

Probing the Low Radio Frequency Emission in PG Quasars with the uGMRT - II

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ABSTRACT

We present results from uGMRT 685 MHz observations of 87 QSOs belonging to the Palomar Green (PG) quasar sample with $z < 0.5$. Radio emission is detected in all sources except for 3 radio-quiet (RQ) sources, viz., PG 0043+039, PG 1121+422, and PG 1552+085. The radio-loud (RL) – RQ dichotomy persists at 685 MHz with only 1 source, PG 1216+069, changing its classification from RQ to RL. Approximately 1/3 of the detected RQ quasars display AGN-dominated radio emission while the rest may show additional contributions from stellar-related processes. Consistent with this, the RL and RQ quasars occupy distinct tracks on the ‘fundamental plane’ of black hole activity. We find that RL quasars have $\log_{10}(L_{685\text{ MHz}}/\text{W Hz}^{-1}) > 25.5$, while RQ quasars have $\log_{10}(L_{685\text{ MHz}}/\text{W Hz}^{-1}) < 23.5$. Furthermore, the radio sizes display the RQ–RL divide as well with RQ sources typically having sizes $\lesssim 30$ kpc, with only 16 ($\sim 22\%$) RQ sources having sizes between 30 and 100 kpc where there is an overlap with RL quasar sizes. A strong correlation exists between 685 MHz radio luminosity and black hole mass which is tightened when accretion rate is considered, highlighting the important role played by the accretion rate and accretion disk structure in jet production. We found no difference in the minimum-energy magnetic field strengths of the radio cores of RL and RQ quasars; however, different assumptions of source volume and volume filling factors may apply. High-resolution X-ray observations and radio-X-ray flux comparisons are needed to independently test the ‘magnetic flux paradigm’.

Keywords: Radio continuum — Radio interferometry — Radio-loud quasars — Radio-quiet quasars

1. INTRODUCTION

Active galactic nuclei (AGN) are powered by mass accretion on to supermassive black holes (SMBHs) in the centers of galaxies (Rees 1984). The majority of AGN ($\sim 90\%$) comprise weak outflows that extend to sub-kpc scales and are often diffuse or wind-like (e.g., Giroletti & Panessa 2009). These are the radio-quiet (RQ) AGN. Radio-loud (RL) AGN, on the other hand, exhibit powerful relativistic jets that extend to hundreds of kpc and megaparsec scales. The radio-loudness parameter, R , defined as the ratio of the 5 GHz flux density to the optical (B band) flux density, is used to distinguish between these two classes (Kellermann et al. 1989), with RL AGN having $R > 10$ and RQ AGN having $R \leq 10$.

Multiple explanations have been proposed for the observed RL-RQ dichotomy including differences in SMBH masses (e.g., Laor 2000; McLure & Dunlop 2001; Wu & Han 2001; Gopal-Krishna et al. 2008; Richings et al. 2011), SMBH spins (e.g., Tchekhovskoy et al. 2010; Sikora et al. 2007), accretion rates (e.g., Ho 2002; Sikora et al. 2007; Best & Heckman 2012) and environments (e.g., Best et al. 2005; Croft et al. 2007; Kauffmann et al. 2008; Wylezalek et al. 2013). One hypothesis is that quasars experience intermittent radio activity; they remain RQ most of their life and become RL during active phases (e.g., Coziol et al. 2017; Silpa et al. 2021). This latter idea can be connected to the ‘magnetic flux paradigm’ by Sikora & Begelman (2013) which has been invoked to explain the RL-RQ divide. According to the ‘magnetic flux paradigm’, RQ AGN must have much lower magnetic field strengths close to the central black holes compared to RL AGN (e.g., Chamani et al. 2021). Alternatively, the ‘spin paradigm’ suggests that SMBH

spin controls jet power with rapidly spinning black holes launching strong relativistic jets (producing radio-loud AGN), while slowly spinning black holes produce only weak radio emission (e.g. Moderski et al. 1998; Sikora et al. 2007; Tchekhovskoy et al. 2010).

