gyr.

In order to constrain the double-peak nature of prominent emission lines such as H β , [O III] $\lambda\lambda 4959, 5007, H\alpha$, [N II] $\lambda\lambda 6548, 6584$, and [S II] $\lambda\lambda 6716, 6731$ in the XRG spectra, we followed the emission-line classification scheme from J.-Q. Ge et al. (2012). Given that the [O III] $\lambda 5007$ is a prominent nebular emission line and an excellent tracer of the extent and kinematics of diffuse ionized gas, we used it as a template for model-fitting all other narrow emission lines of interest, i.e., H β , H α , [N II], and [S II].

We modeled the [O III] $\lambda 5007$ emission line using single- and double-component narrow Gaussian profiles, with typical narrow-line widths of $\lesssim 500 \text{ km s}^{-1}$. We introduced an additional underlying broad component of width $\gtrsim 2000 \text{ km s}^{-1}$, where required, primarily originating in the broad-line region. The fitting has been performed using the nonlinear optimization routine LMFIT (M. Newville et al. 2024). Following J.-Q. Ge et al. (2012) and D. Maschmann et al. (2020), a source is classified as double-peaked in [O III] $\lambda 5007$ only when the following criteria are satisfied:

1. The ratio of amplitudes of the two [O III] Gaussian components is between 1/2.5 and 2.5. This would more likely ensure a clear identification of two peaks and avoid the false positives due to a weak outflow/inflow component.
2. Both peaks are well separated by at least 3 times the spectral resolution offered by the SDSS (i.e., $\sim 210 \text{ km s}^{-1}$) and DESI (i.e., $\sim 120 \text{ km s}^{-1}$).

3. The F-test (R. Lupton 1993, Chap. 12.1) demonstrates that incorporating the double-peaked profile, as the case may be, yields a significantly better fit compared to the single-peaked model, with a significance level of 5%. We further verified this by ensuring a lower Bayesian information criterion (BIC) value (G. Schwarz 1978; A. R. Liddle 2007) for the double-peaked profile as compared to the single-peaked one.

An underlying broad component was required to model 27 XRGs. Based on the properties of the [O III] $\lambda 5007$ emission line, we classified the sources into four categories: (1) single peak, (2) single peak with a broad underlying component, (3) double peak, and (4) double peak with a broad underlying component. Among the 187 XRGs subjected to [O III] $\lambda 5007$ line fitting, 55 sources were part of third and fourth classification and hence identified as exhibiting double-peaked [O III] $\lambda 5007$ emission-line profiles.

The best-fitting [O III] $\lambda 5007$ kinematic model for double-peaked sources was subsequently used as a template to fit other prominent narrow emission lines, namely H β , [O III] $\lambda 4959$, [N II] $\lambda\lambda 6548, 6584, H\alpha$, and [S II] $\lambda\lambda 6716, 6731$. For these lines, the widths and velocity offsets of the two-fitted Gaussian components were tied to those of the corresponding [O III] $\lambda\lambda 4959, 5007$ components. The flux ratios of [O III] $\lambda 5007$ /[O III] $\lambda 4959$ and [N II] $\lambda 6584$ /[N II] $\lambda 6548$ were fixed at 3.0 and 2.96, respectively (D. E. Osterbrock & G. J. Ferland 2006). The width of the broad component was allowed to vary freely for all emission lines in order to achieve a $\sim 20\%$ improvement in χ^2 wherever necessary. Figure 1 presents representative examples of the emission-line decomposition for DPNEL XRGs, together with their optical host-galaxy images and radio morphologies.

4. Results and Discussion

4.1. Occurrence of Dual-AGN Candidates in XRGs

To estimate the fraction of dual-AGN candidates within DPNEL XRGs, we used the BPT diagnostic diagrams, which provide an empirical classification using various emission-line ratios, in order to effectively differentiate between photoionization produced by the harder AGN spectrum (i.e., a larger fraction of higher-energy photons) and that produced by hot stars (J. A. Baldwin et al. 1981). In Figure 2, we show the BPT diagram based on [N II] $\lambda 6584/H\alpha$ versus [O III] $\lambda 5007/H\beta$ and [S II] $\lambda\lambda 6716, 6731/H\alpha$ versus [O III] $\lambda 5007/H\beta$ line ratios. The extreme starburst line for pure stellar photoionization models by G. Kauffmann et al. (2003) is shown as a solid

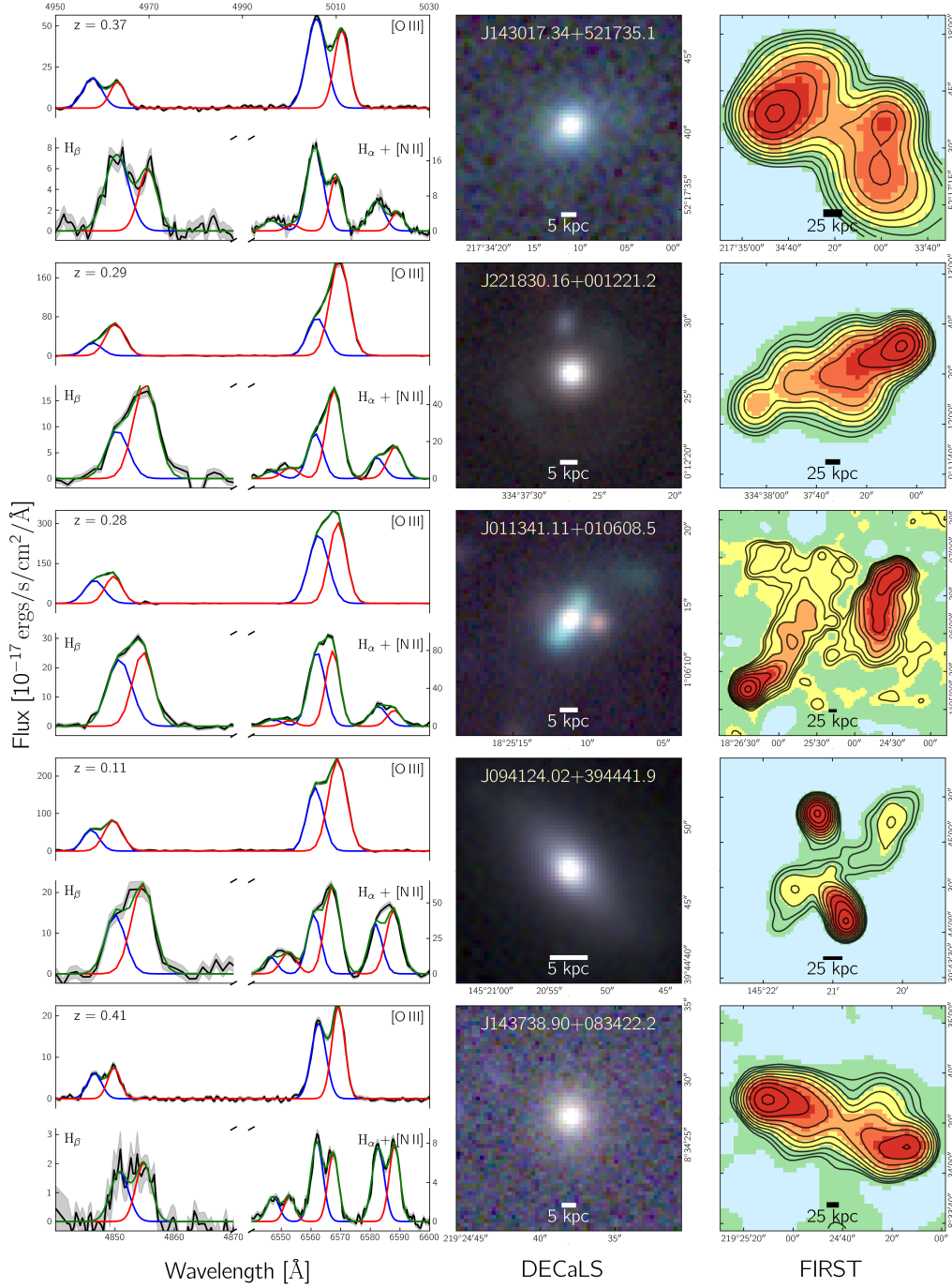


Figure 1. Left: double-peak emission-line profiles for [O III] $\lambda\lambda 4959, 5007$, H β , H α , and [N II] $\lambda\lambda 6548, 6584$ for five XRGs in the sample. The observed spectra (black) were fitted with Gaussian components, where the blue and red curves represent the blue- and redward components, respectively. Middle: color-composite (grz) optical images from DECaLS showing the host galaxy morphology. Right: radio continuum contours from the VLA FIRST 1.44 GHz, highlighting the extended radio wings. The 5 kpc (optical) and 25 kpc (radio) scales represent the physical size of the galaxy at the redshift.

