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The radio emission in radio-quiet quasars: the VLBA perspective

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ABSTRACT

The origin of the radio emission in radio-quiet quasars (RQQ) is not established yet. We present new VLBA observations at 1.6 and 4.9 GHz of 10 RQQ (9 detected), which together with published earlier observations of 8 RQQ (5 detected), forms a representative sample of 18 RQQ drawn from the Palomar–Green sample of low z (< 0.5) AGN. The spectral slope of the integrated emission extends from very steep ($\alpha < -1.98$) to strongly inverted ($\alpha = +2.18$), and the slopes of 9 of the 14 objects are flat ($\alpha > -0.5$). Most objects have an unresolved flat-spectrum core, which coincides with the optical *Gaia* position. The extended emission is generally steep-spectrum, has a low brightness temperature ($< 10^7$ K), and is displaced from the optical core (the *Gaia* position) by ~ 5 –100 pc. The VLBA core flux is tightly correlated with the X-ray flux, and follows a radio to X-ray luminosity relation of $\log L_R/L_X \simeq -6$, for all objects with a black hole mass $\log M_{\text{BH}}/M_\odot < 8.5$. The flatness of the core emission implies a compact source size ($\lesssim 0.1$ pc), which likely originates from the accretion disc corona. The mas-scale extended emission is optically thin and of clumpy structure, and is likely produced by an outflow from the center. Radio observations at higher frequencies can further test the accretion disc coronal emission interpretation for the core emission in RQQ.

Key words: galaxies: active – galaxies: nuclei – quasars: general – radio continuum: galaxies.

1 INTRODUCTION

Active galactic nuclei (AGN) can be divided into radio-loud (RL) and radio-quiet (RQ) based on their radio loudness R , which is the ratio of radio 5 GHz to optical 4400 Å flux density (Kellermann et al. 1989). The majority (~ 90 per cent) of AGN are RQ ($R \leq 10$), and only a fraction (~ 10 per cent) are RL. The radio loudness can also be defined using the ratio of the 5 GHz radio luminosity to the 2–10 keV X-ray luminosity (Terashima & Wilson 2003), where RL objects have $\log R_X > -3.5$ (Panessa et al. 2007; Laor & Behar 2008). The radio emission in RL quasars (RLQ) is generally dominated by a powerful relativistic jet (Urry & Padovani 1995; Blandford, Meier & Readhead 2019). In RQ quasars (RQQ), the radio emission can be produced by a variety of emission mechanisms, from the host galaxy scales ($\sim$ kpc) down to the innermost accretion disc scales (< 0.01 pc) (see Panessa et al. 2019 for a review).

We elaborate briefly on possible radio emission mechanisms in RQQ from large to small scales, and how they can be tested based on the spectral slope α ($S_\nu \propto \nu^\alpha$) and the spatial extension of the radio emission.

1.1 Host galaxy star formation (SF)

AGN activity and enhanced SF are often related. The SF radio emission (Bell 2003) may be responsible for the bulk of the radio emission observed in RQQ (Kimball et al. 2011; Condon et al.

2013; Zakamska et al. 2016). If so, the radio emission would be predominantly optically thin synchrotron radiation ($\alpha < -0.5$), and its radio morphology would be similar to other tracers of SF (e.g. H α line and infrared emission) in the host galaxy.

1.2 An AGN-driven wind interacting with the host interstellar medium (ISM)

Wide angle winds are a common feature of AGN, and are believed to be the dominant AGN feedback mechanism on the host SF, and may eventually lead to the black hole (BH) mass versus the bulge mass relation (Magorrian et al. 1998; Laor 1998; Ho 1999; Gebhardt et al. 2000; Gültekin et al. 2009; Kormendy & Ho 2013). The interaction between the fast ($\sim$ thousands of km s $^{-1}$) wind and the surrounding ISM would generate shocks that accelerate particles to relativistic energies (e.g. Jiang et al. 2010). Relativistic particles in the shocked gas magnetic field results in a steep spectrum ($\alpha < -0.5$) optically thin synchrotron emission (Zakamska et al. 2016), likely at the host galaxy inner regions.

1.3 Thermal free–free emission

The intense ultra-violet radiation of AGN photoionizes large volumes of ambient gas, as indicated by the strength of the narrow and broad line emission in AGN. Photoionization calculations indicate that the free–free emission of this gas may be detectable in millimeter waveband, with the characteristic flat spectral slope of $\alpha = -0.1$ (Baskin & Laor 2021).

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1.4 A low-power jet

The jet mechanism is identical to the one in RL AGN, but the luminosity scales down by a factor of typically 10^3 (e.g. Falcke & Biermann 1995). In this case, RQQ may show similar phenomenology to RLQ, steep spectra in lobe dominated objects, and flat spectra in core dominated objects. The jet emission may produce a linear structure, which may extend only on sub-arcsec scales, and is possibly resolved only on mas scales.

1.5 Coronal emission

RQQ follow tightly the radio versus X-ray luminosity relation of coronally active stars (Guedel & Benz 1993) $L_R/L_X \simeq 10^{-5}$ (Laor & Behar 2008). Since the AGN X-ray emission most likely originates from hot coronal gas at the inner accretion disc, it is possible that the radio emission of RQQ is also of coronal origin (Gallimore, Baum & O’Dea 1997). As the emission originates on sub-pc scales, it will remain unresolved with the VLBA, and will be characterized by an optically thick flat/inverted spectrum. Furthermore, the jet and outflow base may physically coincide with the corona where the relativistic particles are being accelerated (Blundell & Beasley 1998; Merloni & Fabian 2002; King, Lohfink & Kara 2017).

The relatively few available studies of RQQ (e.g. Kellermann et al. 1989, 1994; Barvainis, Lonsdale & Antonucci 1996; Kukula et al. 1998; Ulvestad, Antonucci & Barvainis 2005; Leipski et al. 2006; Padovani et al. 2011; Doi et al. 2011; Zakamska et al. 2016; Silpa et al. 2020; Panessa et al. 2022b; Baldi et al. 2022; Chen et al. 2022a) generally lead to mixed results indicating that the origin of the radio emission in RQQ is still an open question. If a number of different mechanisms are indeed involved, then radio observations can be used as a powerful tool to probe the variety of emission mechanisms that are likely to occur in RQQ, unlike the situation in RLQ where the radio emission is dominated by a relativistic jet (Panessa et al. 2019).

Interesting hints are provided in Laor, Baldi & Behar (2019), based on a compilation of various archival VLA observations of 25 RQ Palomar–Green (PG) quasars, mostly with the highest resolution A configuration. This study found strong relations between the derived 5–8.5 GHz spectral slope $\alpha_{5-8.5}$ of the core emission (< 0.3 arcsec) and a number of properties: the full width at half maximum (FWHM) of the broad H β line, the Eddington ratio L/L_{Edd} , and the Fe II/H β line ratio. All $L/L_{\text{Edd}} > 0.3$ objects have steep spectra, that is $\alpha_{5-8.5} < -0.5$, and nearly all objects with $L/L_{\text{Edd}} < 0.3$ have flat spectra, that is $\alpha_{5-8.5} > -0.5$. In addition, the slopes of all objects with Fe II/H β > 0.5 are steep, and all flat slope objects have Fe II/H β < 0.4 . A possible scenario, suggested by Laor et al. (2019), for the $\alpha_{5-8.5}$ and the L/L_{Edd} correlation is that the extended optically thin emission, which dominates in high L/L_{Edd} objects, is associated with an outflow, which is more prominent at high L/L_{Edd} , such as radiation pressure driven winds. In low L/L_{Edd} objects, the extended component does not dominate the total radio emission, and only a compact optically thick component, possibly associated with coronal emission, is present.

A striking result was found in a recent follow up exploratory VLBA study (Alhosani et al. 2022), where eight of the above 25 RQ PG quasars were observed with the VLBA in the L and C bands, of which four were selected to have a very steep spectrum, $\alpha_{5-8.5} < -1$, and four were selected to have an inverted spectrum, $\alpha_{5-8.5} > 0$. They found that in three of the four flat-spectrum sources, the VLA core flux remains unresolved with the VLBA, while in three of the four steep-spectrum sources, no flux was detected (< 5 – 10 per cent of the VLA flux). This suggests a dichotomy in terms of the dominant

radio emission mechanism in RQQ: extended emission in high L/L_{Edd} RQ AGN versus only a very compact core in low L/L_{Edd} RQ AGN. This dichotomy also supports the $\alpha_{5-8.5}$ versus L/L_{Edd} correlation found in Laor et al. (2019). At low L/L_{Edd} , the compact core (i.e. the disc corona) is primarily responsible for the total radio emission, which remains unresolved on the VLBA scales. At high L/L_{Edd} , the extended emission (i.e. outflows) dominates, and it may be resolved out on the VLBA scales.

In this work, we report new VLBA observations of a representative sample of 10 bright RQQ from the PG catalogue in the L (18 cm) and C (6 cm) bands. These observations complement the exploratory VLBA study (Alhosani et al. 2022), which focused on the eight more extreme RQ PG quasars, four with the steepest and four with the flattest $\alpha_{5-8.5}$ slopes. Our sample is selected to cover a wide luminosity range ($-27 < M_V < -21$) and a broad range of H β FWHM values (~ 1000 – $10\,000$ km s $^{-1}$). In combination with the earlier exploratory VLBA observations, we aim to explore systematically the mas scale radio emission of RQQ, and address the following questions. Do objects with steep VLA slope core emission generally lack emission on the VLBA scales? In contrast, does the core emission in flat VLA slope objects remains unresolved on the VLBA scales? Do the bimodal relations between $\alpha_{5-8.5}$ and L/L_{Edd} found in the VLA data also hold on the VLBA scales? Does the radio emission switch from being compact optically thick at low L/L_{Edd} , to extended optically thin at high L/L_{Edd} ? In this work, we will focus on the origins of the AGN-driven wind, the low-power jet, and the coronal emission as possible emission mechanisms. The host galaxy SF emission is generally diffuse and resolved out on the VLBA resolutions. Free–free emission is not expected to dominate in centimeter waveband, and its expected brightness temperature is too low to be detectable with the VLBA (Baskin & Laor 2021).

The structure of this paper is as follows. Section 2 describes the sample selection, Section 3 presents the data reduction, Section 4 describes the data analysis, Section 5 presents the results, and we discuss them in Section 6. The summary is given in Section 7.

2 SAMPLE SELECTION

The sample is selected from the 71 $z < 0.5$ PG RQQ (Boroson & Green 1992), which is the most extensively studied sample of Type 1 AGN, including a complete coverage of the overall SED (Neugebauer et al. 1987; Sanders et al. 1989), radio cm-band continuum and imaging (Kellermann et al. 1989, 1994; Miller, Rawlings & Saunders 1993), optical spectroscopy (Boroson & Green 1992), optical polarimetry (Berriman et al. 1990), UV spectroscopy (Baskin & Laor 2005), and X-ray spectroscopy (Brandt, Laor & Wills 2000). This sample revealed various interesting trends, such as the Eigenvector 1 set of emission line correlations (Boroson & Green 1992), the BH–bulge mass relation in AGN (Laor 1998), and the BH mass and radio loudness relation (Laor 2000).

A critical property of the sample is that it is optically selected, and is therefore not subject to radio bias. The sample covers AGN over a wide range of intrinsic properties, from Seyfert to quasar luminosities ($L_{\text{bol}} \sim 10^{43} - 10^{46}$ erg s $^{-1}$), and with a BH mass in the range of $M_{\text{BH}} \sim 10^6 - 10^9 M_{\odot}$. The wealth of additional information available for this sample in other bands will allow to explore possible relations of the nuclear spectral slope derived here with other emission and absorption properties (e.g. Boroson & Green 1992).

Fig. 1 shows the distribution of the 71 PG RQQ in the H β FWHM versus absolute magnitude M_V plane. These two parameters can be used to determine M_{BH} and L/L_{Edd} . We divide the plane of

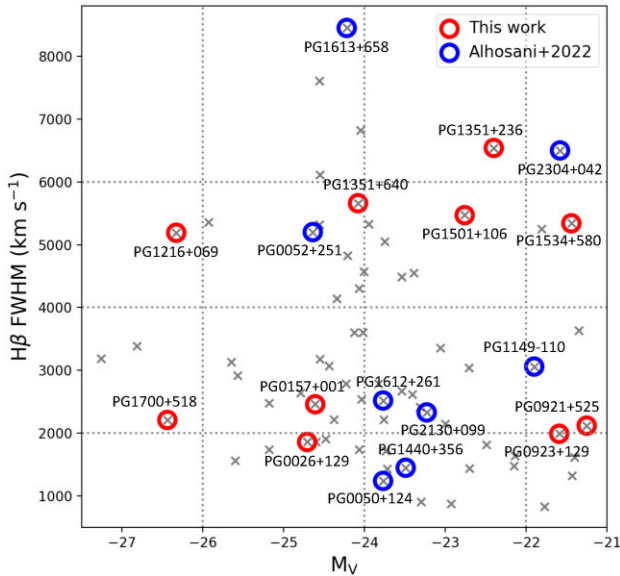


Figure 1. The distribution of the 71 PG RQQ in the $H\beta$ FWHM versus optical luminosity M_V plane. We divide this distribution into four bins along each axis (dotted lines), which forms 16 regions, of which two are empty (the upper and lower left most bins). We select the object with a relatively high 5 GHz flux in each region. This representative sample includes 14 objects. We also include in this paper the eight RQQ already observed in Alhosani et al. (2022) (marked in blue circles), of which four overlap with our sample. The two samples include a total of 18 objects, of which 10 were observed in our new VLBA program (marked in red circles). The merged sample spreads over the observable ranges of M_V and $H\beta$ FWHM, and is likely representative of optically selected RQQ.

Fig. 1 into four bins in M_V and four bins in $H\beta$ FWHM. This forms 16 regions, of which two are not populated. In each of the 14 populated bins, we select the brightest object at 5 GHz based on the VLA D configuration flux (Kellermann et al. 1989). This representative sample thus includes 14 objects, which have a wide spread in luminosity ($-27 < M_V < -21$) and $H\beta$ FWHM (~ 1000 – $10\,000\text{ km s}^{-1}$). Despite the selection criterion of a relatively high radio flux in each bin, the distribution of R values of this sample is consistent with that of the parent sample (Kellermann et al. 1989).