Low-frequency surveys do not show a significant change in the relative fraction of RL to RQ quasars (Ennis et al. 1982; Robson et al. 1985). Studies suggest that geometry and relativistic beaming play a role, with radio emission appearing stronger when jets are oriented toward us (Urry & Padovani 1995; Fan et al. 2004; Xiao et al. 2015; Pei et al. 2016). However, beaming alone is insufficient to explain the dichotomy (Kellermann et al. 1989, 2004). The host galaxy may also influence radio emission, as low-luminosity radio emission have been linked to star formation and supernovae activity (Kellermann et al. 2016).

In RL AGN, jets are thought to originate from the central engine via two key mechanisms: the Blandford–Znajek process, which extracts rotational energy from a spinning supermassive black hole (Blandford & Znajek 1977), and the Blandford–Payne mechanism, an MHD process in which the rotating accretion disk launches outflows by accelerating material along large-scale magnetic field lines anchored in the disk (Blandford & Payne 1982). The radio emission in AGN jets is produced via the synchrotron process. However, the origin of radio emission in RQ AGN remains unclear (Panessa et al. 2019), with proposed mechanisms including star formation (Terzian 1965; Gürkan et al. 2019) and coronal activity (Laor & Behar 2008), starburst and/or AGN-driven winds (Condon et al. 2013; Irwin & Saikia 2003; Hota & Saikia 2006; Mizumoto et al. 2019), weak radio jets (Falcke et al. 2000; Jarvis et al. 2019; Kharb et al. 2019), and free-free emission from disk or torus winds (Blundell & Kuncic 2007; Ho 1999; Lal & Ho 2010).

This paper is the second in the series after Silpa et al. (2020, henceforth, referred to as Paper I), where we examine the origin of radio emission in RQ AGN and investigate the RL–RQ dichotomy using low-frequency data at 685 MHz from the upgraded Giant Metrewave Radio Telescope (GMRT), in the Palomar–Green (PG; Green et al. 1986) sample of quasars. In this paper, we present the results on 65 PG quasars, in addition to the 22 sources presented in Paper I. The GMRT 685 MHz angular resolution of $\sim 4''$, translates to spatial scales of a few kpc for the PG quasars.

The paper is organized as follows. The PG sample is described in Section 2. Section 3 describes the uGMRT data reduction and analysis. The results are presented in Section 4, discussion in Section 5, and the conclusions of

this work are given in Section 6. Throughout this paper, we have assumed Λ cold dark matter cosmology with $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$ and $\Omega_v = 0.73$. The spectral index α_R , derived using the 685 MHz peak flux densities (this work) and the 5 GHz peak flux densities reported by Kellermann et al. (1994), is defined such that flux density at frequency ν , $S_\nu \propto \nu^{\alpha_R}$.

2. THE SAMPLE

The PG catalog encompasses ~ 1800 UV-excess objects (i.e., $U-B < -0.44$), identified through an optical survey covering an area of approximately $\sim 10,714 \text{ deg}^2$ at absolute galactic latitudes exceeding 30 degrees. This survey utilized 266 double U and B exposures from the Palomar 18-inch Schmidt Telescope (Green et al. 1986). The Palomar Bright Quasar Survey (BQS), a subset of the PG survey, selected objects based on specific criteria: (1) morphological criteria indicating a dominant star-like appearance and (2) spectroscopic criteria revealing the presence of broad emission lines. The BQS sample comprised 114 objects, including 92 quasars with $M_B < -23$ and 22 Seyferts or low-luminosity quasars with $M_B > -23$. Our focus is on the PG quasar sample, consisting of objects from the BQS with redshifts $z < 0.5$. This subset includes 87 sources, encompassing both quasars and Seyfert type 1 galaxies (Boroson & Green 1992). Nearly 80% (71/87) of the sample is RQ, while the remaining 20% (16/87) is RL (Kellermann et al. 1989).

The PG quasar sample stands out as one of the most extensively studied samples of low-redshift AGN. It boasts a wealth of data, including accurate black hole masses obtained from reverberation mapping (Kaspi et al. 2000) and single-epoch spectroscopy data (Vestergaard & Peterson 2006), detailed host galaxy morphologies and bulge/disc decompositions from Hubble Space Telescope (HST) imaging data (Kim et al. 2008, 2017), comprehensive broad-band spectral energy distributions (SEDs) and accurate bolometric luminosities across various wavelengths (Shang et al. 2011), observations elucidating dust (Petric et al. 2015; Shangguan et al. 2018) and gas properties (Evans et al. 2006; Shangguan et al. 2020), enabling analyses of the interstellar medium of host galaxies, and infrared (IR) data facilitating investigations into torus properties (Zhuang et al. 2018) and star formation rates (SFR; Shi et al. 2014). There however, remains a dearth of high-sensitivity low-frequency radio data on this sample.