line, whereas the modified model for dividing the pure star-forming galaxies from AGNs and H II composite sources by L. J. Kewley et al. (2001) is shown as a dashed line. We note that, for three of our sources, the H α spectral line region either is corrupted or lies near the edge of the spectral range covered, reducing the sample to 52 XRGs available for BPT analysis. We detected all the nebular emission lines available, i.e., H α , H β , [N II] $\lambda 6548$, at the $\geq 3\sigma$ level only for 16 XRGs. Additionally, using the upper or lower limits on the line ratios, we could reliably place 21 XRGs in the BPT diagram,

yielding a total of 37 out of 52 DPNEL XRGs. The line ratios for the blue and red components are shown as stars and circles, respectively, whereas the upper limits are marked as arrows (see Figure 2). We exclude the remaining 15 sources with nondetection of all the lines required to estimate the line ratios.

It is important to note that 33 out of 37 XRGs ($\sim 90\%$) present in the [N II] BPT diagram reside within the locus where the emission lines are primarily excited by the AGN activity. These estimates of fractions include the possibility that the individual data points for which only upper/lower

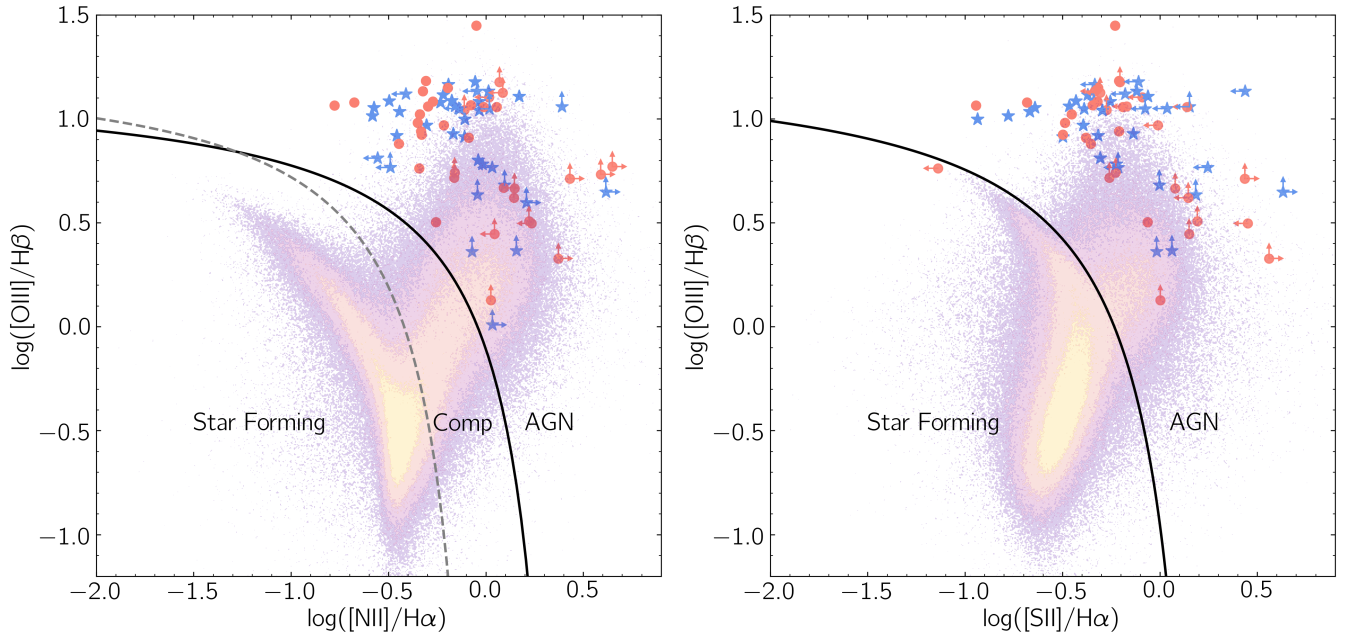


Figure 2. Left panel: the [N II] BPT diagnostic map for the double-peaked XRGs. The line ratios for the blue and red emission-line components are shown as circles and stars, respectively. The upper and lower limits are marked with an arrow. The dashed and solid lines demarcate the AGNs from star-forming galaxies based on the BPT classification from G. Kauffmann et al. (2003) and L. J. Kewley et al. (2006), respectively. The region between the two lines is demarcated as Comp, which stands for composite, indicating photoionization from both star-forming regions and AGNs. Right: same as the left panel, but for the [S II] BPT diagnostic. The colored shaded region in both panels depicts the BPT density map from the SDSS DR8 value-added catalog (H. Aihara et al. 2011).

limits are available can accordingly move across the respective diagrams. Similarly, in the [S II] BPT diagram, available for 48 out of 52 XRGs, we detect 13 galaxies where all emission lines are present at $\geq 3\sigma$. An additional 21 sources can be reliably placed in the BPT diagram based on the upper and lower limits, while the remaining 14 sources with multiple emission lines below 3σ are discarded from classification. This shows that $\sim 85\%$ (29/34) of these XRGs lie within the AGN domain. Taking both the spectral line diagnostics into account, we find that 35 out of 37 XRGs ($\sim 95\%$) exhibit double-peaked components that fall within the AGN locus of the BPT diagram, thus indicating that the line-emitting gas in both kinematic components is predominantly ionized by an AGN. Such an interpretation is consistent with spectroscopic studies of large radio sources, which show that their optical emission-line ratios are primarily governed by AGN photoionization rather than shock-induced ionization (P. N. Best et al. 2000; E. Moy & B. Rocca-Volmerange 2002).

Here it is interesting to recall that for the general galaxy population the fraction of galaxies hosting DPNELs is found to be merely $\sim 1\%$, and only $\sim 30\%$ of these are cases where both line components are classified as AGNs, hence dual-AGN candidates (J.-Q. Ge et al. 2012; D. Maschmann et al. 2020). In contrast, for the XRGs, we find the fraction of DPNELs to be at least 30% (55/187), and moreover, $\sim 95\%$ of them are found to be of dual-AGN type. To draw reliable conclusions on the higher percentages (or not) of dual AGNs in DPNEL XRGs, we design a control sample of double-peaked galaxies from J.-Q. Ge et al. (2012), closely matched in key physical properties. For each double-peaked XRG in our sample, we searched for a minimum of approximately two unique galaxies that are not picked again, closely matched in a stellar mass range of $\Delta \log(M_*) = \pm 0.5$ dex, a redshift of $\Delta z = \pm 0.2$, and a rest-frame color difference of $\Delta(g-r) = \pm 0.3$. We identified at least two control galaxies

from the SDSS catalog for the 34 DPNEL XRGs. Interestingly, albeit matched in mass and color, only 15/68 ($\sim 22\%$) of the members of the DPNEL galaxy population are classified as dual-AGN candidates based on BPT analysis, compared to the high fraction of $\sim 95\%$ in the XRGs. This immediately begs the question about the origin of the huge jump in the dual-AGN candidate fraction from $\sim 0.3\%$ for the general galaxy population to $>30\%$ found here for XRGs. Is this two-order-of-magnitude jump linked to the XRG morphology, or, more generally, to the difference in radio luminosity? To investigate this, we now extend the present analysis to encompass classical double radio sources of Fanaroff–Riley type II (FR II; B. L. Fanaroff & J. M. Riley 1974).