We merge the representative sample with the eight objects already observed with the VLBA in Alhosani et al. (2022), of which four overlap our sample. The merged sample therefore includes 18 objects. Here we report the VLBA observations and the data reduction of the 10 newly observed RQQ. The data analysis and the discussion include all 18 objects, of which 10 are from our new VLBA program and 8 are from Alhosani et al. (2022).

3 DATA REDUCTION

The observations were carried out with the VLBA in the L and C bands using the 8–10 main VLBA stations (see Table 1). The angular resolution can reach 4.3 mas in the 18 cm band and 1.4 mas in the 6 cm band. We used the digital down conversion observing system with a 2-bit sampling at a data rate of 4 Gb s^{-1} and four intermediate frequency (IF) bands with dual polarization and 128 MHz bandwidth. The IFs are centered at 1376, 1504, 1632, and 1760 MHz in the L band and at 4612, 4740, 4868, and 4996 MHz in the C band. We performed phase-referencing continuum observations. Each observation was about three hours long with scans at different frequencies interleaved, which can yield a better UV coverage. A four minutes nodding

cycle was used with two minutes on a target and one minute on a phase calibrator before and after the target. A ‘Fringe Finder’ (3C84, 3C345, 3C454.3, or 4C39.25) was observed twice when all the antennas were up. This strategy yields an integration time of about one hour on the target at each frequency.

The data were calibrated using the VLBA data calibration pipeline procedure VLBARUN¹ in the Astronomical Image Processing System (AIPS; Greisen 2003). A step-by-step usage of VLBARUN is described in Appendix C of the AIPS Cookbook.² The standard steps include first correcting the visibility for ionospheric delays and Earth Orientation Parameters, then applying amplitude corrections from digital sampling, finding the phase delays using the fringe finder and applying phase solutions. An inspection on all baselines (pairs of antennas) for radio frequency interference (RFI) was performed. Data suffered from RFI were removed using the AIPS task UVFLG. A self-calibration was applied on the calibrators. Once the calibration procedure completed, we applied the final calibration table on the target and split the data of the target using the AIPS task SPLIT.

We imaged the visibility data of the target using the AIPS task IMAGR. This task uses the CLEAN algorithm to deconvolve the ‘dirty image’ with the point spread function (PSF), to obtain the residual and the ‘clean image’. We chose natural weighting (i.e. $\text{robust} = 5$) which maximizes sensitivity at the expense of angular resolution. The source images were not self-calibrated, as an additional self-calibration does not improve the images if the signal-to-noise ratio is not too high. The final images were inspected using the AIPS task IMEAN to obtain the background noise in a source-free region. The synthesized beam size can be seen in the header of the images. The AIPS task IMFIT or JMFIT was used to model the source with a 2D Gaussian profile, to obtain the peak intensity, the integrated flux density, the source position, and the source sizes before and after deconvolution. We leave the centroid location, peak intensity, major and minor axes, and position angle, as free parameters in the Gaussian model. If the source in the C band shows two components, which are unresolved in the L band, we modelled the source with two Gaussian components in the L band.

In order to measure the spectral slope, which is less biased by the resolution in the different bands, we created tapered images via setting a UV range of 3000 – $50\,000\text{ k}\lambda$, corresponding to an angular resolution $\sim 5\text{ mas}$, in both L and C bands. The lower limit is equivalent to the minimum UV range in the C band, to recover emission on similar scales in both bands, and the upper limit is equivalent to the maximum UV range in the L band, to obtain comparable resolutions in both bands.

4 DATA ANALYSIS

We consider a 5σ level as the detection criterion, where σ is the background noise, and a 5σ upper limit on the flux density if the source is not detected. Fig. 2 presents the radio maps of the 10 RQ PG quasars observed with the VLBA at 1.6 and 4.9 GHz. The objects are generally detected in both bands, excluding PG0026+129 which is detected only at 4.9 GHz, and PG1351+236 which is not detected in either bands. Four objects (PG0921+525, PG0923+129, PG1351+640, and PG1534+580) exhibit two or three components, which are marked in Fig. 2. Fig. 3 shows an overlap of the 1.6 and 4.9 GHz images of these four objects, in order to see the alignment of different components in the two bands. Table 1 lists the VLBA

¹<http://www.aips.nrao.edu/vlbarun.shtml>

²<http://www.aips.nrao.edu/cook.html>

Table 1. The VLBA positions and their distances from the *Gaia* positions of the 14 RQ PG quasars observed with VLBA.

Name	z	Scale (pc mas ⁻¹)	Observation date	ν (GHz)	RA (hh:mm:ss)	Dec. (dd:mm:ss)	Δ (mas)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
PG0026+129	0.142	3.26	2022 Mar 06	4.9	00:29:13.7014	+13:16:03.9443	5.5
PG0157+001	0.164	3.81	2022 Mar 21	4.9	01:59:50.2543	+00:23:40.8650	25.5
PG0921+525	0.035	0.75	2022 Mar 18	4.9 C1	09:25:12.8480	+52:17:10.3871	1.9
				4.9 C2	09:25:12.8476	+52:17:10.3879	2.3
				1.6 C3	09:25:12.8469	+52:17:10.3908	9.5
				4.9 C1	09:26:03.2697	+12:44:03.7480	17.3
PG0923+129	0.029	0.62	2022 Feb 27	1.6 C2	09:26:03.2709	+12:44:03.7466	25.2
				1.6 C3	09:26:03.2685	+12:44:03.7424	19.5
				4.9	12:19:20.9314	+06:38:38.4698	5.8
PG1216+069	0.334	8.52	2022 Feb 28	—	—	—	—
PG1351+236	0.055	1.19	2022 Mar 14	—	—	—	—
PG1351+640	0.087	1.92	2022 Mar 05	4.9 C1	13:53:15.8310	+63:45:45.6844	1.9
				4.9 C2	13:53:15.8304	+63:45:45.6876	7.1
PG1501+106	0.036	0.77	2022 Mar 24	4.9	15:04:01.1937	+10:26:15.7833	3.6
PG1534+580	0.030	0.64	2022 Mar 19	4.9 C1	15:35:52.4035	+57:54:09.5187	6.2
				1.6 C2	15:35:52.4029	+57:54:09.5238	10.0
PG1700+518	0.292	7.30	2022 Apr 13	4.9	17:01:24.8266	+51:49:20.4492	1.4
PG0050+124	0.060	1.17	2020 May 05	4.8 C2	00:53:34.9337	+12:41:35.9289	5.7
				4.8 C1	00:53:34.9342	+12:41:35.9306	12.6
PG0052+251	0.155	2.71	2020 May 16	4.8	00:54:52.1182	+25:25:38.9859	1.9
PG1149–110	0.050	0.98	2020 May 31	4.8	11:52:03.5505	–11:22:24.0932	1.3
PG1612+261	0.131	2.35	2020 May 12	1.4	16:14:13.2058	+26:04:16.2230	10.2
PG2304+042	0.042	0.83	2020 May 07	4.8	23:07:02.9147	+04:32:57.1019	0.2

Notes. Columns: (1) name, (2) redshift, (3) physical scale, (4) observation date, (5) frequency, (6) right ascension of the centroid of VLBA emission determined using IMFIT, (7) declination of the centroid of VLBA emission determined using IMFIT, and (8) separation between the VLBA and the *Gaia* positions. The positions in C band are reported if the emission is detected, otherwise the positions in L band are listed.

positions of each of the components. The C band coordinates are listed if the source is detected in this band. Otherwise, the L band coordinates are listed. The distances between the VLBA and the *Gaia* positions (Gaia Collaboration et al. 2016, 2022) are also reported in Table 1. The astrometric uncertainty of the *Gaia* DR3 with respect to the optical spectroscopy is about 1–10 mas (Khamitov et al. 2023). For objects with more than one component, we identify the closest component to the *Gaia* position as the core of the AGN (labelled as C1), where the supermassive BH resides.

Table 2 lists the sizes of the synthesized beam and the source before and after deconvolution of the full resolution maps. If the deconvolved source size is smaller than half of the beam size, we consider the source as unresolved. Table 3 reports the flux densities of the full resolution maps and the tapered maps in the L and C bands. For sources with only one component, we use the peak intensity, which is the unresolved flux density in a single beam, as the core flux density, and the total flux density is the greater value between the peak intensity and the integrated flux density. For sources with more than one component, we use the peak intensity of the core component as the core flux density, and the total flux density is the sum of the total flux density of all components. If an object or a component is not detected, we use the 5σ upper limit on the flux density. The extended flux density of each source is defined as the total flux density minus the core flux density. The extended flux density is used only if it is larger than a $3\sigma_{\text{err}}$ level, where σ_{err} is the uncertainty of the extended flux density given in the error propagation. Otherwise, a $3\sigma_{\text{err}}$ upper limit on the extended flux density is used.

Table 4 lists the BH mass, M_{BH} , and the bolometric luminosity, L_{bol} , of the objects (Davis & Laor 2011; Laor et al. 2019). The Eddington ratio, L/L_{Edd} , is calculated using M_{BH} and L_{bol} , where $L_{\text{Edd}} = 1.3 \times 10^{38} (M_{\text{BH}}/M_{\odot})$. Table 4 also reports the radio to X-ray luminosity ratio, $L_{\text{R}}/L_{\text{X}}$, using both the VLBA core flux and the VLA A configuration core flux at 5 GHz. The X-ray flux at 0.2–12.0 keV

is from the *XMM-Newton* DR12 catalogue (Webb et al. 2020). If the object is not detected with the VLBA, we set an upper limit on the VLBA $L_{\text{R}}/L_{\text{X}}$ ratio. PG1351+236 is not detected in either radio or X-ray, so its flux ratio is unknown.

Table 5 lists the VLBA spectral slopes between 1.6 and 4.9 GHz of the core flux density α_{core} , the total flux density α_{total} , and the extended flux density α_{extended} , for each object. Table 5 also includes α_{total} of the individual components in four of the nine objects where more than one component is detected. The spectral slopes are measured based on the flux densities in the tapered maps, which have comparable resolutions and cover emission on similar scales at both 1.6 and 4.9 GHz. PG1351+236 is not detected in either bands, and is therefore not listed. The additional extended components are often detected in only one band. Specifically, in PG0921+525, C3 is not detected at 4.9 GHz, and C1 and C2 are detected in the 4.9 GHz full resolution map and unresolved in the 4.9 GHz tapered map and the 1.6 GHz maps. In PG0923+129, all three components are detected at 1.6 GHz, but only C1 is detected at 4.9 GHz. PG1351+640 exhibits two components at 4.9 GHz, but only a single component at 1.6 GHz, most likely because the separation between C1 and C2 of ~ 5 mas is too small to be resolved at the 1.6 GHz resolution. We identify C1 as the core because it is closer to the *Gaia* position (Table 1). In addition, the 1.6 GHz flux of C2 is one order of magnitude higher than that of C1, while their 4.9 GHz fluxes are comparable (Table 3), which suggests that the slope of C1 is flatter than that of C2 (Table 5). In PG1534+580, the two components are detected at 1.6 GHz, but only C1 is detected at 4.9 GHz.

Table 5 reports the brightness temperature of all components

$$T_{\text{B}} = 1.8 \times 10^9 (1+z) \frac{S_{\nu}}{\nu^2 \theta_{\text{max}} \theta_{\text{min}}}, \quad (1)$$

(e.g. Ulvestad et al. 2005), where S_{ν} is the flux density in mJy, ν is the observing frequency in GHz, and θ_{max} and θ_{min} are the major and minor axes of the source size in mas. We compute the brightness