Paper I discusses the results from our pilot study conducted for a sample of 22 PG quasars (20 RQ and 2 RL) with the uGMRT at 685 MHz. These sources were chosen on the basis of availability of Atacama Large Mil-

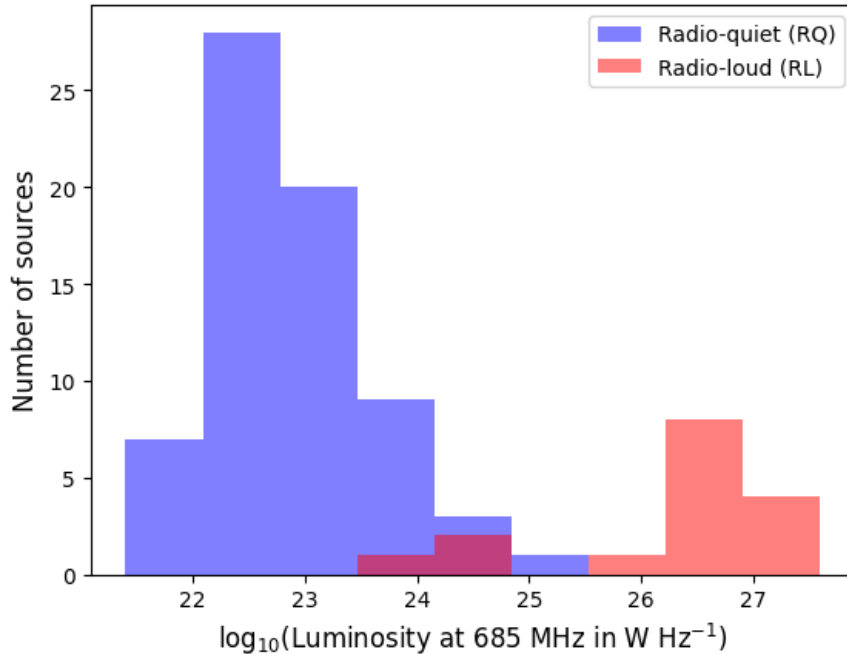


Figure 1. Distribution of the uGMRT 685 MHz luminosities for the PG quasar sample. The RL-RQ dichotomy persists in the low-frequency uGMRT data.

limeter/submillimeter Array (ALMA) data (Shangguan et al. 2020) to study the low-frequency radio emission in tandem with the CO(2–1) molecular emission. In the current paper, we present results from observations carried out at 685 MHz on the 65 remaining PG quasars with the uGMRT, thereby completing the first GMRT low-frequency survey of the PG quasar sample.

3. OBSERVATIONS AND DATA REDUCTION

The GMRT 685 MHz observations of the PG quasars were carried out from 2019 December to 2020 January (Project ID: 37.042; PI: Silpa S.). Data were reduced and analyzed using the standard procedures in CASA¹. To optimize the uv -coverage, each target was observed for at least two scans of ~ 20 min each. The flux calibrators 3C 48, 3C 286, 3C 138, and/or 3C 147, were observed for 5 min at the start and end of the observations. The observations of the phase calibrators (of 4 min) and targets were interspersed, allowing the time-dependent amplitude and phase calibration solutions to be interpolated onto the time intervals of the target observations in between the calibrators. The GMRT observations are summarized in Table 1. These observations can measure the largest angular scale of $\sim 25'$, with the FWHM of

the synthesized beam being $\sim 3\text{--}5''$. The basic calibration strategy is described below.