4.2. Occurrence of Dual-AGN Candidates at Different Morphologies

The above analysis has already provided the occurrence rates of dual-AGN candidates among the general galaxy population and for the XRG population. Given the prevalence of overwhelming dual-AGN candidate signatures in DPNEL XRGs, it is worth exploring the AGN fraction across different radio morphologies, including DPNEL FR II radio galaxies, whose radio powers can be comparable to or even exceed those of XRGs. For this, we employ the FR II radio source catalog from B.-Q. Lao et al. (2024), comprising 45,241 FR II galaxies. It spans a wide range of luminosities $2.63 \times 10^{22} \leq L_{\text{rad}}^{1.4\text{GHz}} \leq 6.76 \times 10^{29} \text{ W Hz}^{-1}$ and redshift $0.0 \leq z \leq 5.01$. We further searched for the optical spectra in SDSS and DESI datasets, following the selection criteria outlined in Section 2.1, resulting in 199 sources with an [O III] $\lambda 5007$ emission-line equivalent width of $\geq 3 \text{ \AA}$. By employing the multiple emission-line modeling, explained in Section 3, we found 21 ($\sim 10\%$) FR II sources to have double-peaked emission lines. For 16 of these sources with the corresponding line ratios

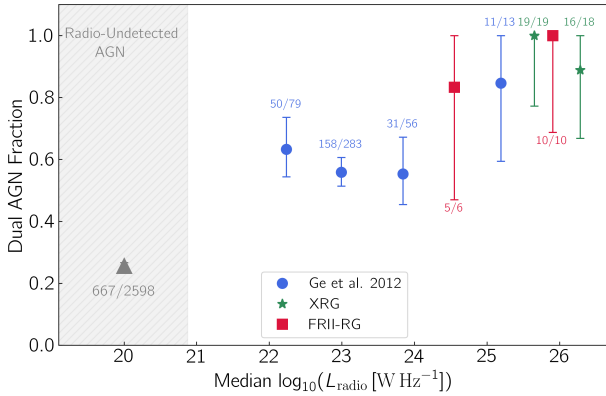


Figure 3. The radio luminosity dependence of dual-AGN fraction in double-peaked emission-line galaxies based on BPT diagnostics. The radio-undetected and radio-detected DPNEL galaxies from J.-Q. Ge et al. (2012) are shown as triangles and circles, respectively. The errors correspond to the 1σ confidence level and are computed using the standard Poisson statistics (N. Gehrels 1986). The higher fraction of dual AGNs in both XRGs (stars) and FR II radio galaxies (squares) underscores the radio dependence.

determined within the above-specified limits, the BPT line diagnostic classified all but one as dual-AGN candidates, yielding a $\sim 94\%$ dual-AGN candidate fraction in FR II radio galaxies. We note that the DPNEL XRGs and FR II galaxy samples share similar characteristics, spanning similar radio luminosities in the range of $2.5 \times 10^{23} \leq L_{\text{rad}}^{1.4\text{GHz}} \leq 7.64 \times 10^{26} \text{ W Hz}^{-1}$ with median luminosities of $L_{\text{rad}}^{1.4\text{GHz}} = 1.2 \times 10^{26} \text{ W Hz}^{-1}$ and $0.5 \times 10^{26} \text{ W Hz}^{-1}$, respectively. In addition, both samples have similar average stellar mass of $\log(M_*/M_\odot) = 10.9 \pm 0.3$ and 11.1 ± 0.3 , respectively. The high dual-AGN fractions observed in both FR II and XRG populations indicate that the occurrence of dual AGNs may not be primarily driven by radio morphology and could instead be associated with radio luminosity.

4.3. Occurrence of Dual-AGN Candidates at Different Radio Luminosities

In order to examine the radio luminosity dependence of the dual-AGN fraction in DPNEL galaxies, we matched the 3030 DPNEL galaxies from J.-Q. Ge et al. (2012) with the 1.4 GHz FIRST catalog (R. H. Becker et al. 1995), resulting in a subsample of 431 radio-detected DPNEL galaxies. In Figure 3, we plot the dual-AGN fractions for radio-detected DPNEL galaxies, which include both the XRGs and FR II sources. It is evident that the dual-AGN fraction strongly correlates with the radio luminosity. While, among the radio-detected DPNEL galaxies, overall $\sim 58\%$ are classified as dual AGNs, the fraction crosses 94% for the XRGs and FR II radio galaxies. Interestingly, the dual-AGN fraction drops to 25% in the case of radio-undetected DPNEL galaxies (see Figure 3). Further, to make a robust comparison, we select a control sample of DPNEL galaxies with radio luminosities outside the range of our parent sample of 55 DPNEL XRGs, matched on all other physical properties (redshift, color, and stellar mass), and filter 369 sources out of the 431 radio-detected DPNEL galaxies. It is worth noting that 199/369 ($\sim 54\%$) of them have been classified as dual AGNs in the BPT diagnostics. This reiterates the higher detection fraction of DPNELs in radio-bright galaxies.

4.4. XRGs with and without Double-peak Emission-line Profiles

Here we compare the physical properties of XRGs with and without DPNELs, along with FR I- and FR II-type radio galaxies. Recall that the mass of the central SMBHs is found to be tightly correlated with the stellar mass of the bulge of the host galaxy (J. Kormendy & L. C. Ho 2013). We determine the SMBH mass based on the galaxy stellar mass versus black hole mass scaling relation from J. E. Greene et al. (2020; see below) for the parent sample of 187 XRGs, including 55 XRGs with DPNELs. For 141 XRGs with SDSS spectra, we obtained the multiband optical (u, g, r, i, z) photometry data from the SDSS DR16 survey (R. Ahumada et al. 2020), complemented by MIR (3.4 and 4.6 μm ; W1 and W2 bands) data from the unWISE catalog (E. F. Schlafly et al. 2019). Next, we model the spectral energy distribution (SED) of 141 XRGs using the piXedfit routine, which uses a Bayesian technique to estimate the underlying parameters (Abdurro'uf et al. 2021). For this, we used the model with a wide parameter space, including double power-law star formation history (A. C. Carnall et al. 2018), initial mass function (G. Chabrier 2003), dust attenuation ($0 \leq A_v \leq 3$) (S. Charlot & S. M. Fall 2000), and dust emission (B. T. Draine & A. Li 2007). Further, to account for the contribution from the active black hole, we added the emission from the dust torus heated by the AGN (M. Nenkova et al. 2008a, 2008b). In addition, for 46 DESI XRGs, we use the stellar mass estimates provided by the DESI value-added catalog (M. Siudek et al. 2024), where the SED modeling is performed with a similar parameter space using DESI g, r, z and W1 and W2 bands. For all but three XRGs with the best fit SED, the stellar masses are in the range of $9.83 \leq \log(M_*/M_\odot) \leq 12.46$, with a median value of 10.86. Using the $M_{\text{BH}} - M_*$ scaling relation by J. E. Greene et al. (2020, see their Table 9), we estimate the black hole mass as

$$\log M_{\text{BH}} = (7.89 \pm 0.09) + (1.33 \pm 0.12) \log \left(\frac{M_*}{3 \times 10^{10} M_\odot} \right) + (0.65 \pm 0.05). \quad (1)$$

The estimated black hole masses for the XRGs with DPNELs are presented in column (2) of Table 3. In the top panel of Figure 4, we compare the SMBH mass distributions of XRGs with and without DPNELs.