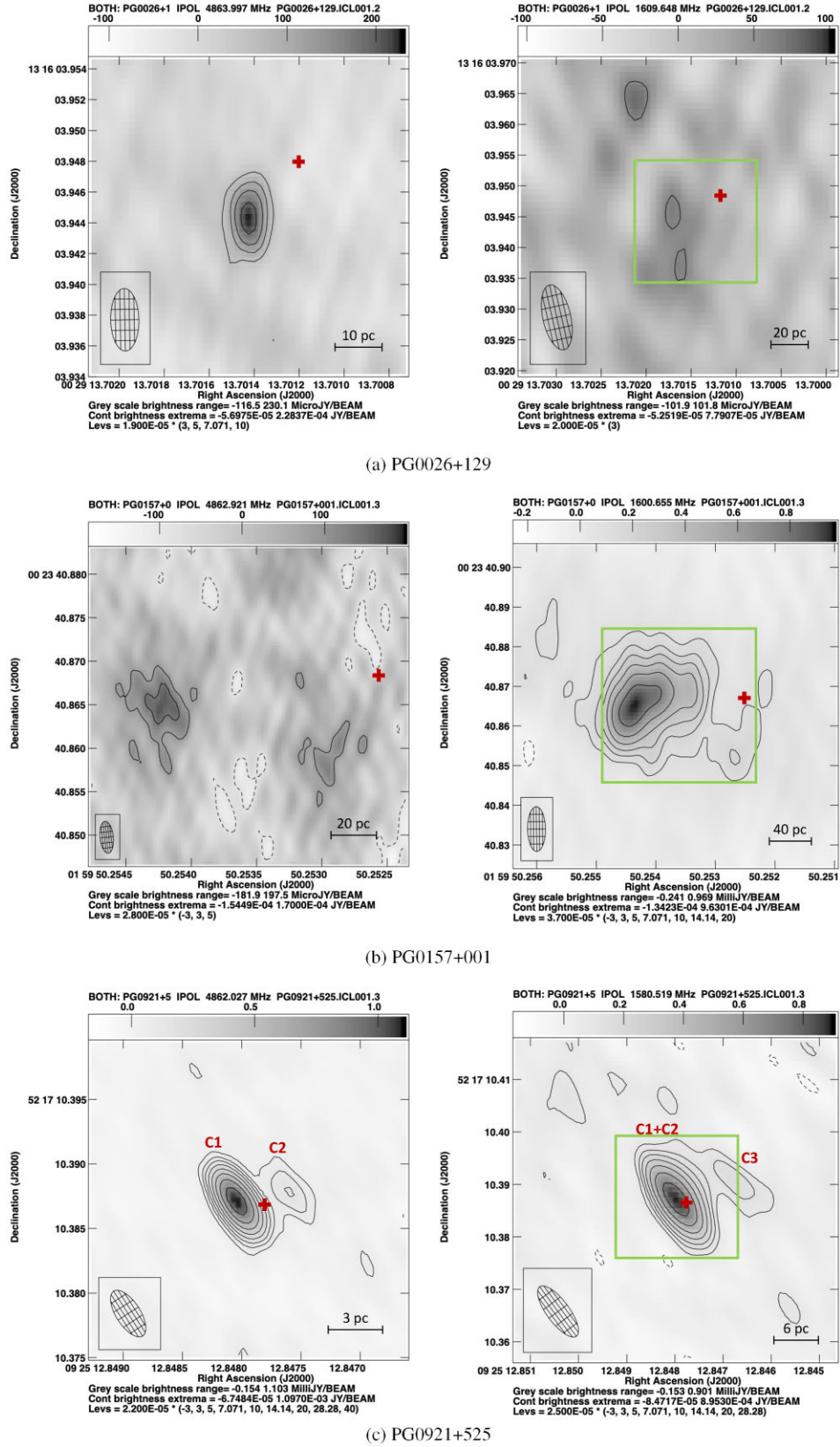
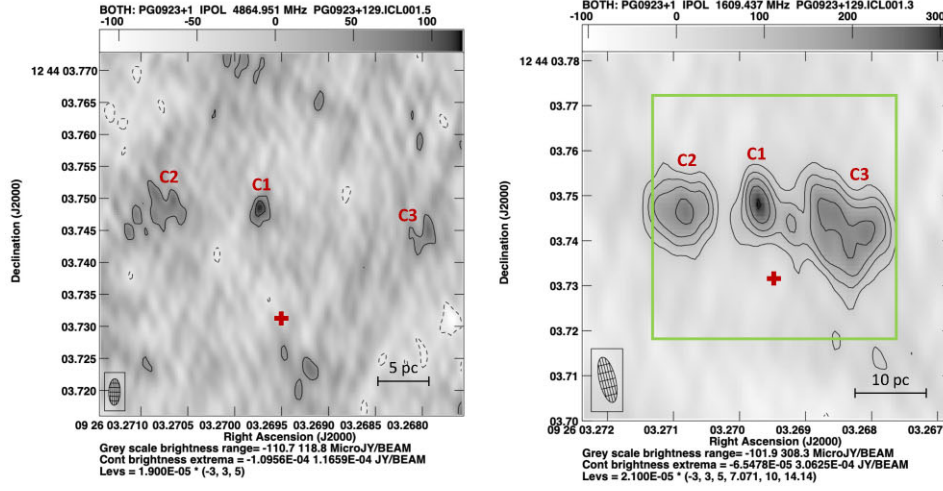
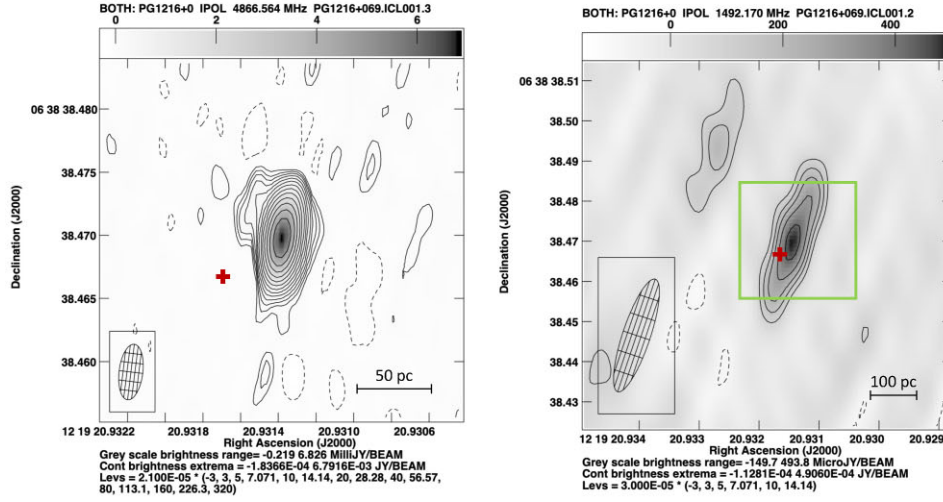


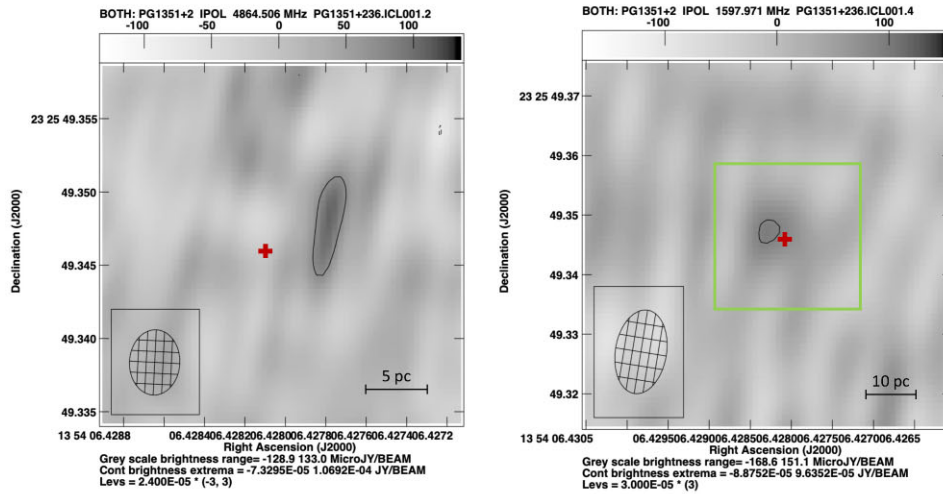
Figure 2. The radio maps at 4.9 and 1.6 GHz. The background noise RMS is reported in Table 3. The contour levels are at $-3, 3, 5 \times \sqrt{2}^n$, $n \in [0, 15]$. The size and orientation of the synthesized beam is shown in the lower-left corner. The grey scale indicates the intensity in unit of Jy beam⁻¹ in a linear scale. The red crosses mark the *Gaia* position. The green squares at 1.6 GHz mark the scale at 4.9 GHz. If the object has more than one component, different components are marked.



(d) PG0923+129



(e) PG1216+069



(f) PG1351+236

Figure 2. Continued.

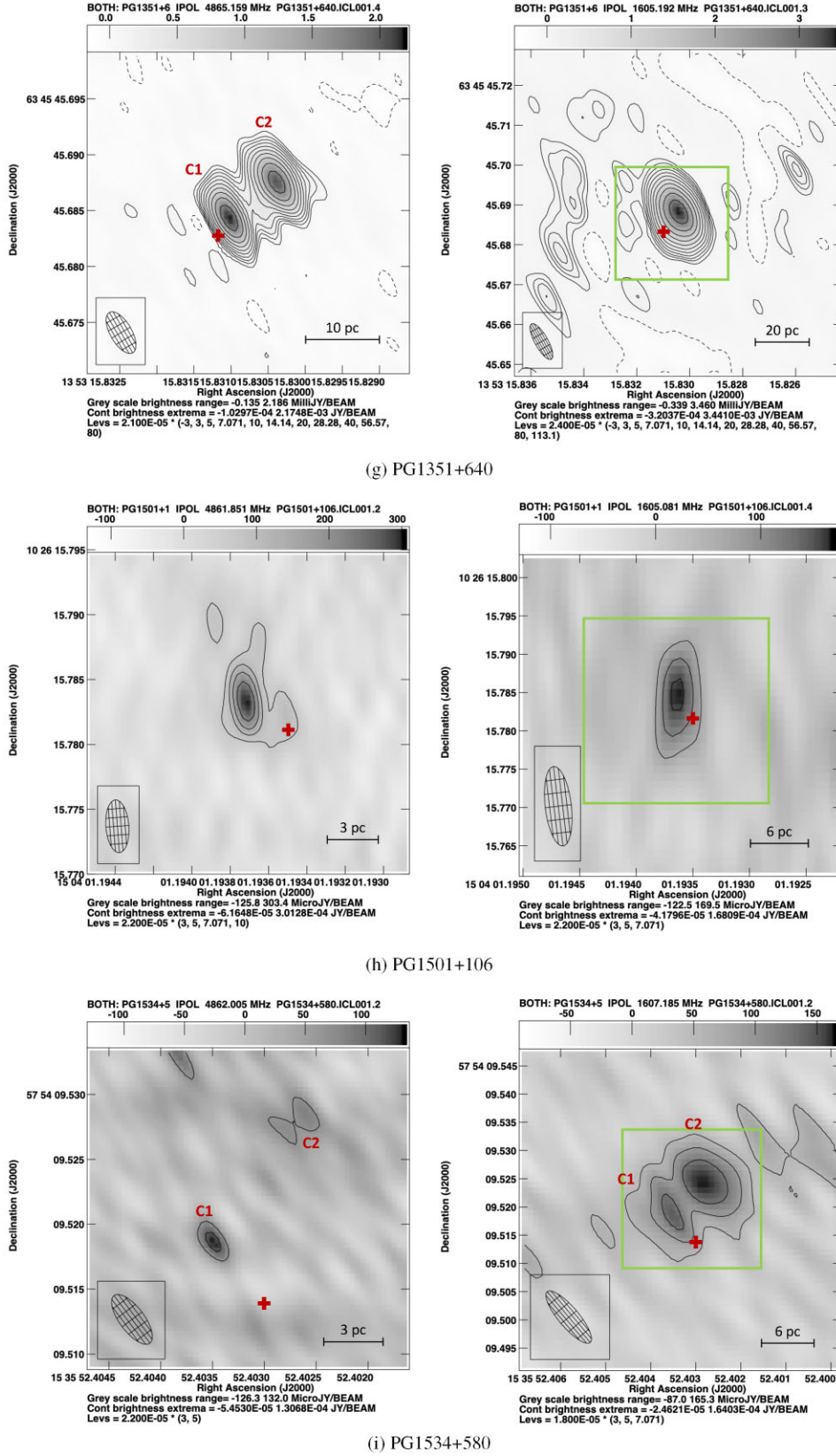


Figure 2. Continued.

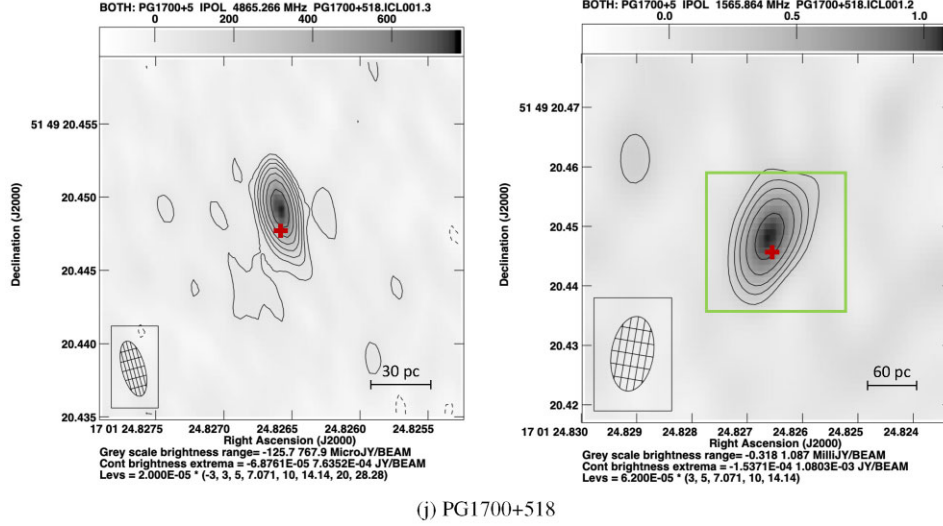


Figure 2. Continued.

temperature at 4.9 GHz, when available, which provides a higher resolution. Otherwise, we calculate the brightness temperature at 1.6 GHz. In objects where $\theta_{\max}$ and/or $\theta_{\min}$ are smaller than half of the measured T_B is a lower limit.

Table 5 lists the VLBA core to total flux ratio, and the VLBA total flux to the VLA A configuration core flux ratio, both at 5 GHz. These ratios provide a measure of the compactness of the mas and arcsec scale emission. PG0921+525, PG0923+129, and PG1534+580 have an upper limit on the VLBA total flux density given that part of the extended emission is undetected at 5 GHz. This yields a lower limit on the VLBA core/total flux ratio and an upper limit on the VLBA/VLA flux ratio.

Five of the eight objects observed by Alhosani et al. (2022) were detected, of which four (PG0052+251, PG1149–110, PG1612+261, and PG2304+042) have one component, and one (PG0050+124) has two components, where C1 and C2 are the extended and the core components (reverse of the convention here). PG1612+261 was only detected in the L band, and the other four objects were detected in both L and C bands. A taper was applied by Alhosani et al. (2022) in the L band with a limit on the minimum baseline, to recover a comparable scale of emission in both bands, but it was not applied in the C band with a limit on the maximum baseline, to make comparable resolution images in both bands. We use the spectral slopes in Alhosani et al. (2022), which were computed using the total flux density of each component, as their α_{total} . The α_{total} of all components in PG0050+124 is calculated using the sum of the total flux density of the two components. We do not use the peak intensity in Alhosani et al. (2022) to estimate the spectral slopes, α_{core} and α_{extended} , as they are biased due to the different resolutions. The VLBA core/total flux ratio at 5 GHz in PG0052+251, PG1149–110, and PG2304+042, is estimated using the peak intensity and the total flux density. In PG0050+124, the VLBA core/total flux ratio is the core flux (C2) to the total flux of the two components (C1+C2). PG1612+261 was not detected in the C band, its VLBA core/total flux ratio is thus not available. The other parameters, including the distance between the VLBA and the *Gaia* positions (Table 1), the VLBA and the VLA radio to X-ray luminosity ratios (Table 4), the brightness temperature, and the VLBA/VLA flux ratio at 5 GHz (Table 5) are calculated as described earlier.

The sample extends over a wide range of BH mass $6.8 \lesssim \log M_{\text{BH}}/M_{\odot} \lesssim 9.1$, luminosity $44.47 \lesssim \log L_{\text{bol}} \lesssim 46.61$, and Eddington ratio $-1.64 \lesssim \log L/L_{\text{Edd}} \lesssim +0.43$. The VLBA flux densities S_{total} are in the range of 0.1–6.9 mJy at 4.9 GHz and 0.36–8.72 mJy at 1.6 GHz. The ranges of the spectral slope and the brightness temperature are $-1.98 \lesssim \alpha_{\text{total}} \lesssim +2.18$ and $6.0 \lesssim \log T_B \lesssim 8.5$. The $\log L_R/L_X$ is distributed from -6.6 to -2.7 using the VLBA flux and from -6.1 to -2.3 using the VLA flux. The span of the VLBA core/total flux ratio is 0.1–1.0 and that of the VLBA/VLA flux ratio is 0–1.6.