The GMRT produces data in the Long-Term Archive (LTA) format, which needs to be first converted to the Flexible Image Transport System (FITS) format. This step was carried out using the LISTSCAN and GVFITS utilities. 4096 channels spanning 560–810 MHz were used in these observations; beyond 810 MHz, the sensitivity drops significantly. The non-usable frequency range (810–950 MHz) and non-working antennas were omitted from the log file generated by LISTSCAN, resulting in the final FITS file covering the frequency range 560–810 MHz. Using the CASA task IMPORTUVFITS, the FITS file was converted to a measurement set (MS), which was then provided as the input file to the respective pipelines described below. Out of the 65 sources, 25 were analysed using our CASA-based pipeline available at <https://sites.google.com/view/silpasasikumar/>, while the remaining 40 sources were reduced using the CAsa Pipeline-cum-Toolkit for Upgraded GMRT data REduction (CAPTURE) pipeline (Kale & Ishwara-Chandra 2021), available at <https://github.com/ruta-k/CAPTURE-CASA6>.

We performed four iterations of phase-only self-calibration and four iterations of amplitude and phase self-calibration, except for PG 2251+113, where four iterations of phase-only self-calibration and only two rounds of amplitude and phase self-calibration were performed, as further rounds did not improve the image

¹ Common Astronomy Software Applications; McMullin et al. (2007)

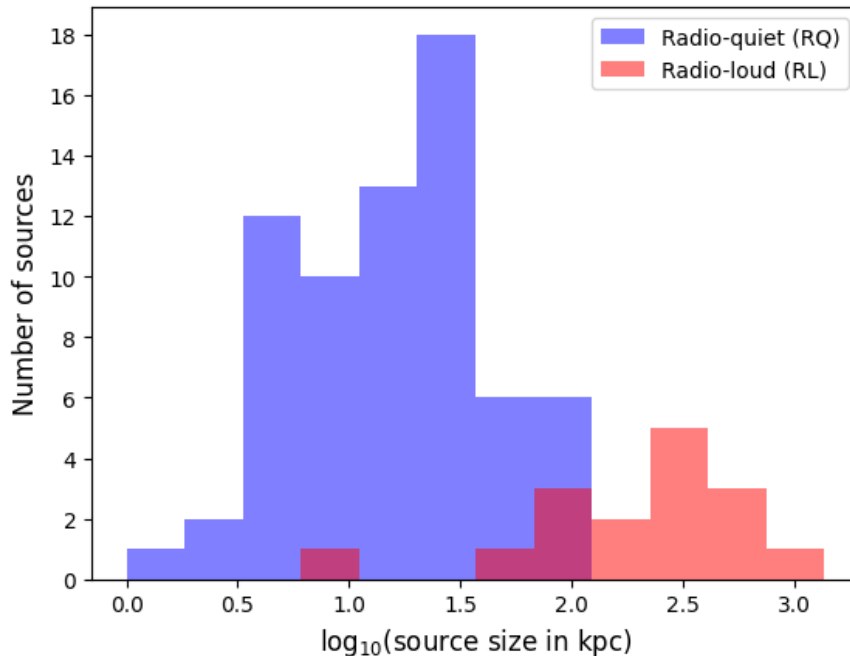


Figure 2. Distribution of 685 MHz projected radio source sizes in kpc for the PG quasar sample.

quality. For all the sources, the `ROBUST` parameter was chosen to be 0.5, except for PG 0003+158 where a value of `ROBUST` = 1 was adopted in order to mitigate the imaging artefacts and improve sensitivity, while still maintaining adequate resolution. The basic calibration and imaging steps have been discussed in detail in Paper I.

The 685 MHz peak and total flux density of individual sources was calculated using the `AIPS` task `JMFIT`. For the sources where `JMFIT` did not converge and/or the sources that have multiple components, tasks `TVMAXF` and `TVSTAT` were used to calculate the peak flux and total flux densities, respectively. All flux density measurements are reported in Table 1. The peak flux densities range from $0.3 \text{ mJy beam}^{-1}$ to $\sim 3 \times 10^4 \text{ mJy beam}^{-1}$ (Table 1). The rms noise for the sample, measured locally from blank sky regions around each quasar, is typically around $\sim 30 - 40 \mu\text{Jy beam}^{-1}$ (except for a few sources where it is explicitly mentioned).