The estimated black hole masses for XRGs with DPNELs range from $7.71 \leq \log M_{\text{BH}}[M_\odot] \leq 11.05$, with a median of $\langle \log M_{\text{BH}}[M_\odot] \rangle = 9.04 \pm 0.11$. The XRGs without DPNELs exhibit a similar average black hole mass of $\langle \log M_{\text{BH}}[M_\odot] \rangle = 9.08 \pm 0.12$, ranging from $7.67 \leq \log M_{\text{BH}}[M_\odot] \leq 11.18$. A Kolmogorov-Smirnov (KS) test yields a null probability value of $p_{\text{null}} = 0.58$, supporting the null hypothesis that the SMBH mass distributions of XRGs with and without DPNELs are drawn from the same parent population. This suggests that XRGs with and without double-peaked emission lines have undergone a similar evolutionary phase. All the DPNEL XRGs showing two active AGNs in a BPT diagram indicate that the XRGs are likely formed through mergers. Thus, the similar black hole masses in XRGs with and without DPNELs can be reconciled under a common evolutionary phase. A larger sample of double-peak XRGs from next-generation optical and radio surveys should help us further understand this.

Table 3
Summary of Model Parameters for the [O III] $\lambda 5007$ Nebular Emission in Sources with Double-peaked [O III] Profiles

SDSS Name	z	$\log M_{\text{BH}}$	$\log R_{\text{NLR},1}$	$\log R_{\text{NLR},2}$	$F_{[\text{O III}] 5008}$		$\sigma_{[\text{O III}]}$		$z_{1,2}$		T
					(erg s ⁻¹ cm ⁻²)		(km s ⁻¹)				
					(n1)	(n2)	(σ_1)	(σ_2)	(z_1)	(z_2)	
J2000 (1)	(2)	($M_{\odot}$) (3)	(pc) (4)	(pc) (5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
J011341.11+010608.5	0.2809	8.6 ± 0.10	3.9 ± 0.03	3.9 ± 0.03	1178.96 ± 11.88	1191.05 ± 11.42	126.3 ± 2.4	108.2 ± 1.6	0.2805	0.2813	1
J014316.72-011901.0	0.5193	8.6 ± 0.10	3.8 ± 0.03	3.7 ± 0.03	35.87 ± 4.76	31.37 ± 4.74	132.0 ± 30.5	183.6 ± 79.3	0.5189	0.5199	0
J014719.28-085119.6	0.4547	7.9 ± 0.12	3.7 ± 0.03	3.9 ± 0.03	342.99 ± 2.92	128.8 ± 4.2	115.1 ± 2.2	189.2 ± 2.8	0.4532	0.4550	1
J021635.79+024400.9	0.1451	9.3 ± 0.13	3.3 ± 0.04	3.5 ± 0.04	37.81 ± 6.31	139.85 ± 13.45	≥42.0	≤198.0	0.1445	0.1450	0
J065514.73+540857.2	0.2380	9.5 ± 0.13	3.9 ± 0.03	4.1 ± 0.04	809.42 ± 10.68	4493.35 ± 14.73	68.8 ± 2.5	190.1 ± 1.3	0.2375	0.2382	1
J072423.22+362032.2	0.2970	9.0 ± 0.11	3.5 ± 0.03	3.6 ± 0.03	44.45 ± 4.78	68.03 ± 5.81	92.9 ± 16.6	109.7 ± 16.4	0.2965	0.2974	1
J072645.57+510407.0	0.3390	10.2 ± 0.18	4.0 ± 0.03	3.9 ± 0.03	1011.98 ± 8.05	464.51 ± 6.36	190.2 ± 7.7	92.3 ± 4.4	0.3385	0.3393	1
J074125.22+333319.9	0.3640	8.7 ± 0.10	4.2 ± 0.05	4.1 ± 0.04	1202.66 ± 9.48	124.57 ± 5.02	194.7 ± 5.0	72.8 ± 8.3	0.3634	0.3652	1
J074845.10+232445.8	0.1901	9.0 ± 0.11	3.5 ± 0.03	3.4 ± 0.04	93.91 ± 6.13	46.02 ± 5.24	85.0 ± 12.8	61.6 ± 11.6	0.1899	0.1905	1
J081841.57+150833.5	0.3304	8.9 ± 0.11	3.9 ± 0.03	3.6 ± 0.03	425.70 ± 6.68	87.32 ± 4.82	≤170.3	≤96.3	0.3299	0.3310	1

Notes. Column (1) lists the SDSS source name, and column (2) gives the spectroscopic redshift. Column (3) provides the black hole mass ($\log M_{\text{BH}}$), while columns (4) and (5) give the logarithm of the NLR radii ($\log R_{\text{NLR},1}$ and $\log R_{\text{NLR},2}$), determined using Equation (2) (in Section 4.4.4). Columns (6) and (7) list the fluxes of the two [O III] components, columns (8) and (9) give their corresponding velocity dispersions, and columns (10) and (11) present the relative redshifts (z_1 , z_2) of the individual components. Column (12), denoted as T , represents the BPT classification: $T = 1$ indicates that both components are classified as AGNs, $T = 0$ corresponds to cases where multiple robust lines are not detected and classification is not possible, and $T = 2$ denotes all other cases such as AGN + star-forming (SF) or SF + SF systems. The table includes the first 10 out of 55 XRGs exhibiting DPNELs.

(This table is available in its entirety in machine-readable form in the [online article](#).)

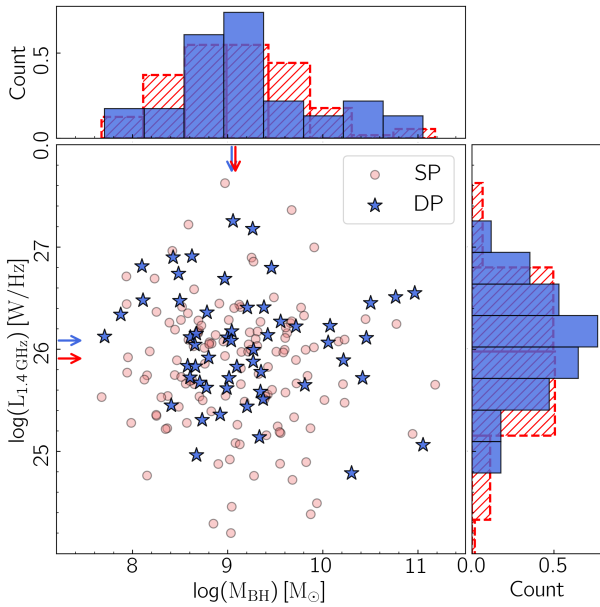


Figure 4. The black hole mass vs. 1.4 GHz radio luminosity for the single-peaked (circles) and double-peaked (stars) XRGs. The double-peaked XRGs ($\langle \log M_{\text{BH}} \rangle = 9.04 \pm 0.11 M_{\odot}$) host very similar black hole masses as compared to single-peaked XRGs ($\langle \log M_{\text{BH}} \rangle = 9.08 \pm 0.12 M_{\odot}$). The radio luminosities of double-peaked XRGs ($\langle \log L_{1.4 \text{ GHz}} \rangle = 26.08 \pm 0.01 \text{ W Hz}^{-1}$) are also similar to those of single-peaked XRGs ($\langle \log L_{1.4 \text{ GHz}} \rangle = 25.91 \pm 0.02 \text{ W Hz}^{-1}$).