5 RESULTS

5.1 The L_R/L_X relation

Fig. 4 compares the distribution of L_R/L_X as a function of M_{BH} using the VLBA (left panel) and the VLA (right panel) core flux both at 5 GHz, including nine objects in our new VLBA observations and eight objects from Alhosani et al. (2022). The VLA flux is measured with the A configuration, where the resolution beam is ~ 0.3 arcsec, and the VLBA resolution beam is typically ~ 3 mas, which is 100 times smaller.

The VLA scale emission follows $\log L_R/L_X \simeq -5$ (a mean value of -5.3 and a scatter of 0.6 if the three outliers mentioned further are excluded), as found for the complete sample of 71 RQQ in the PG sample (Laor & Behar 2008). There is a trend where L_R/L_X increases gradually with M_{BH} starting at $\log M_{\text{BH}}/M_{\odot} \sim 7$, which is consistent with the dependence of the optically defined radio loudness R on M_{BH} (Laor 2000). The VLBA scale emission follows $\log L_R/L_X \simeq -6$ with a smaller scatter (a mean value of -6.2 and a scatter of 0.3 if the three outliers mentioned further are excluded). At $\log M_{\text{BH}}/M_{\odot} \gtrsim 8.5$, three of the five objects become more RL with $\log L_R/L_X \gtrsim -4$. The Kolmogorov–Smirnov (KS) test on L_R/L_X suggests that the objects with $\log M_{\text{BH}}/M_{\odot} \gtrsim 8.5$ or $\lesssim 8.5$ come from different populations at a confidence level of 90 per cent ($p = 0.096$). The lower L_R/L_X of the mas emission compared to the sub-arcsec emission is expected, as the VLBA/VLA flux ratio is generally below unity. The mas scale L_R appears to show a tighter relation with L_X than the sub-arcsec scale L_R , with a smaller scatter in the mas scale L_R/L_X (0.3) than the sub-arcsec scale L_R/L_X (0.6), which may reflect the fact

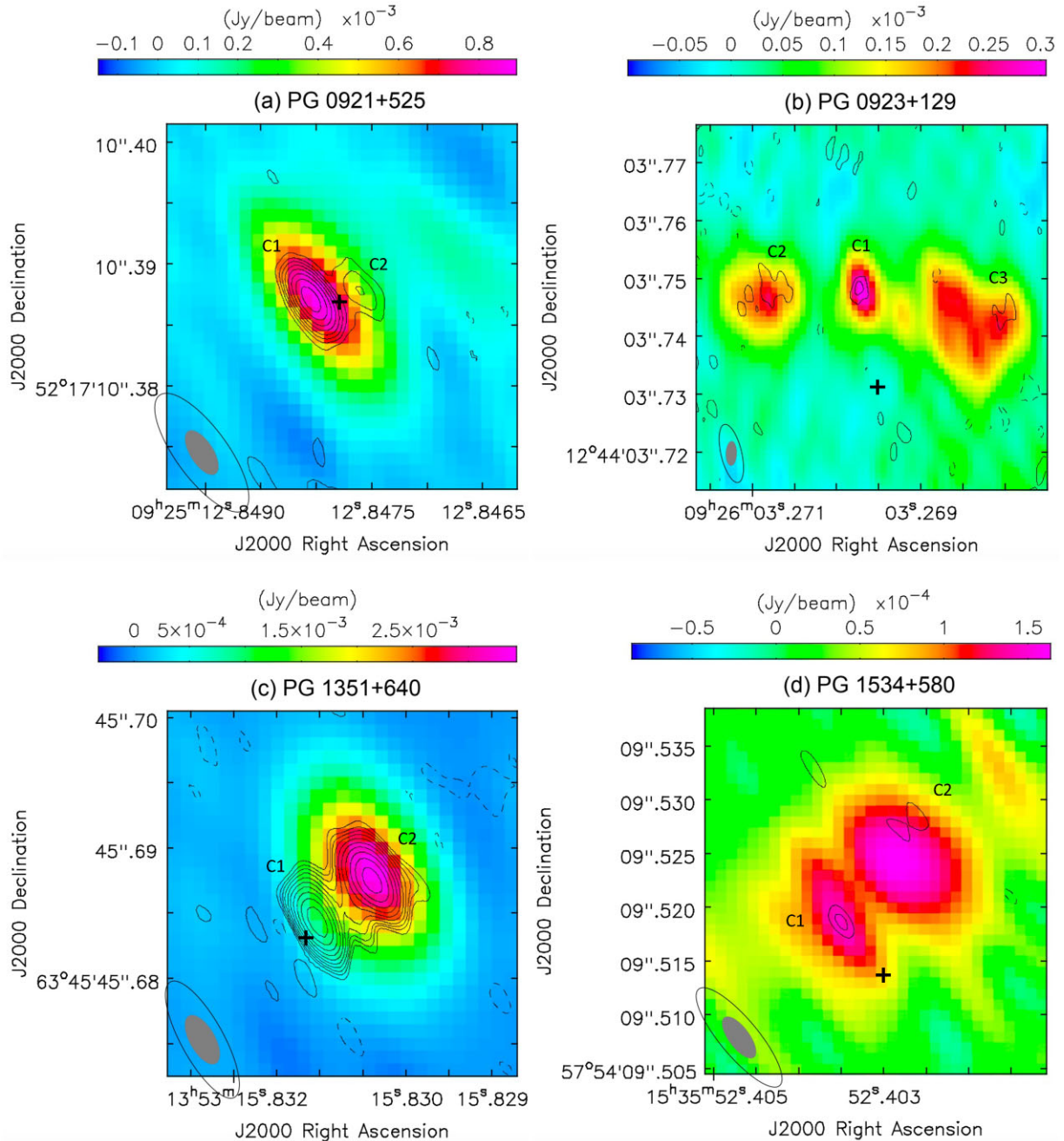


Figure 3. An overlap of the radio maps at 1.6 and 4.9 GHz for the objects with multiple components. The colour scales show the 1.6 GHz images. The contour levels, which are the same as Fig. 2, represent the 4.9 GHz images. The size and orientation of the synthesized beam in both bands is shown in the lower-left corner. The black crosses mark the *Gaia* position. The components are also labelled.

that the VLBA core emission is highly compact, and originates close to the X-ray source. In contrast, the VLA unresolved emission of ~ 300 mas, corresponding to ~ 200 – 2000 pc, may be associated with additional extended emission and may also depend on the host galaxy properties. A larger sample is required to establish the tightness of the VLBA based L_R/L_X relation.

The three outliers at $\log L_R/L_X \gtrsim -4$ are all at $\log M_{\text{BH}}/M_\odot \gtrsim 8.5$. The KS test on the M_{BH} distribution of the objects with $\log L_R/L_X > -5$ or < -5 shows that a similar M_{BH} distribution can be excluded at a confidence level of 97 per cent ($p = 0.029$). The three outliers are,

PG1216+069, which is likely very compact as it shows significant variability and appears to be synchrotron self-absorbed (see Section 6.3), PG1351+640, which may have a mildly relativistic jet on a scale of 10 pc (Wang et al. 2023b) and appears to be intermediate ($3 < R < 200$; Kellermann et al. 1989; Falcke, Sherwood & Patnaik 1996) between RL and RQ AGN (see Section 6.5), and PG1700+518, which is a broad absorption line (BAL) quasar with a very low X-ray flux (Pettini & Boksenberg 1985; Ballo et al. 2011; Luo et al. 2013) that leads to the high L_R/L_X ratio, and it also shows a fast outflow (see Section 6.3).

Table 2. The beam and source size of the 10 RQ PG quasars in our new VLBA observations.

Name	Frequency ν (GHz)	Beam size θ_{maj} (mas)	θ_{min} (mas)	PA (degree)	Source size θ_{maj} (mas)	θ_{min} (mas)	PA (degree)	Deconvolved source size θ_{maj} (mas)	θ_{min} (mas)	PA (degree)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
PG0026+129	4.9	4.06	1.83	1.0	4.32	2.57	1.8	<2.03	1.45	–
PG0157+001	4.9	3.69	1.53	6.0	9.01	7.50	8.2	8.22	7.34	10.1
	1.6	11.26	4.49	0.7	22.16	16.97	126.2	21.10	13.67	114.7
PG0921+525	4.9 C1	4.12	1.86	32.9	4.29	1.98	32.8	<2.06	<0.93	–
	4.9 C2				5.42	3.71	41.3	3.71	3.00	68.9
	1.6 C1	11.73	4.26	36.6	12.82	5.54	34.2	<5.87	3.29	–
	1.6 C2				15.06	9.16	62.5	11.65	4.38	89.3
	1.6 C3				21.48	6.68	56.8	18.51	2.77	63.5
PG0923+129	4.9 C1	4.14	1.80	178.2	4.64	2.90	174.5	2.41	1.97	120.0
	1.6 C1	10.30	3.59	13.6	13.54	10.39	23.2	10.13	8.33	79.4
	1.6 C2				14.10	13.02	25.4	12.58	9.54	98.5
	1.6 C3				21.85	16.70	42.9	20.09	15.29	56.9
PG1216+069	4.9	4.43	1.88	173.0	4.51	1.88	172.2	<2.22	<0.94	–
	1.6	29.56	6.87	161.6	28.00	7.17	162.4	<14.78	<3.44	–
PG1351+640	4.9 C1	4.16	1.91	30.0	4.20	2.01	27.6	<2.08	<0.96	–
	4.9 C2				4.25	2.53	31.1	<2.13	<1.27	–
	1.6 C1	10.14	3.26	29.2	19.18	6.54	72.4	17.74	<1.63	–
	1.6 C2				11.30	7.00	27.8	6.22	4.96	127.1
PG1501+106	4.9	4.07	1.77	4.4	5.99	3.55	18.1	4.56	2.82	32.5
	1.6	10.43	3.41	6.8	14.20	6.04	175.1	10.07	4.05	161.7
PG1534+580	4.9 C1	4.58	1.89	37.0	3.06	1.59	34.5	<2.29	<0.95	–
	1.6 C1	11.74	3.53	40.2	15.75	12.74	35.4	12.31	10.42	139.9
	1.6 C2				15.94	14.15	77.1	14.59	9.54	117.6
PG1700+518	4.9	3.87	1.56	15.0	4.20	1.77	13.2	<1.94	<0.78	–
	1.6	12.65	7.04	170.5	15.05	8.04	158.7	8.85	<3.52	–

Notes. Columns: (1) name, (2) frequency, (3) major axis of the beam in unit of mas, (4) minor axis of the beam in unit of mas, (5) position angle of the beam in unit of degree, (6) major axis of the source in unit of mas, (7) minor axis of the source in unit of mas, (8) position angle of the source in unit of degree, (9) deconvolved major axis of the source in unit of mas, (10) deconvolved minor axis of the source in unit of mas, and (11) deconvolved position angle of the source in unit of degree.

5.2 The spectral slope

The spectral slope of the 5–8.5 GHz VLA unresolved emission of a sample of 25 RQQ shows a trend with L/L_{Edd} (Laor et al. 2019). Objects with $L/L_{\text{Edd}} \lesssim 0.3$ have flat slopes, while higher L/L_{Edd} objects generally show steep slopes. This suggests that compact optically thick radio emission at low L/L_{Edd} switches to more extended optically thin radio emission at higher L/L_{Edd} , which is possibly a switch from the compact coronal emission to a larger scale wind emission. The follow-up VLBA study in Alhosani et al. (2022) of the four flattest and four steepest objects in Laor et al. (2019), confirms this interpretation, as the radio emission of three of the four flat spectrum objects remains unresolved on mas scales, while the radio emission of three of the four steep spectrum objects is resolved out with the VLBA and must be produced on larger scales.

Fig. 5 (left panel) shows an extension study of the correlation between α_{total} and L/L_{Edd} in a larger and more representative sample with a total of 14 RQ PG quasars, including nine objects detected in our new VLBA observations and five objects detected in Alhosani et al. (2022). Although there is only a weak trend of α_{total} with L/L_{Edd} , the slopes of seven of the eight objects with $\log L/L_{\text{Edd}} < -0.5$ are flat ($\alpha_{\text{total}} > -0.5$), only one is steep ($\alpha_{\text{total}} < -0.5$). In contrast, of the six objects with $\log L/L_{\text{Edd}} > -0.5$, only two are flat. The KS test on the slopes suggests that the objects with $\log L/L_{\text{Edd}} > -0.5$ or < -0.5 come from different populations at a confidence level of 94 per cent ($p = 0.061$). Two objects in Fig. 5

(left panel) are outliers, which have strongly inverted spectra ($\alpha_{\text{total}} \sim 1-2$), PG1216+069, which is consistent with the flat spectra in the low- L/L_{Edd} regime, and PG0026+129, which stands in contrast with most other high- L/L_{Edd} objects.

The correlation between $\alpha_{5-8.5}$ and L/L_{Edd} is tighter for the VLA scale emission (Laor et al. 2019), which may indicate that the correlation is driven by the larger scale radio emission, which becomes more prominent at higher L/L_{Edd} objects. On the VLBA scale, most of the larger scale radio emission is resolved out, and the emission is dominated by the flat compact core emission. This suggests that the flat compact core emission is present in most of the RQQ regardless of the Eddington ratio, and its contribution dilutes the trend of α_{total} with L/L_{Edd} . Fig. 5 (right panel) further confirms the presence of the core emission in five objects with multiple components, of which four are from our VLBA observations and one is from Alhosani et al. (2022). Each of the five objects shows a flat compact component, and one or more steep extended components.

Fig. 6 presents the dependence of α_{core} on L/L_{Edd} (left panel), and of α_{extended} on L/L_{Edd} (right panel) for the nine objects detected in our new VLBA observations. The distributions of α_{core} and α_{extended} are clearly different. The KS test on the slopes suggests that the core and extended components are drawn from different distributions at a confidence level of 99.7 per cent ($p = 0.003$). In eight of the nine objects, α_{core} is flat. In contrast, α_{extended} is steep within 1σ uncertainty in all six objects where it is detected. In PG0157+001, both α_{core} and α_{extended} are steep. The VLBA core/total flux ratio is ~ 0.1 , which

Table 3. The flux densities of the 10 RQ PG quasars at 4.9 and 1.6 GHz in our new VLBA observations.