The errors in the flux densities were calculated by considering a 10% amplitude calibration uncertainty (for the uGMRT) and the rms noise of individual sources. The size of the sources reported in this paper were measured using the Gaussian-fitting `AIPS` task `JMFIT` (for unresolved sources) and `TVDIST` (for extended sources). The typical errors in sizes are $\sim 3\%$.

The results of our analysis are presented in the following section. Linear fits ($y = mx + c$) to all correlation plots were obtained using the `numpy.polyfit` routine in

Python. The corresponding correlation coefficients and p-values are summarized in Table 2.

4. RESULTS

We detect 685 MHz radio emission in all sources except for the RQ quasars PG 0043+039, PG 1121+422, and PG 1552+085, at the 3σ level. Figure 1 presents the 685 MHz luminosities of the PG sample with sources classified RL and RQ following Kellermann et al. (1989). Figures 9 to 19 present the 685 MHz images of the PG quasars. RL sources in the sample exhibit large-scale jets on hundreds of kiloparsec scales, except for PG 2209+184 with ~ 7 kpc size and PG 1425+267 with a total extent of ~ 1.3 Mpc.

Of the 16 RL sources, seven exhibit morphological features such as X-shaped lobes, hybrid morphology, and highly bent or knotty jets, which could arise either due to environmental effects or due to restarted AGN jet activity. Five sources (see Table 1), remain unresolved at the uGMRT resolution of $\sim 4''$. Below we discuss the RL-RQ luminosity and size divide followed by results on the core radio spectral indices and the possible origins of the low-frequency radio emission.

4.1. The RL-RQ Divide: 685 MHz Luminosity, Sizes & Equipartition Magnetic Field Strengths

The RQ and RL populations display a bimodal distribution in the 685 MHz luminosities, ($L_{685 \text{ MHz}}$), with a small overlap (Figure 1). Based on this distribution, we find the follow-

ing empirical division: RQ quasars typically show $\log_{10}(L_{685 \text{ MHz}}/\text{W Hz}^{-1}) < 23.5$, while RL quasars mostly show $\log_{10}(L_{685 \text{ MHz}}/\text{W Hz}^{-1}) > 25.5$. ‘Intermediate’ sources have $23.5 \leq \log_{10}(L_{685 \text{ MHz}}/\text{W Hz}^{-1}) \leq 25.5$.

The RL sources with $L_{685 \text{ MHz}} < 10^{25.3} \text{ W Hz}^{-1}$ are: PG 0007+106 (III Zw 2), PG 1309+355, PG 1425+267, and PG 2209+184. Of these, PG 2209+184 is a flat-spectrum radio quasar (FSRQ) without any signature of kpc-scale jets (see [Silpa et al. 2020](#)). PG 1425+267 is a large FR II radio galaxy without a dominant core or hotspots. The following RQ sources have $L_{685 \text{ MHz}} > 10^{24} \text{ W Hz}^{-1}$: PG 0157+001, PG 1216+069, PG 1543+489, PG 1612+261, PG 1700+518, and PG 2112+059. All these sources are core-dominant sources without substantial extended emission.

We also examined the distribution of the source sizes in kpc (Table 1) for the PG sample. As shown in Figure 2, the radio sizes display the RQ–RL divide as well, with RQ sources typically having sizes $\lesssim 30$ kpc, with only 16 ($\sim 22\%$) RQ sources having sizes between 30 and 100 kpc where there is an overlap with RL quasar sizes. For a source size of 30 kpc with a jet speed equal to the speed of light (the actual jet speed would indeed be a fraction of this) would imply a lower limit to the source age to be $\sim 10^5$ yrs. The RL quasars, PG 1226+023, PG 1302-102, PG 1309+355, PG 2251+113, and PG 2209+184 have sizes < 100 kpc. Among these sources, PG 1226+023, PG 1302-102, PG 1309+355, and PG 2209+184 are FSRQs, while PG 2251+113 is a NLSy1/SSRQ. Hence, their small size is likely due to projection effects caused by small viewing angle. The RQ source PG 1216+069 has a large extent of ~ 98 kpc. Our image shows the source to be a regular radio galaxy albeit with weak diffuse emission. This source appears to be misclassified RL AGN; its 685 MHz luminosity also places it into the RL category. The radio size appears to be a better discriminant of the radio-loudness/radio-quietness of a quasar compared to the radio luminosity.