In previous efforts to constrain the formation scenarios of XRGs, involving either the merger of two SMBHs leading to the jet reorientation or the presence of two active SMBHs, M. Mezcuca et al. (2011) analyzed 29 XRGs from a sample of 100 sources selected by C. C. Cheung (2007). They found that the XRGs are hosted in elliptical galaxies, likely formed through hierarchical mergers (see also G. Efstathiou & J. Silk 1983; C. S. Frenk et al. 1988; P. F. Hopkins et al. 2006b). Additionally, the average black hole mass in XRGs ($\langle \log M_{\text{BH}} [M_{\odot}] \rangle = 8.32$) was found to be 1.94 times higher than that of a limited control sample of 20 radio galaxies, including 10 each of non-FR II ellipticals and FR II radio galaxies, with similar redshifts and comparable optical and radio luminosities, i.e., $\langle \log M_{\text{BH}} [M_{\odot}] \rangle = 8.04$. However, using a larger set of 106 XRGs, R. Joshi et al. (2019) have found the average black hole mass of XRGs ($\langle \log M_{\text{BH}} [M_{\odot}] \rangle = 8.81$) to be slightly lower than that of a control sample of 388 FR II radio sources hosting powerful jets ($\langle \log M_{\text{BH}} \rangle = 9.07 [M_{\odot}]$). The relatively lower black hole mass of XRGs compared to their more powerful FR II counterparts suggests that even minor mergers can cause jet reorientation, contributing to their distinctive X-shaped radio morphology.

In Figure 4, we compare the black hole mass versus the radio luminosity of XRGs with (stars) and without (circles) double peaks. For this, we estimate the radio flux using the NRAO VLA Sky Survey (NVSS) at 1.4 GHz, which uses a much larger beam of $45''$ in diameter. The NVSS, with good UV coverage, is known to be sensitive to diffuse radio emission extending up to at least $10'$ (J. J. Condon et al. 1998). Assuming a spectral index of $\alpha \sim -0.7$, we estimate the radio luminosity for all of the XRGs. The radio luminosities for XRGs with DPNELs are in the range of $24.79 \leq \log L_{1.4 \text{ GHz}} [\text{W/Hz}] \leq 27.25$, with an average of $\langle \log L_{1.4 \text{ GHz}} \rangle = 26.08 \text{ W Hz}^{-1}$. We also see that XRGs

without DPNELs show similar radio luminosities, in the range of $21.04 \leq \log L_{1.4 \text{ GHz}} [\text{W/Hz}] \leq 27.62$, with an average luminosity of $\langle \log L_{1.4 \text{ GHz}} \rangle = 25.91 \text{ W Hz}^{-1}$, hinting at a common powering source. This aligns with the findings of X. Yang et al. (2019) that XRGs have intermediate radio luminosity between FR II and FRI radio sources. However, we report no correlation between black hole mass and radio luminosity in our parent sample of XRGs, with a Spearman’s rank correlation coefficient of $r_s = -0.061$ and a null probability of $p_{\text{null}} = 0.41$.

Finally, we explore the MIR color properties of the double-peaked XRGs in Figure 5. The MIR diagnostic colors can be used to distinguish star-forming galaxies from AGNs even in cases where one or both of the AGNs are obscured (M. Lacy et al. 2004; D. Stern et al. 2005; R. Coziol et al. 2015). Among the 55 XRGs harboring DPNELs, we could obtain the colors of 54 XRGs using four MIR bands of the Wide-field Infrared Survey Explorer (WISE) survey (E. L. Wright et al. 2010), W1 ($3.4 \mu\text{m}$), W2 ($4.6 \mu\text{m}$), W3 ($12 \mu\text{m}$), and W4 ($22 \mu\text{m}$), in Vega magnitudes. We use three different classification schemes: (a) W1 – W2 versus W2 – W3 (T. H. Jarrett et al. 2011; S. Mateos et al. 2012; D. Stern et al. 2012; F. Herpich et al. 2016; R. J. Assef et al. 2018; R. E. Hviding et al. 2022), (b) W3 – W4 versus W2 – W3 (see Section 3.1 of R. Coziol et al. 2015), and (c) W1 – W2 versus [N II] $\lambda 6584/\text{H}\alpha$ (H. F. M. Yao et al. 2020). In W1 – W2 versus W2 – W3 WISE classifications, we find that 38/55 (69%) are ionized by AGNs following at least one criterion. Similarly, in the W3 – W4 versus W2 – W3 classification, we find that 49/54 (91%) of the sources are ionized by AGNs. Finally, W1 – W2 versus [N II] $\lambda 6584/\text{H}\alpha$ classifies 32 out of 41 (78%) with detected [N II] $\lambda 6584/\text{H}\alpha$ as candidate dual AGNs. The high fraction in these classifications is consistent with that determined from the BPT diagrams (See Section 4.1).

4.5. Parsec-scale view of XRGs

In previous studies, galaxies hosting DPNELs have been proven to be potential dual-AGN candidates, and their binary structures have been explored using high-resolution VLA observations (H. Fu et al. 2015a, 2015b; A. C. Gross et al. 2023). However, VLBA, with its very high angular resolution, probes the radio properties at parsec scales, which are crucial for studying the origins of radio emission (W. Xu et al. 2024). Notably, X. Yang et al. (2022) conduct a high-resolution 5 GHz VLBA observation of XRG J0725+5835, which has a resemblance in radio morphology to the archetypal binary AGN 0402+379 (C. Rodriguez et al. 2006). In this observation, two milliarcsecond-scale nonthermal radio cores were detected. These cores coincide with two optical counterparts with similar photometric redshifts and magnitudes, corresponding to a dual AGN. Similarly, B. Sebastian et al. (2024) have recently examined the reliability of identifying dual AGNs in a sample of six sources exhibiting both X-shaped radio morphology and DPNELs using VLBA observations and found three XRGs with two resolved central components, making them strong candidates for binary SMBHs.

In what follows, we discuss the 1.4 GHz VLBA maps from our VLBA campaign of four XRGs exhibiting double-peak emission lines (see Figure 6). We also searched for the 55 double-peaked XRGs in the “Radio Fundamental Catalogue” (L. Y. Petrov & Y. Y. Kovalev 2025), which includes all the sources observed with VLBA for absolute astrometry and

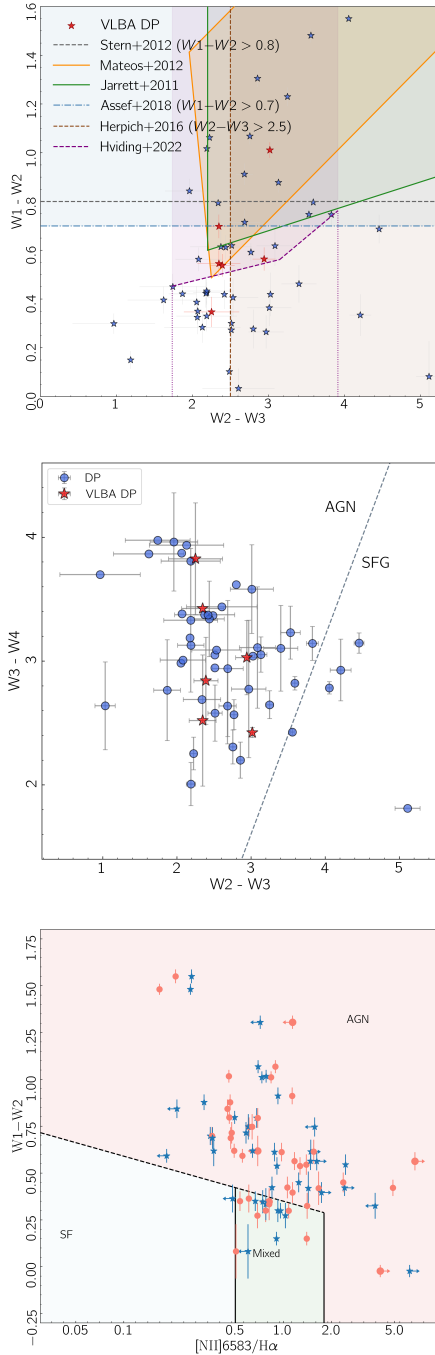


Figure 5. The MIR color diagnostic diagram for the XRGs hosting DPNELs (circles) with emphasis on the VLBA sample (stars). In the top panel, 69% of the sample is classified to host AGNs following at least one of the diagnostic criteria. In the middle panel, the dotted line (R. Coziol et al. 2015) separates the AGN locus from the star-forming region. All but five (91%) indicate AGN photoionization in agreement with the BPT diagnostic (Figure 2). In the bottom panel, the H. F. M. Yao et al. (2020) classification scheme indicates 79% of the sources to have both components classified as AGNs.

geodesy from 1980 April 11 to 2024 September 5. As a result, we identified three additional sources with VLBA maps, J1115+4314, J1134+3835, and J1604+3221, which are reproduced in Figure 7. We also found additional 4.4 and 7.6 GHz observations to supplement our 1.4 GHz observations of J1430+5217. The sample summary, including source name, date of observation, frequency, beam size, rms noise, redshift,

separation between the optical and radio cores, and in-band spectral index (or dual-band in “Spectral Index” column), is listed in Table 4.