Name	Frequency ν (GHz)	Full resolution maps			Tapered (3000–50 000 $k\lambda$) maps		
		S_{core} (mJy beam $^{-1}$)	S_{total} (mJy)	RMS (mJy beam $^{-1}$)	S_{core} (mJy beam $^{-1}$)	S_{total} (mJy)	RMS (mJy beam $^{-1}$)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
PG0026+129	4.9	0.21 ± 0.02	0.31 ± 0.04	0.019	0.25 ± 0.02	0.28 ± 0.04	0.024
	1.6	–	–	0.020	–	–	0.021
PG0157+001	4.9	0.15 ± 0.02	1.79 ± 0.30	0.028	0.27 ± 0.03	0.95 ± 0.16	0.038
	1.6	0.82 ± 0.03	6.10 ± 0.28	0.037	0.62 ± 0.03	2.60 ± 0.17	0.037
PG0921+525	4.9 C1	1.10 ± 0.02	1.21 ± 0.04	0.022	1.02 ± 0.03	1.02 ± 0.03	0.027
	4.9 C2	–	0.35 ± 0.07	–	–	0.43 ± 0.06	–
	4.9 C3	–	< 0.11	–	–	< 0.14	–
	1.6 C1	0.87 ± 0.02	1.24 ± 0.05	0.025	0.84 ± 0.03	1.19 ± 0.06	0.026
	1.6 C2	–	0.36 ± 0.09	–	–	0.28 ± 0.08	–
	1.6 C3	–	0.44 ± 0.09	–	–	0.33 ± 0.08	–
	1.6 C3	–	–	–	–	–	–
PG0923+129	4.9 C1	0.11 ± 0.02	0.21 ± 0.05	0.019	0.17 ± 0.02	0.17 ± 0.02	0.025
	4.9 C2	–	< 0.10	–	–	< 0.13	–
	4.9 C3	–	< 0.10	–	–	< 0.13	–
	1.6 C1	0.24 ± 0.02	0.91 ± 0.09	0.021	0.20 ± 0.02	0.29 ± 0.04	0.021
	1.6 C2	–	1.15 ± 0.11	–	–	0.58 ± 0.10	–
	1.6 C3	–	2.39 ± 0.20	–	–	1.13 ± 0.14	–
	1.6 C3	–	–	–	–	–	–
PG1216+069	4.9	6.77 ± 0.02	6.91 ± 0.04	0.021	6.74 ± 0.03	6.89 ± 0.05	0.027
	1.6	0.47 ± 0.03	0.47 ± 0.03	0.030	0.50 ± 0.03	0.60 ± 0.07	0.035
PG1351+236	4.9	–	–	0.024	–	–	0.025
	1.6	–	–	0.030	–	–	0.034
PG1351+640	4.9 C1	2.16 ± 0.02	2.30 ± 0.04	0.021	2.26 ± 0.03	2.42 ± 0.05	0.026
	4.9 C2	–	2.67 ± 0.04	–	–	2.58 ± 0.05	–
	1.6 C1	0.16 ± 0.01	0.59 ± 0.07	0.024	0.59 ± 0.01	0.78 ± 0.03	0.021
	1.6 C2	–	8.13 ± 0.05	–	–	7.29 ± 0.04	–
PG1501+106	4.9	0.21 ± 0.02	0.62 ± 0.08	0.022	0.33 ± 0.03	0.40 ± 0.05	0.028
	1.6	0.15 ± 0.02	0.37 ± 0.07	0.022	0.16 ± 0.02	0.37 ± 0.07	0.024
PG1534+580	4.9 C1	0.14 ± 0.02	0.14 ± 0.02	0.022	0.14 ± 0.02	0.14 ± 0.02	0.024
	4.9 C2	–	< 0.11	–	–	< 0.12	–
	1.6 C1	0.13 ± 0.02	0.63 ± 0.09	0.018	0.08 ± 0.02	0.20 ± 0.06	0.018
	1.6 C2	–	0.84 ± 0.10	–	–	0.35 ± 0.07	–
PG1700+518	4.9	0.75 ± 0.02	0.92 ± 0.04	0.020	0.77 ± 0.03	1.00 ± 0.05	0.026
	1.6	1.07 ± 0.06	1.46 ± 0.13	0.062	1.06 ± 0.06	1.36 ± 0.13	0.065

Notes. Columns: (1) name, (2) frequency, (3) core flux density of the full resolution map, (4) total flux density of the full resolution map, (5) background noise of the full resolution map, (6) core flux density of the tapered map, (7) total flux density of the tapered map, and (8) background noise of the tapered map. The tapered maps have a UV range of 3000–50 000 $k\lambda$ in both bands.

is exceptionally low as the median core/total flux ratio is ~ 0.6 (see Fig. 7). A compact optically thick flat source is not detected. The core which is detected resides far from the *Gaia* position (Table 1), and is likely not the true core but rather optically thin emission away from the center.

Although neither α_{core} or α_{extended} are significantly correlated with L/L_{Edd} , α_{core} appears to show a trend of getting steeper with increasing L/L_{Edd} . To summarize, Fig. 6 demonstrates that most objects have a compact core with a flat spectrum on mas scales, while the extended emission, when detected, has a steep spectrum.

Fig. 7 shows α_{total} as a function of the VLBA core/total flux ratio (left panel), and the VLBA total flux to the VLA A configuration core flux ratio (right panel), both ratios measured at 5 GHz, for the 14 RQ PG quasars. There is a clear trend where α_{total} increases with increasing flux ratios, that is the source becomes more compact as the emission becomes flatter. The Spearman correlation gives $r = 0.57$ and $p = 4.1 \times 10^{-2}$ for the VLBA core/total flux ratio and $r = 0.94$ and $p = 5.6 \times 10^{-7}$ for the VLBA/VLA flux ratio. The VLBA emission becomes generally flat ($\alpha_{\text{total}} > -0.5$) in seven of the eight objects where the core emission dominates the total

emission ($S_{\text{core}}/S_{\text{total}} > 0.5$). This is consistent with the results earlier that the core emission is flat, while the extended emission is steep. The correlation becomes significantly stronger when we take the VLBA to the VLA (~ 300 mas) flux ratio. In five of the nine objects where $\alpha_{\text{total}} > -0.5$, the VLBA emission also dominates the VLA emission on sub-arcsec scales ($S_{\text{VLBA}}/S_{\text{VLA}} > 0.5$). In contrast, if the steep extended emission dominates on the VLBA scales, there is significantly more (a factor of 5–10) extended emission which contributes further out on the VLA scales.

In three of the 14 objects, $S_{\text{VLBA}}/S_{\text{VLA}} > 1$, which indicates the objects are variable. Their variability implies that the source sizes are smaller than the light crossing times. The earlier VLA observations in Kellermann et al. (1989) were carried out in 1983 or 40 yr ago, which implies a size $\lesssim 10$ pc. Much tighter constraints on the size are given by the flat spectral slopes. Since the spectra are optically thick, the source sizes at 5 GHz are constrained to be ~ 0.01 – 0.4 pc (Laor & Behar 2008), which is consistent with the observed variability time-scale.

Fig. 8 shows the VLBA slope α_{total} (left panel) and the brightness temperature T_{B} (right panel) as a function of the distance between the

Table 4. The BH mass, the Eddington ratio, the unresolved flux density at 5 GHz with the VLA A configuration, the X-ray flux at 0.2–12.0 keV, and the ratio of radio to X-ray luminosity of the 18 RQ PG quasars observed with VLBA, including 10 objects from our new observations and 8 objects from Alhosani et al. (2022).

Name	$\log M_{\text{BH}}/M_{\odot}$	$\log L_{\text{bol}}$	$\log L/L_{\text{Edd}}$	$S_{5\text{GHz}}^{\text{VLA}}$ (mJy)	References	$f_{0.2-12.0\text{keV}}$ ($10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$)	VLBA $\log L_{\text{R}}/L_{\text{X}}$	VLA $\log L_{\text{R}}/L_{\text{X}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
PG0026+129	7.74	46.15	+0.30	0.20 ± 0.06	a	9.25 ± 0.10	-5.88 ± 0.04	-5.97 ± 0.13
PG0157+001	8.00	45.93	-0.18	5.58 ± 0.06	a	2.82 ± 0.05	-5.34 ± 0.06	-4.00 ± 0.01
PG0921+525	6.87	44.47	-0.51	1.87 ± 0.06	a	55.80 ± 0.10	-6.05 ± 0.01	-5.78 ± 0.01
PG0923+129	6.82	44.53	-0.40	2.82 ± 0.02	b	34.10 ± 0.13	-6.61 ± 0.06	-5.38 ± 0.01
PG1216+069	9.06	46.61	-0.56	4.95 ± 0.06	a	3.65 ± 0.03	-4.04 ± 0.01	-4.17 ± 0.01
PG1351+236	8.10	44.57	-1.64	≤ 0.25	a	—	—	—
PG1351+640	8.49	45.31	-1.29	20.0 ± 0.06	a	0.95 ± 0.02	-3.93 ± 0.01	-2.98 ± 0.01
PG1501+106	8.11	44.90	-1.32	0.50 ± 0.06	a	32.90 ± 0.13	-6.31 ± 0.04	-6.12 ± 0.05
PG1534+580	7.71	44.49	-1.33	1.80 ± 0.06	a	17.10 ± 0.10	-6.41 ± 0.08	-5.28 ± 0.01
PG1700+518	8.59	46.63	-0.07	2.05 ± 0.06	a	0.02 ± 0.01	-2.70 ± 0.13	-2.27 ± 0.13
PG0050+124	6.99	45.12	+0.03	2.41 ± 0.12	c	14.90 ± 0.04	-6.10 ± 0.09	-5.10 ± 0.02
PG0052+251	8.64	46.06	-0.68	0.68 ± 0.04	c	13.70 ± 0.06	-6.06 ± 0.03	-5.61 ± 0.03
PG1149-110	7.34	44.75	-0.70	2.27 ± 0.05	c	9.12 ± 0.08	-5.64 ± 0.02	-4.91 ± 0.01
PG1612+261	7.69	45.38	-0.41	5.58 ± 0.08	c	8.07 ± 0.09	$< -6.31 \pm 0.01$	-4.47 ± 0.01
PG2304+042	7.91	44.49	-1.52	0.77 ± 0.07	c	30.00 ± 0.13	-6.35 ± 0.03	-5.90 ± 0.04
PG1440+356	7.09	45.62	+0.43	1.24 ± 0.07	c	10.90 ± 0.05	$< -6.44 \pm 0.01$	-5.25 ± 0.02
PG1613+658	8.89	45.89	-1.10	3.03 ± 0.07	c	10.70 ± 0.19	$< -6.44 \pm 0.01$	-4.86 ± 0.01
PG2130+099	7.49	45.52	-0.07	2.18 ± 0.07	c	10.00 ± 0.06	$< -6.46 \pm 0.01$	-4.97 ± 0.01

Notes. Columns: (1) name, (2) logarithm of BH mass, (3) logarithm of bolometric luminosity in unit of erg s^{-1} , (4) logarithm of Eddington ratio, (5) flux density at 5 GHz with the VLA A configuration from literature, (6) reference for the VLA 5 GHz flux density, (7) X-ray flux at 0.2–12.0 keV in unit of $10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ from the *XMM-Newton* DR12 catalogue, (8) radio to X-ray luminosity ratio using the VLBA core flux, and (9) radio to X-ray luminosity ratio using the unresolved VLA A configuration flux. The BH mass and bolometric luminosity are from Davis & Laor (2011) or Laor et al. (2019). Reference: (a) Kellermann et al. (1989), (b) Berton et al. (2018), (c) Alhosani et al. (2022).

VLBA and the *Gaia* positions for individual components of the 14 RQ PG quasars. In general, the flat slope components are closer (≤ 7 mas) to the *Gaia* position, and their offsets are consistent with the *Gaia* astrometric uncertainty (~ 1 –10 mas) (Khamitov et al. 2023). In contrast, the steep slope components are all located further out ($\gtrsim 10$ mas). The Spearman correlation indeed shows that the slope is correlated with the distance from the *Gaia* position with $r = -0.70$ and $p = 4.5 \times 10^{-4}$. No significant correlation is present between T_{B} and the distance from the *Gaia* position, where $r = -0.29$ and $p = 0.20$. However, we do see a trend that all sources with $T_{\text{B}} \sim 10^7$ – 10^9 K are $\lesssim 7$ mas offset from the *Gaia* position, and all sources with an offset $\gtrsim 10$ mas have $T_{\text{B}} \sim 10^6$ – 10^7 K. These trends suggest that the flat optically thick sources may be located at the physical center of the AGN, while the steep optically thin components are located $\sim$ a few tens of pc away from the central core (see the physical scale in unit of pc mas^{-1} in Table 1).

6 DISCUSSION

The main result of our study is that most of the RQQ have a compact core, which is still unresolved on pc scales, regardless of the Eddington ratio. The compact core emission is flat at 1.5–5 GHz, it overlaps with the optical core (*Gaia*) position, and can reach $T_{\text{B}} \gtrsim 10^7$ K. The physical size of an optically thick synchrotron source can be estimated via (equation 22 in Laor & Behar 2008)

$$R_{\text{RS}} = 0.47 L_{30}^{0.4} L_{46}^{0.1} \nu_p^{-1}, \quad (2)$$

where R_{RS} is the radius of the radio sphere in pc, ν_p is the turnover frequency in GHz, L_{30} is the luminosity density at the turnover frequency in $10^{30} \text{ erg s}^{-1} \text{ Hz}^{-1}$, and L_{46} is the bolometric luminosity in $10^{46} \text{ erg s}^{-1}$. The 5 GHz emission of the RQQ in our sample comes from a radio sphere with a size of $R_{\text{RS}} \sim 0.01$ – 0.4 pc or 10–500 light

days. Such a compact physical size corresponds to an angular scale which is typically below 0.1 mas (Table 1), and is indeed expected to remain unresolved with the VLBA at 5 GHz. What is the source of this emission?