As differences in magnetic field strengths close to the central black holes has been suggested to explain the RL–RQ divide (e.g. [Tchekhovskoy et al. 2010](#); [Chamani et al. 2021](#); [Lopez-Rodriguez et al. 2023](#)), we examined the distribution of ‘minimum-energy’ magnetic field strengths ($B_{\min}$) for the RQ and RL sources in our sample, following the relations in [O’Dea & Owen \(1987\)](#). We adopted a proton-to-electron energy ratio (k) of unity and assumed a volume filling factor (ϕ) of 1. The radio spectrum was taken to span a frequency range from 10 MHz (ν_l) to 100 GHz (ν_u). For each source, the integrated flux density of the core (listed in Table 1) was used along with a fixed flat

spectral index of $\alpha = -0.2$.² The theoretical value of the dimensionless parameter C_{12} , that incorporates the frequency integration over the synchrotron spectrum and depends on the adopted spectral index and frequency limits, is taken for $\alpha = -0.2$ to be 8.3×10^6 (see [Pacholczyk 1970](#)). A spherical geometry was assumed for the emitting volume, with the radius derived from the core sizes measured using the task JMFIT in AIPS.

Figure 3 shows the histogram of $\log_{10}(B_{\min})$ for the RQ and RL sources. We do not observe any bimodality in the distribution, and the $B_{\min}$ values for the two populations show an overlap, with the exception of the RL source, PG 1226+023, a.k.a. 3C 273. While on the surface, this may suggest no difference in the magnetic field strengths, it is important to note that the assumptions made in the magnetic field estimation are likely not valid for both AGN classes. For instance, differences in parameters such as the source volume and volume filling factors, as well as the source relativistic proton-to-electron energy ratio (k), are likely to be different between the AGN sub-classes which may result in the net magnetic field strengths being lower in RQ sources (e.g., [Chamani et al. 2021](#)). It is interesting to note that the RQ and RL AGN differ statistically significantly at the $\sim 3\sigma$ level when $k = 3$ in the RL sources. Independent estimates of magnetic field strengths need to be made using core radio and X-ray flux density, the former being due to synchrotron emission and the latter due to inverse-Compton. As of now, high resolution Chandra X-ray observations that can isolate the core emission, do not exist for the PG quasar sample to test the above.

4.2. Radio Core Spectral Indices & Origin of Radio Emission

The radio core spectral index values (α_R) derived using the 685 MHz peak flux densities (this work) and the 5 GHz peak flux densities reported by [Kellermann et al. \(1994\)](#) have been noted in Table 3. For the sources studied in Paper I, the values were recalculated using the same methodology and are provided in the same Table with source names in bold. The cores of RQ sources, on average, exhibit steeper spectra (mean α_R : -0.7) than the cores of RL sources (mean α_R : -0.2). All RL sources in our sample, except PG 1100+772 and PG 1704+608 have flat or inverted spectrum cores, indicative of synchrotron self-absorbed bases of jets. PG 1100+772 and PG 1704+608 exhibit very steep spectrum cores ($\alpha_R \sim -1$). The spectral index for PG 2251+113, when calculated using the 5 GHz flux

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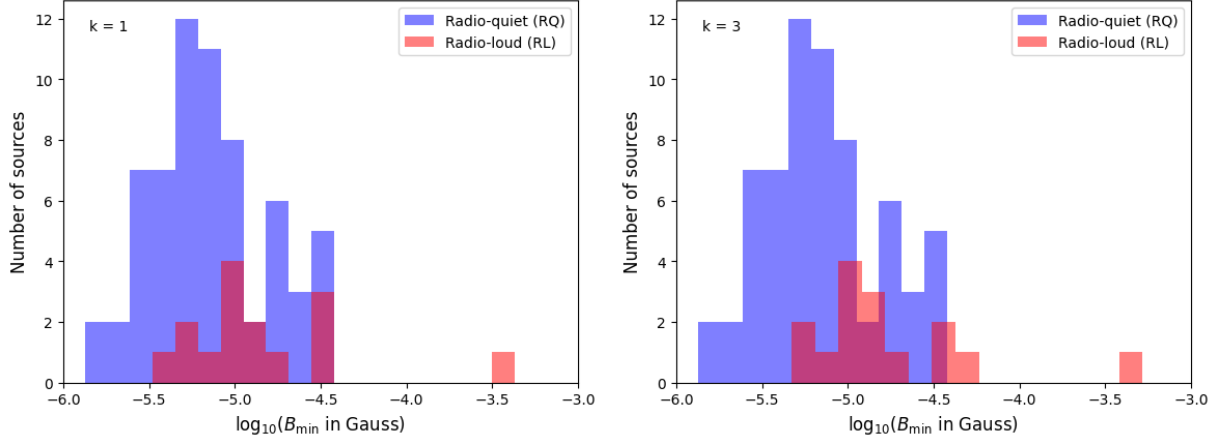