4.5.1. J2315+1027

Among the seven XRGs with VLBA counterparts, we detect a resolved central core for only J2315+1027 in our 1.4 GHz VLBA maps (see Figure 6). At $z = 0.255$, the beam size of 10.4 milliarcseconds (mas) offers a spatial resolution of 40 pc. Interestingly, the resolved cores are seen at a separation of ~ 40 pc (see Figure 6). At parsec scales, the core is found to extend at a position angle (PA) of 61° , measured from north to east. It aligns with the primary kiloparsec-scale jet observed at a PA of 61.2° in the VLA FIRST observations. A follow-up high-frequency VLBA observation constraining the spectral index would help to verify the possibility of a binary black hole or core-jet system. Interestingly, the kiloparsec-scale active FR II jet is aligned toward the major axis of the optical host galaxy. This is in agreement with the observed tendency of active jets in XRGs to align along the major axis of their optical host galaxies (R. Joshi et al. 2019; G. Giri et al. 2026). Further, the DECaLS optical field reveals three close companion galaxies with photometric redshifts near that of the XRG, suggesting a potential merger scenario (see Figure 6).

4.5.2. 3C 223.1

3C 223.1 is known to have a kiloparsec-scale “double-boomerang” morphology. Recently, Gopal Krishna & P. Dabhade (2022) have shown that the wings anomalously exhibit a flatter radio spectrum even compared to the hot spots in the primary lobes, which supports the particle acceleration associated with the rebounding of collimated backflow of synchrotron plasma streaming through the primary lobes. Our 1.4 GHz VLBA maps provide a hint of a resolved structure at a PA of 22° , which is roughly aligned toward the active radio jets having a PA of 11° . The resolved jet structure is further supported by the 5 GHz VLBA maps by B. Sebastian et al. (2024, see their Figure 4) showing an extended parsec-scale (PA of 25°) morphology, likely indicating a core-jet structure. Furthermore, a relatively flat spectral index of $\alpha = 0.32$, derived from the 1.4 and 5 GHz VLBA maps, in conjunction with the presence of double-peaked emission lines in the AGN locus of the BPT diagram, suggests that this source is a promising candidate for follow-up observations to search for a binary AGN.

For the remaining five sources, the core is unresolved, with a typical spatial beam size resolution ranging between 8.7 and 82 pc. Based on multifrequency VLBA observations for these five sources, we estimate spectral indices ranging from 0.01 to 0.54 (see Table 4, column (9)). This suggests that if XRGs with DPNELs host binary SMBHs, their separation must be smaller than the beam size.

4.5.3. Gaia–VLBA Offsets

We may recall that the positional offset of radio–optical emission cores may signify the presence of multiple AGNs (Y.-C. Chen et al. 2023; P. Cigan et al. 2024; W. Xu et al. 2024). To test the multi-AGN hypothesis, which we have seen is hinted at by multiple indirect indicators, notably DPNELs, X-shaped morphology, and flat-spectrum core, we now compare

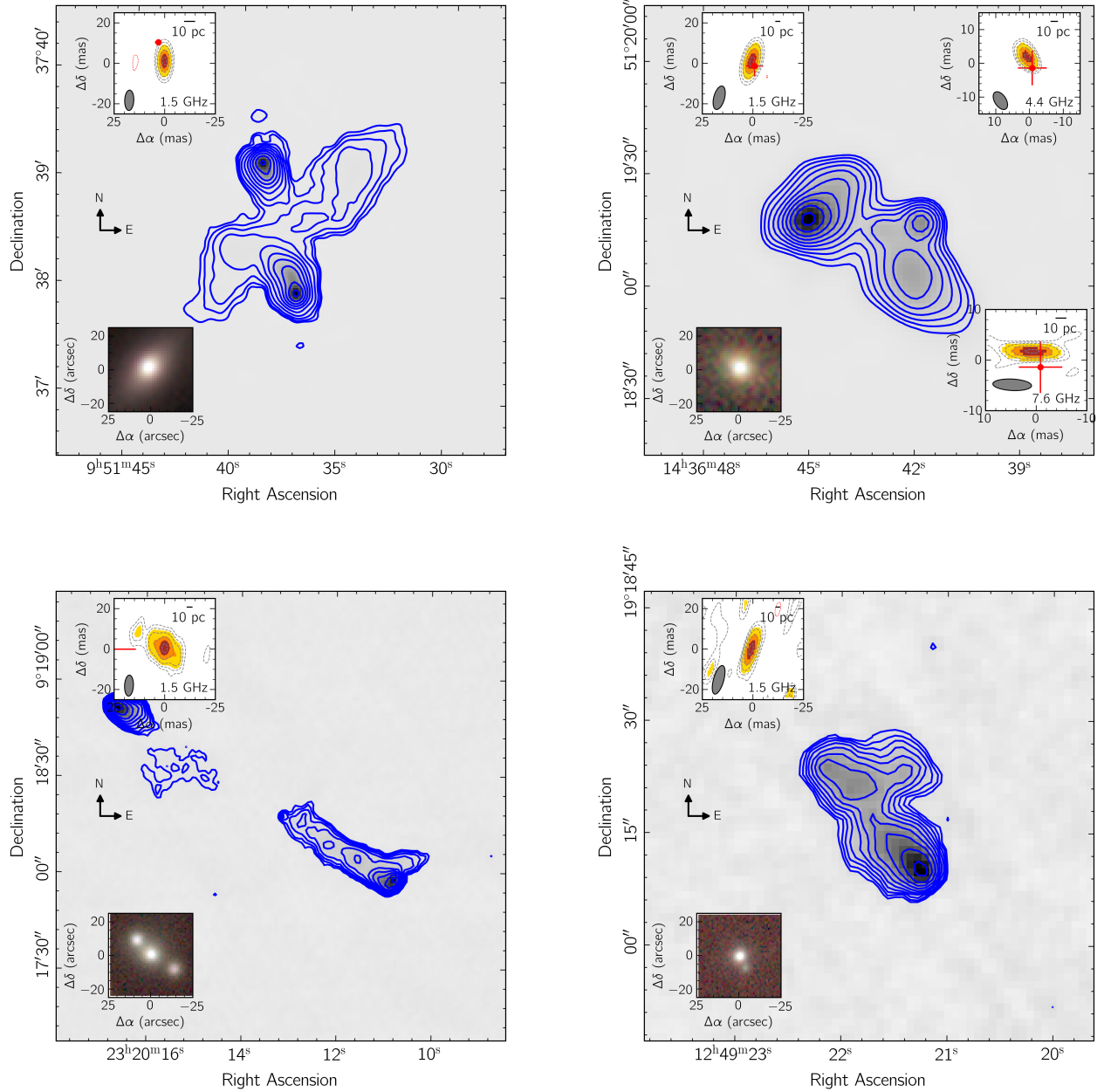


Figure 6. The extended kiloparsec-scale radio morphology for 3C 223.1 using 144 MHz LOFAR (top left) and maps from the 2.5 GHz VLASS survey (M. Lacy et al. 2020) for J1430+5217 (top right), J2315+1027 (bottom left), and TXS 1244+200 (bottom right). The insets show the parsec-scale VLBA radio core in available 1.5 GHz, 4.3 GHz, or 7.6 GHz maps and respective beam FWHM with contour levels set on $\sigma \times [0.1, 0.2, 0.3, 0.5, 1, 2, 4, 7, \dots]$ in log scale. The Gaia DR3 positions are indicated by red crosses, with their lengths representing the 1σ rms errors. The inset in the lower left corner shows a DECaLS (g, r, z) color-composite image centered on the radio host galaxy.