6.1 The compact emission: jet versus corona

The compact size and the association with the optical position suggest that the emission originates close to the center of the AGN, on a scale comparable in size to the broad-line region, or smaller. The physical origin is possibly the accretion disc corona or a compact jet.

If the origin of the core emission is a compact jet, the jet needs to be small enough to remain unresolved with the VLBA, that is to be smaller than a few pc. Since the 5 GHz core emission is optically thick, the size of the jet is constrained to be below typically ~ 0.1 pc. A jet which extends beyond ~ 0.1 pc becomes optically thin. It is therefore not clear why the jet would be confined to ~ 0.1 pc in about half of the objects without evidence of extended emission.

The core emission may be dominated by the jet base, that is, the jet launching region, which may spatially overlap with the accretion disc corona. VLBA observations of RL AGN indeed often show only compact core emission (Lister et al. 2009; Wang et al. 2023a), but such objects do generally show also significant extended 10–100 kpc jet emission (Baghel et al. 2023). This is in contrast with RQ PG quasars, where in about half of the objects, the spectral slopes are flat, and there is no significant extended emission. Similarly, low-luminosity RQ AGN show flat-spectrum compact cores on sub-kpc scales (Baldi et al. 2018, 2021; Kharb et al. 2021).

In contrast with the jet interpretation, the accretion disc corona is expected to be extremely compact, on a scale of ~ 10 – 100 grav-

Table 5. The spectral slopes, brightness temperature, and compactness of the 14 RQ PG quasars observed with VLBA, including 9 objects detected in our new observations and 5 objects detected in Alhosani et al. (2022).

Name	Component	α_{core}	α_{total}	α_{extended}	ν (GHz)	$\log T_B$	$f(\frac{S_{\text{core}}}{S_{\text{total}}})$	$f(\frac{S_{\text{VLBA}}}{S_{\text{VLA}}})$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
PG0026+129	–	$>+0.79 \pm 0.09$	$>+0.89 \pm 0.14$	–	4.9	> 7.0	0.67 ± 0.11	1.55 ± 0.51
PG0157+001	–	-0.75 ± 0.13	-0.90 ± 0.16	-0.95 ± 0.22	4.9	6.4	0.08 ± 0.02	0.32 ± 0.05
PG0921+525	All	$+0.18 \pm 0.04$	$<-0.12 \pm 0.07$	$<-0.48 \pm 0.16$	–	–	$>0.65 \pm 0.03$	$<0.90 \pm 0.05$
	C1	–	-0.14 ± 0.05	–	4.9	> 7.7	–	–
	C2	–	$+0.37 \pm 0.28$	–	4.9	6.4	–	–
	C3	–	$<-0.80 \pm 0.21$	–	1.6	6.8	–	–
PG0923+129	All	-0.16 ± 0.16	$<-1.40 \pm 0.09$	$<-1.78 \pm 0.15$	–	–	$>0.28 \pm 0.06$	$<0.14 \pm 0.02$
	C1	–	-0.48 ± 0.19	–	4.9	6.5	–	–
	C2	–	$<-1.39 \pm 0.15$	–	1.6	6.8	–	–
	C3	–	$<-1.98 \pm 0.11$	–	1.6	6.8	–	–
PG1216+069	–	$+2.33 \pm 0.06$	$+2.18 \pm 0.10$	–	4.9	> 8.5	0.98 ± 0.01	1.40 ± 0.02
PG1351+640	All	$+1.20 \pm 0.02$	-0.43 ± 0.01	-0.90 ± 0.02	–	–	0.44 ± 0.01	0.25 ± 0.01
	C1	–	$+1.01 \pm 0.04$	–	4.9	> 8.0	–	–
	C2	–	-0.93 ± 0.02	–	4.9	> 8.0	–	–
PG1501+106	–	$+0.63 \pm 0.14$	$+0.08 \pm 0.21$	–	4.9	6.6	0.34 ± 0.05	1.25 ± 0.22
PG1534+580	All	$+0.45 \pm 0.24$	$<-0.70 \pm 0.17$	$<-1.24 \pm 0.30$	–	–	$>0.57 \pm 0.10$	$<0.14 \pm 0.01$
	C1	–	-0.36 ± 0.29	–	4.9	> 6.7	–	–
	C2	–	$<-0.98 \pm 0.17$	–	1.6	6.6	–	–
PG1700+518	–	-0.29 ± 0.06	-0.28 ± 0.10	$>-0.59 \pm 0.23$	4.9	> 7.8	0.81 ± 0.04	0.45 ± 0.02
PG0050+124	All	–	-0.90 ± 0.15	–	–	–	0.44 ± 0.12	0.23 ± 0.04
	C2	–	0.00 ± 0.29	–	4.8	6.1	–	–
	C1	–	-1.21 ± 0.19	–	4.8	6.0	–	–
PG0052+251	–	–	-0.13 ± 0.16	–	4.8	7.6	0.81 ± 0.10	0.44 ± 0.05
PG1149–110	–	–	-0.31 ± 0.12	–	4.8	6.8	0.72 ± 0.06	0.26 ± 0.02
PG1612+261	–	–	$<-1.61 \pm 0.11$	–	1.4	7.1	–	$<0.01 \pm 0.01$
PG2304+042	–	–	-0.09 ± 0.12	–	4.8	6.6	0.56 ± 0.06	0.64 ± 0.08

Notes. Columns: (1) name, (2) component, (3) spectral slope of the core flux density at 1.6–4.9 GHz measured in the tapered maps, (4) spectral slope of the total flux density at 1.6–4.9 GHz measured in the tapered maps, (5) spectral slope of the extended flux density at 1.6–4.9 GHz measured in the tapered maps, (6) frequency at which the brightness temperature calculated, (7) logarithm of surface brightness temperature at 4.9 or 1.6 GHz in unit of K, (8) ratio of the VLBA core/total flux at 5 GHz, and (9) ratio of the VLBA/VLA flux at 5 GHz.

itational radii, or ~ 0.001 pc, which naturally explains the compact size of $\lesssim 0.1$ pc in all objects. Coronal mass ejections, as observed in coronally active stars, can produce more extended radio emission. However, the expected drop in the gas synchrotron emission as it expands outward, will prevent the extended optically thin emission from becoming dominant.

Additionally, the rather tight correlation of the VLBA core flux and the X-ray flux (Fig. 4) also points toward a coronal origin as the more likely explanation. In the near future, we have a VLBA program of observing this sample at higher frequencies and thus on higher resolutions, which will test if the core emission remains flat and unresolved, as expected for the coronal emission origin.

6.2 The extended emission

The extended radio emission detected in some of the RQQ is generally spatially resolved, has a steep slope and a low brightness temperature, and is therefore optically thin synchrotron emission. The emission is offset from the *Gaia* position by ~ 10 – 25 mas, which corresponds to a physical distance of ~ 5 – 100 pc from the center. The extended clumped emission may be produced by an outflow of magnetized plasma from the center, in the form of a weak jet with intermittent activity, or coronal mass ejection events,

or it may be produced by an AGN driven wind, which shocks on the clumped ambient gas and leads to particle acceleration and synchrotron emission.

The slope of the sum of the compact and extended emission, that is α_{total} , shows a clear trend with L/L_{Edd} (Fig. 5). The flat core emission dominates in the lower L/L_{Edd} (<0.3) objects, and the steep extended emission dominates in about half of the higher L/L_{Edd} (>0.3) objects. This is consistent with the trend suggested in Alhosani et al. (2022), for a relation of the emission compactness with L/L_{Edd} , though the trend found here is less sharp than that found in Alhosani et al. (2022). The sample of eight objects in Alhosani et al. (2022) was selected to have the flattest and steepest VLA scale slopes at 5–8.5 GHz in Laor et al. (2019), while the sample observed here was selected to be more representative of the RQ PG quasars. The conclusion remains that the radio emission in low- L/L_{Edd} (<0.3) RQQ is generally core-dominated, while some high- L/L_{Edd} (>0.3) RQQ can have significant extended emission. However, the core emission is detected also in high- L/L_{Edd} sources, and the extended components are also detected in low- L/L_{Edd} sources.

The correlation between the α_{total} and the compactness, that is, the VLBA core/total flux ratio and the VLBA/VLA flux ratio (Fig. 7), further supports that the flat slope objects are compact on pc scales and are dominated by the core, possibly the coronal emission, and

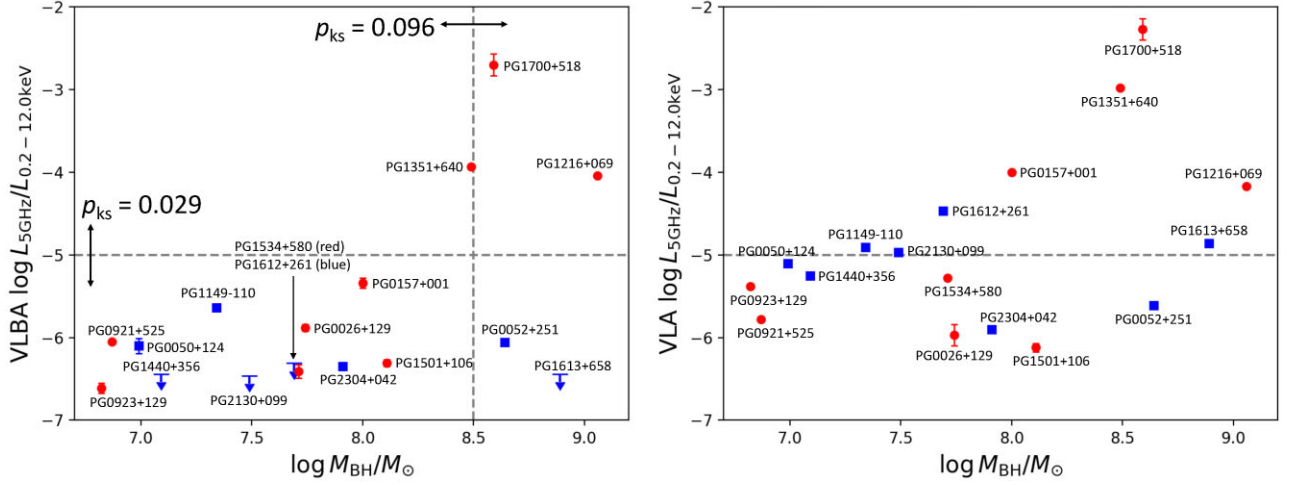


Figure 4. The radio 5 GHz to X-ray 0.2–12.0 keV luminosity ratio as a function of the BH mass. The VLBA core flux on ~ 3 mas scale is shown in the *left panel*, and the VLA unresolved flux with the A configuration on ~ 300 mas is shown in the *right panel*. The red circles and blue squares represent the nine objects in our new VLBA observations and the eight objects from Alhosani et al. (2022), respectively. The VLBA scale emission is characterized by $\log L_{\text{R}}/L_{\text{X}} \simeq -6$ with three outliers at $\log L_{\text{R}}/L_{\text{X}} \gtrsim -4$ and $\log M_{\text{BH}}/M_{\odot} \gtrsim 8.5$. The p -values of the KS test on $L_{\text{R}}/L_{\text{X}}$ with $\log M_{\text{BH}}/M_{\odot} \gtrsim 8.5$ or $\lesssim 8.5$ and on M_{BH} with $\log L_{\text{R}}/L_{\text{X}} > -5$ or < -5 are labelled in the *left panel*. In contrast, the VLA scale emission shows $\log L_{\text{R}}/L_{\text{X}} \simeq -5$, with a rising trend which starts already at $\log M_{\text{BH}}/M_{\odot} \sim 7$. The mas scale L_{R} shows a tighter relation with L_{X} than the sub-arcsec scale L_{R} , which may indicate a common origin of the mas scale radio and X-ray sources, as expected for coronal emission.

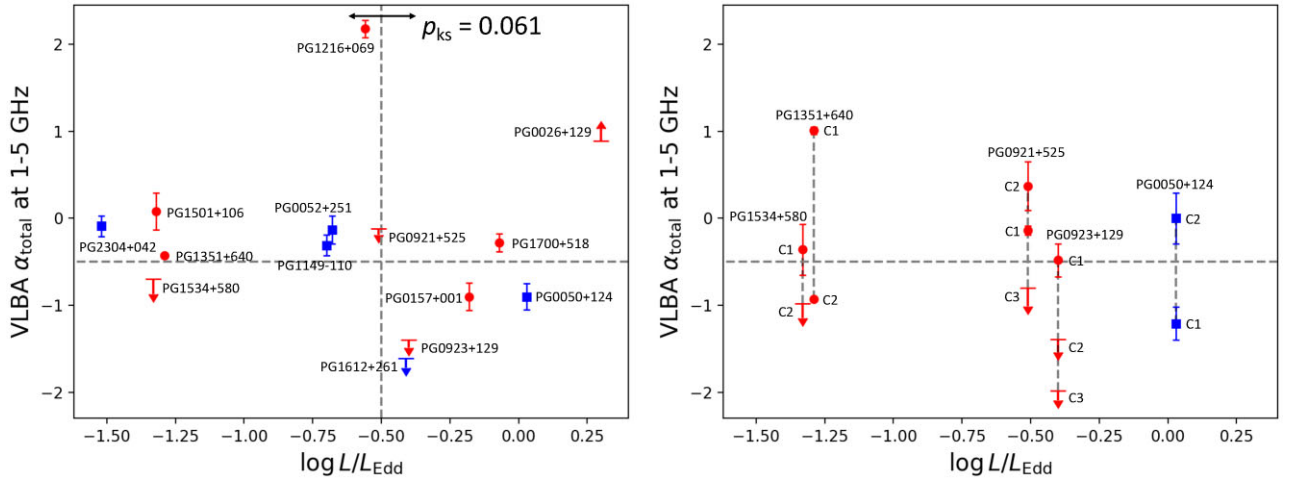


Figure 5. *Left panel:* the VLBA spectral slope of the total flux density α_{total} at 1.6–4.9 GHz as a function of the Eddington ratio L/L_{Edd} . The red circles and blue squares represent the nine objects detected in our new VLBA observations and the five objects detected in Alhosani et al. (2022), respectively. Although no significant correlation is found between α_{total} and L/L_{Edd} , there is a trend: the radio emission in only one of the eight objects at $\log L/L_{\text{Edd}} < -0.5$ is steep, and in only two of the six objects at $\log L/L_{\text{Edd}} > -0.5$ are flat. The p -value of the KS test on α_{total} with $\log L/L_{\text{Edd}} > -0.5$ or < -0.5 are labelled. *Right panel:* the α_{total} of individual components in the five objects with more than one component. Each object is comprised of a flat compact component plus steep extended components.

the steep slope objects show extended emission on sub-kpc scales, likely in the form of an AGN wind. This result is consistent with the earlier study by Orienti & Prieto (2010) of a few nearby low-luminosity Seyfert galaxies, where the steep-spectrum objects show a low VLBA/VLA flux ratio, whereas in flat-spectrum objects the flux ratio is close to unity. In a jet scenario, the low VLBA/VLA flux ratio may be due to a jet–ISM interaction (Nagar, Falcke & Wilson 2005; Kharb et al. 2021).