Figure 3. Distribution of ‘minimum energy’ magnetic field strength for RQ and RL sources for $k = 1$ (left panel) and $k = 3$ (right panel). The outlier source with the largest $B_{\min}$ value is PG 1226+023 or 3C 273.

density from Kellermann et al. (1989), yielded an unrealistic value of approximately -3 . Therefore, a spectral index of -0.7 has been adopted here (consistent with Baghel et al. 2024).

The RQ cores exhibit a range of spectral indices, varying from flat to steep, in agreement with the previous studies (Silpa et al. 2020; Chiaraluce et al. 2020). PG 1351+640 and PG 1435-067 have flat spectrum cores, while PG 1216+069 has an inverted spectrum core. A flat/inverted spectrum can be interpreted as arising from unresolved synchrotron self-absorbed bases of small-scaled radio jets, ‘frustrated’ radio jets in dense environments (O’Dea et al. 1991), or coronal emission (Laor & Behar 2008; Raginski & Laor 2016). PG 1626+554 has a spectral index of -0.1 ; therefore, thermal free-free emission from the accretion disk, torus, or HII regions cannot be ruled out as alternative explanations for this source. PG 0804+761 and PG 1416-129 lie at the cusp of flat-steep division.

The remaining RQ sources have steep spectrum cores. A steep radio spectrum can arise from unresolved or barely resolved jet/lobe emission on even smaller spatial scales (such as on a few- to 10-kpc scales; Falcke et al. 2000; Jarvis et al. 2019; Kharb et al. 2019) or optically thin synchrotron emission from AGN or starburst-driven winds (Cecil et al. 2001; Irwin & Saikia 2003; Hota & Saikia 2006; Hwang et al. 2018).

To understand the origin of the observed spectral indices, α_R , we examined the same with respect to the Eddington ratios (see Figure 4). We found an anti-correlation between the two for both the RL and RQ quasars, suggesting a link between accretion rate and the presence of optically thin steep-spectrum synchrotron emission arising from either unresolved jets or AGN-driven winds.

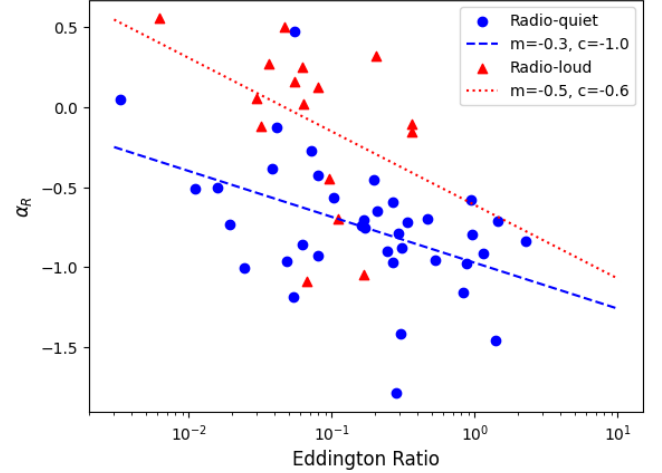


Figure 4. The 685 MHz - 5 GHz spectral index versus Eddington ratios for the PQ sample. In this and following plots, red triangles denote the RL QSOs, the blue circles denote RQ QSOs, the blue-dashed and red-dotted lines represent the best-fit lines for RQ and RL sources, respectively.