the spatial positions of VLBA radio maps with those from Gaia DR3 (Gaia Collaboration et al. 2023). We obtain a significant offset (between 1.5 and 33 mas) for five out of seven sources. A flat-spectrum core along with a radio–optical offset in XRGs J1430+5217, J1115+4314, and J1604+3221 makes them strong binary black hole candidates (G. Orosz & S. Frey 2013). Even though significant offsets are detected in the multifrequency observations of 3C 223.1 and J2315+1027, their spectral indices are used to confirm the possibility of dual AGNs. For the above sources, the Gaia optical counterparts are offset toward the resolved (or hint of resolved) VLBI components. Such offsets can plausibly arise from a radio-loud

core with optical emission rendered undetected (due to obscuration) and a radio-quiet secondary core dominating the emission detected by Gaia. The majority of recent Gaia–VLBI studies at milliarcsecond or submilliarcsecond level show an offset that could arise from strong optical jet emission preferentially being located either downstream or upstream of the peak of the AGNs' jet radio emission (Y. Y. Kovalev et al. 2017; A. V. Plavin et al. 2019). Therefore, other explanations, such as a single core driving both optical and radio emission with a significant separation, or a frequency-dependent core position shift due to flaring, cannot be discounted (K. V. Sokolovsky et al. 2011; A. V. Plavin et al. 2019).

Table 4
Summary of VLBA Observation Details for the Dual-AGN Candidates

Source	Obs. Date	ν_{cen} (GHz)	Beam (mas)	Separation (pc)	PA (deg)	rms (mJy)	z	Spectral Index	VLBA–Gaia offset (pc)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
3C 223.1	2019-03-13	1.55	10.10×4.34	20	-0.74	0.02	0.11	0.25	22
	2018-08-11 ^a	4.98	3.46×1.62	6.7	15.56	0.02		0.32 ^b	
J1115+4314 ^c	2016-08-14	4.34	4.73×1.89	29	37.4	0.07	0.46	0.54 ^d	74
	2016-08-14	7.62	2.90×1.07	18	39.88	0.09			
J1134+3835 ^c	2016-08-19	4.34	5.11×4.34	30	36.73	0.08	0.50	0.23	
	2016-08-19	7.62	3.05×1.30	18	6.84	0.09			
TXS 1244+200	2019-04-27	1.55	16.01×5.70	82	-15.80	0.01	0.43	0.24	
J1430+5217	2019-03-22	1.55	9.79×3.78	61	-4.70	0.02	0.37	0.00	8
	2022-05-25	4.35	5.89×3.4	30	32.8	0.10		0.19 ^e	
	2022-05-25	7.62	7.66×2.27	39	87.12	0.20			
J1604+3221 ^f	2014-01-27	4.34	4.61×2.03	27	21.40	0.09	0.45	0.01 ^g	128
	2014-01-27	7.62	2.65×1.25	15	22.007	0.10			
J2315+1027	2019-03-08	1.55	11.80×4.69	42	-4.72	0.02	0.26	0.49	137

Notes. Column (1): source name. Column (2): observation date. Column (3): central observing frequency (ν_{cen}) in GHz. Column (4): synthesized beam size in milliarcseconds (mas). Column (5): potential separation that could be resolved at the given frequency in parsecs (pc). Column (6): position angle (PA) of the separation vector in degrees. Column (7): image rms noise in mJy. Column (8): spectroscopic redshift (z). Column (9): spectral index between the indicated frequency pairs. Column (10): Gaia–VLBA positional offsets in parsec. Multiple rows per source correspond to observations at different frequencies. References and notes for individual sources are provided below the table.

^a B. Sebastian et al. (2024).

^b Nonsimultaneous spectral index between 1.55 GHz (2019-03-13) and 4.98 GHz (2018-08-11).

^c S. Bera et al. (2020).

^d Between 4.34 and 7.62 GHz on 2016-08-14.

^e Between 4.34 and 7.62 GHz on 2022-05-25.

^f D. Patra et al. (2025).

^g Between 4.34 and 7.62 GHz on 2014-01-27.

4.5.4. Role of NLRs in the Occurrence of DPNELs

We further explore the binary black hole scenario, where the DPNELs are considered to be originating from the separate NLRs of the individual SMBHs. Following X. Liu et al. (2013), we determine the size of the NLR as

$$\log\left(\frac{R_{\text{NLR}}}{\text{pc}}\right) = (0.250 \pm 0.018) \times \log\left(\frac{L_{[\text{O III}]}}{10^{42} \text{ ergs s}^{-1}}\right) + (3.746 \pm 0.028), \quad (2)$$

where $L_{[\text{O III}]}$ represents the [O III] $\lambda 5007$ luminosity, corrected for the Balmer extinction of the individual emission-line components. In the above scenario, one expects the separation of individual NLRs to be smaller than the BH separation. The size of NLR is listed in columns (6) and (7) of Table 3. The NLR size for DPNEL XRGs ranges between 1.52 and 17.74 kpc, which is significantly larger than the expected binary black hole separation of 0.1 kpc (see also C. Villforth & F. Hamann 2015). Nonetheless, considering the extended structure of the NLR along with the multiple double-peak emission lines (H β , and H α) that trace the same kinematics as [O III] $\lambda\lambda 4959, 5007$, [N II] $\lambda\lambda 6548, 6584$, and [S II] $\lambda\lambda 6716, 6731$, the observed DPNELs in the XRGs could still be associated with the binary black hole system (S. Tang & J. Grindlay 2009; D. Xu & S. Komossa 2009). It is worth reiterating that the DPNELs can also arise from alternative processes, notably complex kinematics within the NLR, such as rotating disks and biconical outflows (see Section 1).

Follow-up narrowband imaging and IFS observations would help to distinguish the various possibilities.

4.6. Double-peaked XRGs and the Role of Galaxy Merger

High-resolution hydrodynamical simulations of the NLR regions in the AGNs hosted by merging galaxies suggest the presence of DPNELs in the late stages of the merger (L. Blecha et al. 2013). Probably only a small fraction of double peaks are directly relatable to the relative motion of the SMBHs, while most originate from complex gas kinematics near the SMBH. Nevertheless, around 80% of these profiles show some influence of SMBH dynamics, manifested as shifted peaks or velocity offsets. Among the merger-induced DPNELs, approximately 10%–40% result in SMBH separations in the range of 0.1–1 kpc. Furthermore, P. R. Capelo et al. (2017) explored AGN triggering in merging systems by varying parameters such as galaxy mass ratios, orbital configurations, gas content, and black hole properties, concluding that dual AGNs are found in up to 20%–30% of major mergers and 1%–10% of minor mergers. This is further supported by A. Bhattacharya et al. (2023), where, using automated techniques, 159 dual AGNs are detected within $z \leq 0.75$ and are mainly associated with red and evolved galaxies, indicating a merger origin. In contrast, the follow-up optical long-slit spectroscopy by J. M. Comerford et al. (2018) of 95 SDSS galaxies exhibiting double-peaked narrow AGN emission lines revealed that only eight sources (<10%) possess companion galaxies with line-of-sight velocity separations below 500 km s^{−1} and projected physical separations under 30 kpc.