The extended emission is two-sided only in one object, PG0923+129. In the other three spatially resolved objects, PG0921+525, PG1351+640, and PG1534+580, detected here

(Fig. 3), and also in PG0050+124 (Alhosani et al. 2022), the extended emission is one-sided, although a weak counter-jet is detected in an EVN + e-MERLIN 5 GHz observation of PG0050+124 (Yang et al. 2023). In a jet scenario, the one-sided emission could be caused by the Doppler boosting and dimming effects. However, a significant Doppler effect requires a bulk motion at a relativistic speed, which will also produce a strong enhancement to the emission with a high T_{B} . Evidence for mild relativistic speed is observed only in PG1351+640 (Wang et al. 2023b), which may be large enough to explain the lack of counter-jet detection. In PG0921+525 and PG1534+580, there is no evidence for highly beamed emission ($T_{\text{B}} <$

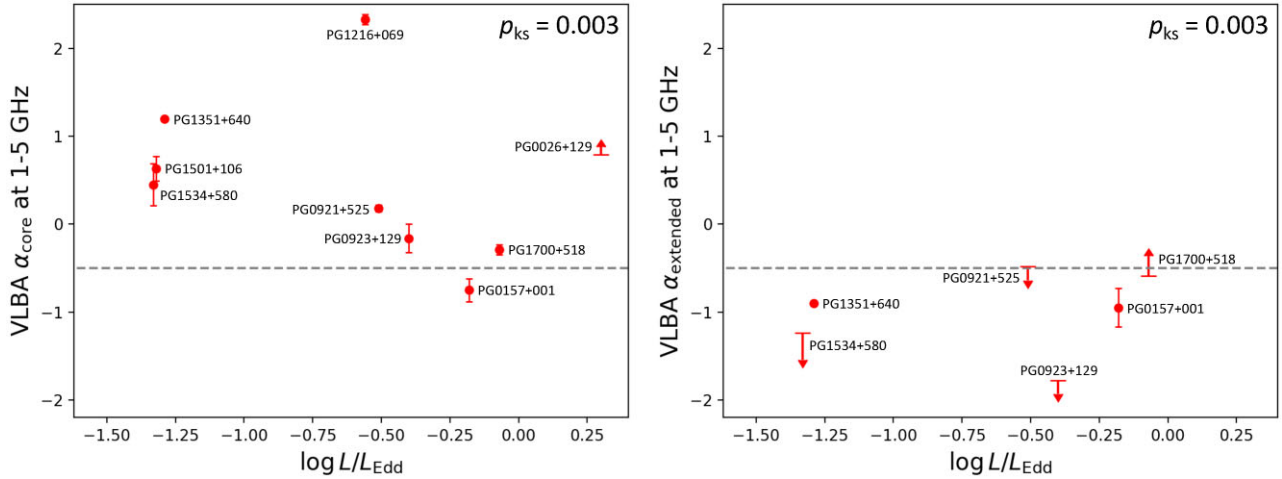


Figure 6. The VLBA spectral slope of the core flux density α_{core} (left panel) and extended flux density α_{extended} (right panel) at 1.6–4.9 GHz as a function of the Eddington ratio L/L_{Edd} for the nine objects detected in our new VLBA observations. The core emission is generally flat, while the extended emission is generally steep. There is a possible trend of α_{core} getting steeper as L/L_{Edd} increases, while α_{extended} shows no trend. The p -value of the KS test on the slopes of the core and extended components are labelled in both panels.

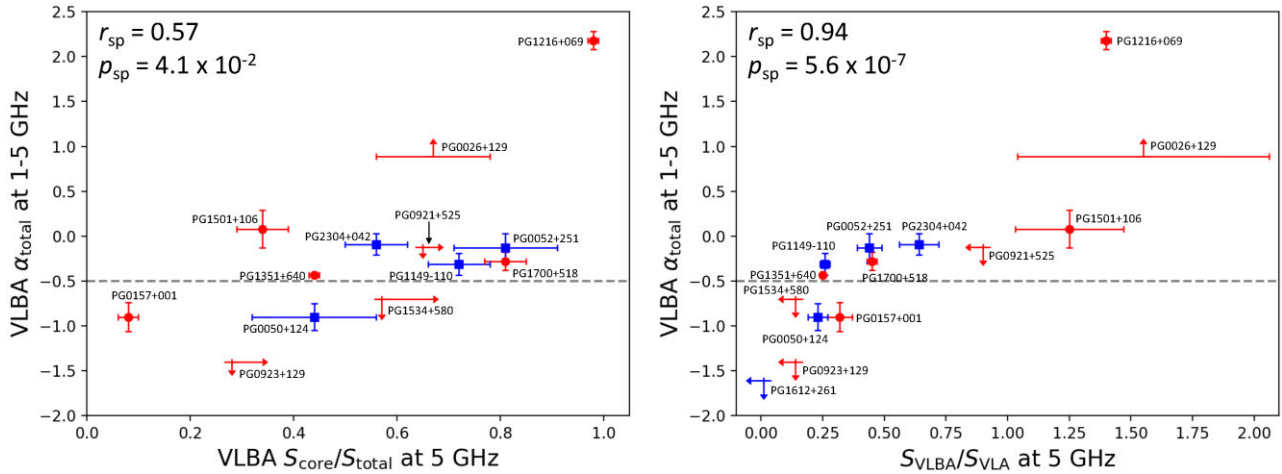


Figure 7. The VLBA spectral slope of the total flux density α_{total} at 1.6–4.9 GHz as a function of the VLBA core/total flux ratio (left panel) and the VLBA/VLA flux ratio (right panel) for the 14 RQ PG quasars. A similar trend of increasing flatness with increasing compactness is seen. The VLBA slope is flat for $S_{\text{core}}/S_{\text{total}} > 0.5$, that is, when the VLBA core emission dominates. A flat α_{total} also implies that the VLBA scale (~ 3 mas) emission dominates the VLA scale (~ 300 mas) emission. The Spearman correlation, r and p values, are labelled in both panels.

10^7 K). In these two objects, the observed asymmetry of the extended emission may reflect the host ISM asymmetry, in the case of a wind interaction with the ambient medium.

An alternative interpretation is that the radio outflow is symmetric, but the missing counterpart is the receding one, which is further away from the nucleus, and is obscured by free–free absorption from intervening ionized gas. The free–free absorption drops as ν^{-2} and a free–free absorbing screen will become optically thin at higher frequencies. If the free–free absorbing gas is photoionized by the AGN, then a screen located at ~ 10 pc is expected to become optically thin at $\nu > 10$ GHz, as indeed observed in a number of nearby AGN (see Baskin & Laor 2021, Section 4.1 therein). Radio interferometry observations at higher frequencies will allow to test the free–free absorbing screen interpretation.

The extended emission can also have a flat slope, if it is produced by optically thin free–free emission, where $\alpha \simeq -0.1$. Such a

component is not observed here, which is not surprising, as optically thin free–free emission on pc scales is characterized by $T_B \ll 10^6$ K (Baskin & Laor 2021), while the extended emission detected here has $T_B \gtrsim 10^6$ K (Fig. 8). This lower limit on T_B just reflects the sensitivity limit of current VLBA observations. Lower resolution and higher sensitivity observations may be able to detect extended free–free emission.

We further discuss the individual objects in more details, and compare the current VLBA results to earlier observations.

6.3 Core-dominated sources

The radio emission on the VLBA scales of four objects (PG0026+129, PG1216+069, PG1501+106, and PG1700+518) is dominated by the compact core, and is possibly associated with the accretion disc corona.

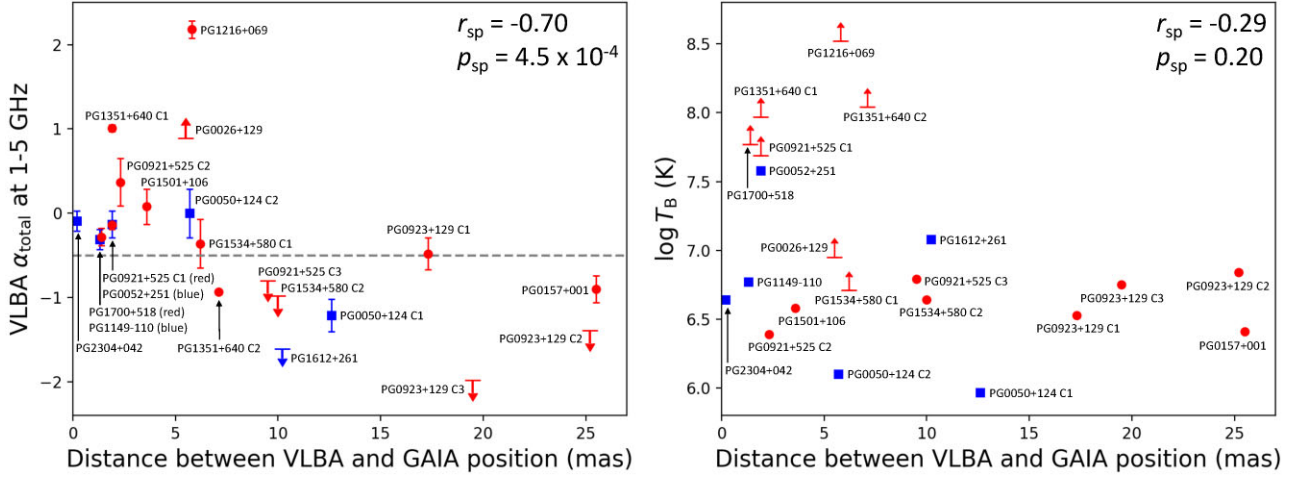


Figure 8. The VLBA spectral slope of the total flux density α_{total} at 1.6–4.9 GHz (left panel) and the brightness temperature T_B (right panel) as a function of the distance between the VLBA and the *Gaia* positions in mas for individual components of the 14 RQ PG quasars. The flat optically thick sources are all located within the astrometric position accuracy of the optical center, and are likely associated with the AGN core, while the steep optically thin sources are all physically offset from the core by $\gtrsim 10$ mas, which typically corresponds to a few tens of pc. Similarly, the components with $T_B \gtrsim 10^7$ K are all located within the *Gaia* position uncertainty, while the components away from the center are all at $T_B \lesssim 10^7$ K. The Spearman correlation, r and p values, are labelled in both panels.

PG0026+129 has an inverted slope with $\alpha_{\text{total}} > +0.9$ and $\alpha_{\text{core}} > +0.8$. It was observed with the VLA A configuration at 1.4, 4.8, 8.4, and 45 GHz. The 1.4 GHz image shows a slightly extended structure with a flux level of $\sim 3\text{--}4$ mJy (Kukula et al. 1998). The flux densities at 4.8, 8.4, and 45 GHz are $\sim 0.2\text{--}0.3$ mJy (Kellermann et al. 1989; Leipski et al. 2006; Baldi et al. 2022), which is consistent with our VLBA measurement. This indicates that the core emission on the VLBA scale dominates also on the VLA scale. The core emission has an inverted slope at 1–5 GHz and a flat slope at 5–45 GHz, which suggests that it is synchrotron self-absorbed and remains optically thick at $\nu > 45$ GHz (e.g. Raginski & Laor 2016). The source therefore is compact and variability may happen, as demonstrated by the VLBA core/total flux ratio ~ 0.7 and the VLBA/VLA flux ratio > 1 . The consistency with the *Gaia* position (~ 5.5 mas) and the high T_B ($> 10^{7.0}$ K), again indicate a compact optically thick source.

PG1216+069 has a strongly inverted slope with $\alpha_{\text{total}} = +2.2$ and $\alpha_{\text{core}} = +2.3$, which indicates synchrotron self-absorption, and again a compact optically thick source smaller than ~ 0.01 pc. The VLBA coordinate is consistent with the *Gaia* position (~ 5.8 mas) and the T_B is the highest one ($> 10^{8.5}$ K) in our sample. The object is highly compact as indicated by the VLBA core/total flux ratio ~ 1 , and is variable, since the VLBA/VLA flux ratio > 1 . Large variability is also seen by comparing the flux density at 5 GHz in our observation ($S_{\text{total}} = 6.9$ mJy) which is a factor of 5 higher than that in Wang et al. (2023a) ($S_{\text{total}} = 1.3$ mJy). The two observations were made a few years apart, so the light crossing times imply a size smaller than pc scales, which is consistent with the small size derived from synchrotron self-absorption. The object was observed with the VLBA at 1.4, 2.3, 5, and 8.4 GHz (Blundell & Beasley 1998; Ulvestad et al. 2005; Wang et al. 2023a). The 5 and 8.4 GHz maps show a very compact core and a slightly extended structure, which is consistent with our observations. The VLBA slope at 1–5 GHz in Ulvestad et al. (2005) is flat ($\alpha_{1.4-2.3} = +0.4$ and $\alpha_{2.3-5} = -0.1$), while it is inverted ($\alpha_{1.6-4.9} = +2.3$) in our new VLBA observations and is consistent with the slope of synchrotron self-absorption. A possible explanation is that we may be observing a new compact synchrotron component, and the compact radio emission observed

in Ulvestad et al. (2005) may have expanded and become optically thin at 1–5 GHz with weaker and negligible emission by now. On the VLA scales, this object shows slightly extended emission with the A configuration (Kellermann et al. 1989, 1994), which may reflect past activity that faded and expanded to larger scales by now.

PG1501+106 has a slightly inverted total slope $\alpha_{\text{total}} = +0.1$ and a more inverted core slope $\alpha_{\text{core}} = +0.6$. The VLBA coordinate is consistent with the *Gaia* position (~ 3.6 mas), though the T_B is not too high ($\sim 10^{6.6}$ K). There is some extended emission, as the VLBA core/total flux ratio < 0.5 . The VLBA/VLA flux ratio > 1 again manifests that the source is variable. This object was observed with the VLA A configuration at 4.8 and 8.4 GHz (Kellermann et al. 1989; Kukula et al. 1995). It shows a compact core and an inverted VLA slope ($\alpha_{4.8-8.4} = +0.4$), which indicates that the emission detected in our VLBA observation is still dominant on the VLA scales. This is consistent with the picture that the radio emission in low- L/L_{Edd} objects is dominated by the compact optically thick core.

PG1700+518 is a BAL quasar. It has a flat slope with both α_{total} and $\alpha_{\text{core}} = -0.3$. The VLBA coordinate is consistent with the *Gaia* position (~ 1.4 mas), and the T_B is high ($> 10^{7.8}$ K). The object is very compact as indicated by the VLBA core/total flux ratio ~ 0.8 . The VLBA/VLA flux ratio ~ 0.5 suggests that part of the extended emission is resolved out on the VLBA scales but unresolved on the VLA scales. This object was previously observed with the VLBA at 4.8 and 8.4 GHz, and both images show a core and a little extended emission (Blundell & Beasley 1998; Wang et al. 2023a). Moreover, observations with the VLA A configuration at 4.8 and 8.4 GHz reveal two components (Kellermann et al. 1989, 1994; Kukula et al. 1998). An EVN observation at 1.6 GHz of one of the two components reveals a core plus two-sided extended structures (Yang et al. 2012). These structures may result from an outflow, as the object is a BAL quasar, which has a high velocity outflow (Young et al. 2007; Runnoe, Gültekin & Rupke 2018). However, the extended emission detected in Yang et al. (2012) is resolved out on the VLBA scales, and we thus only see a compact core, which is probably the base of the outflow.

6.4 Radio outflows

Four sources (PG0157+001, PG0921+525, PG0923+129, and PG1534+580) are likely to produce an outflow emission on the VLBA scales, though they are distributed at both high and low L/L_{Edd} .

PG0157+001 has a steep slope with $\alpha_{\text{total}} = -0.9$ and $\alpha_{\text{core}} = -0.8$, which indicates that an optically thick compact core is probably missing or below the detection limit. The steep slope emission is in agreement with earlier VLBA observations, where it was detected at 5 GHz (Wang et al. 2023a), but not detected at 8.4 GHz (Blundell & Beasley 1998). Observations with the VLA A configuration at 1.4, 4.8, 8.4, and 45 GHz were carried out. The 4.8 and 8.4 GHz maps reveal multiple components, a central core plus one/two-sided aligned extended structures (Kellermann et al. 1989, 1994; Kukula et al. 1998; Leipski et al. 2006). The VLA slope at 5–45 GHz is still steep with $\alpha_{5-45} = -1$ (Baldi et al. 2022), which is comparable to the VLBA slope at 1–5 GHz. This suggests that the emission detected with the VLBA and the VLA, though at different scales, may have the same origin, possibly an optically thin outflow, which extends from pc to sub-kpc scales. Moreover, the large distance from the *Gaia* position (~ 26 mas), the relatively low T_B ($\sim 10^{6.4}$ K), the VLBA core/total flux ratio (~ 0.1), and the VLBA/VLA flux ratio (~ 0.3), again manifest that the emission is likely associated with an extended outflow.

PG0921+525 has three components. The slopes of C1 ($\alpha_{\text{total}} = -0.1$) and C2 ($\alpha_{\text{total}} = +0.4$) are flat/inverted, and that of C3 ($\alpha_{\text{total}} < -0.8$) is steep. The T_B is high for C1 ($> 10^{7.7}$ K), and is lower for C2 ($\sim 10^{6.4}$ K) and C3 ($\sim 10^{6.8}$ K). C1 and C2 are consistent with the *Gaia* position (~ 1.9 and 2.3 mas), and C3 is farther away (~ 9.5 mas). These properties suggest that C1 may be the core, C2 may be a new ejection as it is still optically thick and very close to the core, and C3 may be an older ejection as it is already optically thin and farther away from the core. The radio emission is dominated by the core component, as indicated by the VLBA core/total flux ratio (> 0.7) and the VLBA/VLA flux ratio (< 0.9). This object was observed with the VLBA at 1.7 and 5 GHz. Both images show a compact core with comparable flux densities (~ 1.0 – 1.2 mJy) (Doi et al. 2013; Wang et al. 2023a), which indicates a flat slope ($\alpha_{1.7-5} = -0.1$) and is consistent with our measurement. The extended structure was not detected in earlier VLBA observations, which may be due to the detection limit. On the VLA scales, it was observed with the A configuration at 1.4, 4.8, and 8.4 GHz. The 1.4 and 4.8 GHz images show a core plus extended structure, while the 8.4 GHz image only shows a core (Kellermann et al. 1989, 1994; Kukula et al. 1998). The flux density of the core at 1.4 GHz (~ 5.8 mJy) is three times higher than that at 4.8 and 8.4 GHz (~ 1.7 – 1.9 mJy), which suggests that a steep slope ($\alpha_{1.4-4.8} = -0.9$) component is dominant at 1–5 GHz, and a flat slope ($\alpha_{4.8-8.4} = -0.2$) component becomes prominent at 5–8 GHz. In addition, radio variability was detected on both the VLBA and the VLA scales (Panessa et al. 2022a; Chen, Laor & Behar 2022b).

PG0923+129 also has three components, the slope of C1 is flat ($\alpha_{\text{total}} = -0.5$), and that of C2 ($\alpha_{\text{total}} < -1.4$) and C3 ($\alpha_{\text{total}} < -2.0$) is steep, which suggests that C1 is likely the core emission, and C2 and C3 are probably the linear extended outflow emission. The source is indeed extended, as indicated by the VLBA core/total flux ratio and the VLBA/VLA flux ratio both < 0.5 . The T_B of all three components are not too high ($\sim 10^{6.5}$ – $10^{6.8}$ K). They are also far away from the *Gaia* position (~ 17 – 25 mas). An earlier VLBA observation of this object show a compact core plus a weak extended structure at 1.7 GHz (Doi et al. 2013). The two-sided linear extended emission at 1.6 GHz in our new VLBA observation is not detected in Doi et al. (2013),

though the flux density of the two extended components is higher than their detection limit. In addition, the core flux density (~ 0.9 mJy) in our observation is only half of the value (~ 1.8 mJy) in Doi et al. (2013). This may demonstrate that the core emission becomes fainter while the extended emission becomes brighter. A possible explanation is that the outflow carries energy and propagates from the central core when it launches, which makes the core emission decreases and the extended emission increases. However, the core component at 4.9 GHz in our new VLBA observation is not detected in earlier VLBA observations at 4.8 and 8.4 GHz (Blundell & Beasley 1998; Wang et al. 2023a), which may be due to different detection limits. A compact core with a flux density of ~ 2.0 mJy at 8.5 GHz was detected with the VLA A configuration (Schmitt et al. 2001).

PG1534+580 has two components. The core component (C1) has a flat slope ($\alpha_{\text{total}} = -0.4$), a high T_B ($> 10^{6.7}$ K), and is consistent with the *Gaia* position (~ 6.2 mas). The extended component (C2) has a steep slope ($\alpha_{\text{total}} < -1.0$), a lower T_B ($\sim 10^{6.6}$ K), and is farther away from the *Gaia* position (~ 10 mas), which is possibly an outflow emission. The extended emission is in a scale of being resolved out with the VLBA and unresolved with the VLA, as indicated by the VLBA core/total flux ratio > 0.6 and the VLBA/VLA flux ratio < 0.1 . This object shows a compact core with a flux density of ~ 1.8 – 2.2 mJy at 4.8 GHz with the VLA A configuration (Kellermann et al. 1989; Leipski et al. 2006).

6.5 A mildly relativistic jet?

PG1351+640 is an intriguing object exhibiting two components. The core component C1 has a flat slope with $\alpha_{\text{total}} = +1.0$, a high T_B ($> 10^{8.0}$ K), and is consistent with the *Gaia* position (~ 1.9 mas), which is in agreement with a compact optically thick synchrotron source. The extended component C2 is optically thin with a steep slope $\alpha_{\text{total}} = -0.9$, and is farther away from the *Gaia* position (~ 7.1 mas). Its T_B is still high ($> 10^{8.0}$ K), which is 1–2 orders of magnitude higher than the extended emission in the other objects, which makes this extended component resemble the lobe of a radio jet. Furthermore, the object has a large fraction of extended emission as indicated by the VLBA core/total flux ratio and the VLBA/VLA flux ratio both < 0.5 (Fig. 7).

PG1351+640 was observed with the VLBA at 1.4, 2.3, and 5 GHz in 2000 (Ulvestad et al. 2005) and at 8.4 GHz in 1996 (Blundell & Beasley 1998). The 5 GHz map shows a single unresolved component, and the 8.4 GHz map shows a core and some extended emission $\lesssim 2$ mas to the northwest, which may be because the extended structure was closer inwards, marginally resolved at 8 GHz and unresolved at 5 GHz. This object also has VLBI observations at 2.3 and 8.4 GHz in 2011. The maps from the Astrogeo Center³ show only one component at 2.3 GHz and two components, a core plus an extended component ~ 5 mas to the northwest, at 8.4 GHz.

The extended emission at 8 GHz in 2011 was ~ 5 mas away from the core, while it was $\lesssim 2$ mas from the core in 1996. This implies that the jet moved $\gtrsim 3$ mas, corresponding to $\gtrsim 5.7$ pc, in $\lesssim 15$ yr with an apparent velocity of $\gtrsim 1.2c$ (c is the speed of light). A recent study by Wang et al. (2023b) who observed this object with the VLBA at 5 GHz in 2015, also finds that this object has a core + jet morphology which is similar to our result. A comparison on the separation of the two components in 2015 and 2022 shows that the jet only moved ~ 0.5 mas, corresponding to ~ 1.0 pc, in ~ 7 yr, which suggests that the jet moved at a speed of only $\sim 0.5c$ (Wang et al.

³<http://astrogeo.org/index.html>

2023b). The earlier estimates are rough, and more VLBI monitoring are necessary to clarify the proper motion of the jet. The presence of the proper motion in this object clearly excludes a possible binary BH interpretation, and confirms that it is a core + jet system.

The spectral slope at 1–5 GHz in Ulvestad et al. (2005) is steep ($\alpha_{1.4-2.3} = -0.8$ and $\alpha_{2.3-5} = -1.0$), while the measurement in our observations is flat ($\alpha_{\text{total}} = -0.4$). A possible explanation is that we may be observing a new compact synchrotron component, and the extended emission observed in Ulvestad et al. (2005) may have expanded and become faint and undetectable by now.

PG1351+640 was also observed with the VLA A configuration at 5 GHz. It shows a central core with a flux density of ~ 20 mJy in Kellermann et al. (1989). The flux density decreased to ~ 7 –9 mJy, that is, by a factor of 2–3 in Leipski et al. (2006), and the source shows two-sided extended emission, in addition to the central core. The linear extended morphology and the high variability (Barvainis & Antonucci 1989) are in agreement with the jet origin of the radio emission.

7 SUMMARY

In this work, we present the mas-scale radio emission properties of optically selected RQQ. The sample is selected from the 71 RQ PG quasars at $z < 0.5$, and covers a wide range in luminosity ($-27 < M_V < -21$) and H β FWHM (~ 1000 – $10\,000$ km s $^{-1}$). The study is based on our new VLBA observations of 10 RQQ at 1.6 and 4.9 GHz, of which nine were detected, and earlier similar observations of eight more RQQ, of which five were detected (Alhosani et al. 2022), which together yields a sample of 18 objects, of which 14 were detected. The main results are summarized as follows.

(1) The mas-scale emission in most of the RQQ is composed of a compact core, which is consistent with the *Gaia* optical position. The spectral slope of the compact core emission is flat or inverted in nearly all cases with T_B extending to $> 10^8$ K. The compact optically thick sources have a physical size of ~ 0.01 – 0.4 pc, and possibly originate from the accretion disc corona.

(2) The extended emission detected in some of the RQQ is generally optically thin synchrotron emission, and is characterized by a steep slope and a lower T_B ($< 10^7$ K). The extended sources located ~ 5 – 100 pc from the center, may be formed by a clumped outflow of magnetized plasma, for example, the coronal mass ejection or an intermittent jet. Alternatively, it may originate from a shocked nuclear wind.

(3) The VLBA core luminosity of all objects at $\log M_{\text{BH}}/M_\odot < 8.5$ is correlated with the X-ray luminosity following $\log L_R/L_X \simeq -6$, which may indicate a coronal origin of the radio core emission. Three of the five objects at $\log M_{\text{BH}}/M_\odot > 8.5$ have $\log L_R/L_X \gtrsim -4$, of which one potentially shows a mildly relativistic jet/outflow.

(4) The larger scale VLA emission (~ 300 mas) of the 18 objects follows $\log L_R/L_X \simeq -5$, as found in earlier studies. The L_R/L_X shows a gradual rise with M_{BH} above $\sim 10^7 M_\odot$, which suggests that the larger the BH mass, the higher the chances to produce extended emission.

(5) In one object PG1351+640, a comparison with earlier VLBI observations suggests a mildly relativistic jet in the past ~ 7 yr, and potentially a super-luminal jet in the past ~ 15 yr. This may well represent an intermediate RQQ, which is powered by a jet weaker than that in RLQ.

Our recent e-MERLIN and uGMRT observations of this sample (Chen et al. in preparation), forthcoming higher frequency VLBA observations, and future VLA observations, will help to establish the

dominant radio emission mechanisms on different scales, and the interaction of the AGN with the host galaxy from pc to kpc scales. In addition, future observations at higher frequencies, especially in mm-wave bands (e.g. Behar et al. 2015, 2018; Ricci et al. 2023), can help to clarify the nature of the AGN core emission.

Finally, the results have to be taken with caution given the small sample size. Further studies of a large sample are necessary to confirm these findings and draw a more reliable picture of the radio emission in RQ AGN.

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8 DATA AVAILABILITY

The radio data underlying this article are available in the NRAO Science Data Archive at <https://archive.nrao.edu/archive/advquery.jsp>, and can be accessed with the project code of BC273.

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