Given that $\sim 95\%$ of double-peaked emission-line XRGs likely host dual AGNs, and considering the galaxy overdensity

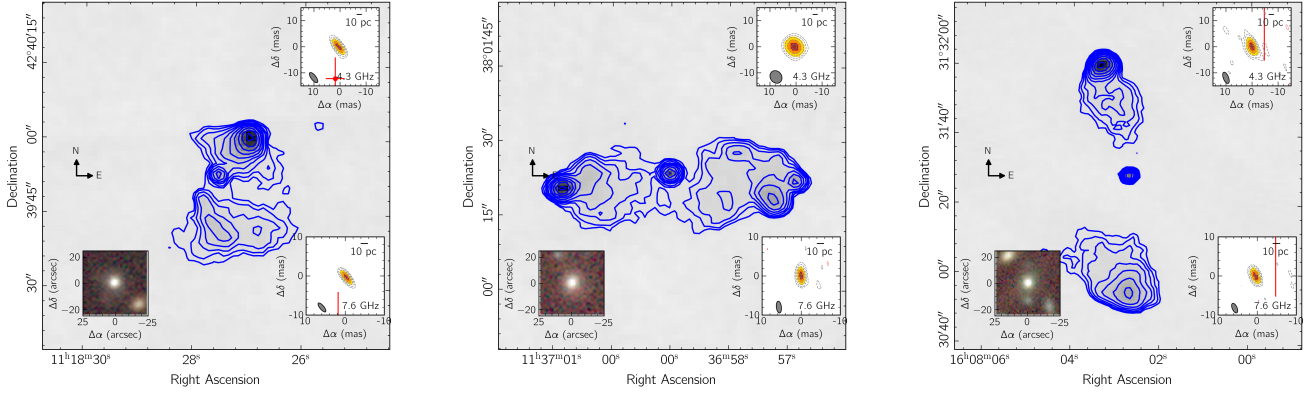


Figure 7. Same as Figure 6, but with 2.5 GHz VLASS maps showing extended kiloparsec-scale radio morphology for J1115+4314, J1134+3835, and J1604+3221 (left to right).

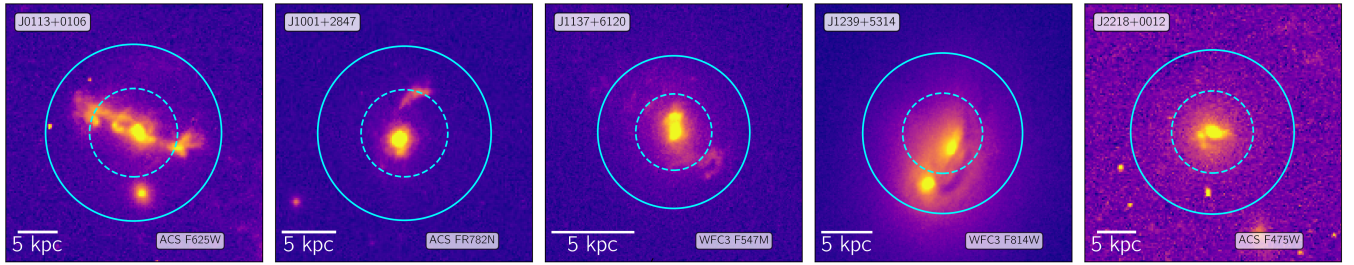


Figure 8. The high-resolution HST/WFC3 images of XRGs with DPNELs revealing signatures of galaxy mergers and distinct tidal tails, indicative of an ongoing or recent galactic merger. The SDSS fiber of $3''$ diameter (blue solid circle) and the DESI fiber of $1''.5$ diameter (blue dashed circle), encompassing the merging galaxies, capture the double-peak emission lines, suggesting the presence of a likely dual-AGN system.

with similar color in proximity to the central radio source in deep DECaLS images, we further explore the role of galaxy mergers in the formation of XRGs. To identify potential mergers, we search for galaxies located near the central radio core that have potential companion matching spectroscopic redshifts within $\Delta z = 0.003$, corresponding to a peculiar velocity of $\sim 1000 \text{ km s}^{-1}$ in small groups (S. A. Gregory & L. A. Thompson 1978; M. Girardi et al. 1993). Here we examine galaxies within a $30''$ radius, which corresponds to $\sim 150 \text{ kpc}$ at the average redshift of 0.3, well within the typical virial radius of a central galaxy hosting an AGN. In our study, we crossmatch these galaxies with DECaLS DR10 to obtain photometric redshifts derived using a random forest algorithm (R. Zhou et al. 2023), while spectroscopic redshifts are taken from the SDSS and DESI samples. For our sample of 55 DPNEL XRGs, 17 ($\sim 30\%$) exhibit at least one companion galaxy likely indicative of a merger event, whereas 2 are associated with multiple companion galaxies. The fraction of multiple galaxies rises to $\sim 45\%$ (26/58) if we consider the photo- z -selected systems within $\Delta z = 0.05$. The galaxy overdensity around XRGs is further supported by R. Joshi et al. (2019), where a higher median clustering richness (quantified by the number of SDSS galaxies with $M_r \geq -19$ located within a projected radius of 1 Mpc and a redshift interval of $\Delta z = 0.04(1+z)$ of 8.9 is found around 107 XRGs at $z < 0.4$. The excess merger fraction further suggests that the large NLR sizes estimated from the central black hole (Equation (2)) may possibly be due to the fact that empirical relations may not hold true for merger systems. Interestingly, among the total sample of the 187 XRGs, all five with DPNELs that have deep Hubble Space Telescope (HST) high-

resolution images available reveal a close companion and show strong merger signatures with tidal tails (see Figure 8). The SDSS and DESI fiber spectra integrate light from both galaxies, resulting in a double-peaked emission profile. This highlights the possible contribution of mergers, which may produce jet reorientation, leading to X-shaped morphology, and making them probable hosts for dual/binary SMBHs as well (G. Giri et al. 2026).

5. Conclusions

In this study, we performed a systematic search for dual AGNs among 187 XRGs with available SDSS and DESI spectra. Additionally, we report the parsec-scale morphology of several double-peaked XRGs using radio VLBA maps, leading to the following key findings:

1. The XRGs preferentially show a higher (30%) occurrence rate of double-peaked narrow emission lines than the rate of just $\sim 1\%$ found for the general population of galaxies. In addition, the probability of both emission-line components in the DPNEL profile exhibiting AGN nature, based on the BPT diagnostic diagram of both [N II] and [S II] lines, is three times higher in XRGs ($\sim 95\%$) than in the control sample of non-XRGs (22%). This is further corroborated by various MIR color excesses and diagnostics in XRGs, yielding an AGN fraction of 91%. This indicates a higher probability of XRGs hosting dual/binary AGNs. However, given the strong radio jets in XRGs, the excess DPNEL fraction may also arise from alternative mechanisms, including jet-ISM interactions and outflows.

2. The fraction of DPNEL galaxies hosting dual-AGN signature is found to depend strongly on the radio luminosity. This fraction increases from 25% for the radio-undetected galaxies to 54% in radio-detected galaxies. The $\sim 95\%$ likelihood of dual-AGN candidates, seen as nebular emission-line ratios induced by AGN-like photoionization in radio-bright DPNEL XRGs and FR II radio galaxies, supports the merger-driven scenario for the formation of dual/binary AGNs.
3. The radio core is resolved for one XRG, J2315+1028, in the parsec-scale VLBA maps. The resolved/extended structure reported here is collinear with the jet direction, indicating either a core-jet configuration or a dual-AGN scenario. For five of six XRGs with an unresolved VLBA core, the spectral index between 4 and 8 GHz, ranging from 0.01 to 0.54, indicates a flat spectrum for the central AGN. The milliarcsecond-scale radio–optical offset between VLBA and Gaia detections also signifies the presence of multiple cores. In conjunction with both the double-peak emission-line components exhibiting an AGN nature, radio cores with flat spectral indices, and radio–optical offsets between the VLBA and Gaia positions, these features are strongly indicative of XRGs as dual/binary AGN candidates.
4. The double-peaked XRGs harbor similarly massive black holes and have similar radio luminosities to single-peaked XRGs. We find that more than 30% of DPNEL XRGs have a spectroscopically matched companion galaxy, suggesting that mergers play a substantial role in the formation of X-shaped radio morphology.

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