4.3. The Radio-IR & $\alpha_R - q_{\text{IR}}$ Correlations

Continuing our exploration on the origin of radio emission, we looked at the radio-infrared correlation, which is one of the best-studied and robust correlations in astrophysics. Figure 5 shows L_{1400} as a function of $L_{\text{IR,host}}$. The straight line in the plot represents the radio-IR correlation from Bell (2003), as given by Silpa et al. (2020):

$$\log L_{1400} \text{ W Hz}^{-1} = 1.10 \log L_{\text{IR,host}} + 10.34 \quad (1)$$

The 1σ and 3σ limits are derived using a scatter of 0.26 dex in the radio-IR correlation (Bell 2003). We find that all RL PG sources and $\sim 1/3^{\text{rd}}$ (20/59) of the RQ PG sources (with known IR luminosities and q_{IR} values) lie above the 3σ limit of the radio-IR correlation.

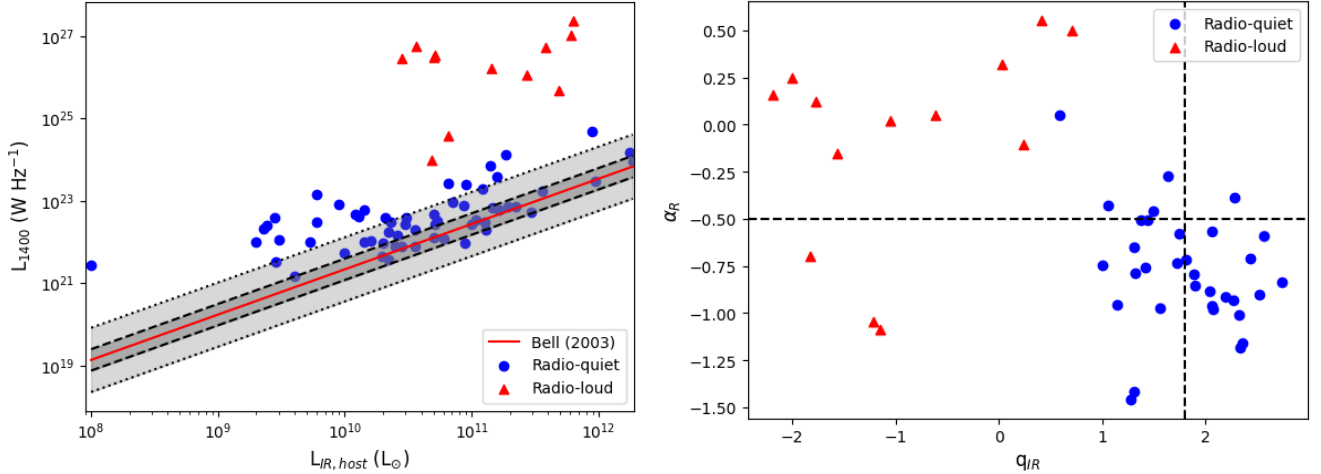


Figure 5. (Left) The radio-IR correlation for PG sources. The solid black line is the radio-IR correlation for star-forming galaxies (Bell 2003). The black dashed lines mark the 1σ regions and the black dotted lines mark the 3σ regions. (Right) The mean core spectral index as a function of q_{IR} . The black dashed vertical line represents $q_{\text{IR}} = 1.8$ (which is about 2.1σ below the (Bell 2003) relation), which discriminates the AGN versus star formation contributions. The black horizontal line is $\alpha_R = -0.5$, which we use to discriminate between steep ($\alpha_R < -0.5$) and flat ($\alpha_R > -0.5$) spectrum cores.

Additionally, Bell (2003) have defined the parameter, q_{IR} , to quantify the radio-IR correlation, which is given by:

$$q_{\text{IR}} = \log(L_{\text{IR}}/3.75 \times 10^{12} \text{ W}) - \log(L_{1400}/\text{W Hz}^{-1}) \quad (2)$$

A low q_{IR} value, along with a significant positional offset in the radio-IR correlation plane, would imply that AGN likely dominates the radio emission in the source (e.g. see White et al. 2017). A value of $q_{\text{IR}} < 1.8$ classifies the source as being “radio-excess” due to dominant AGN contribution (Condon et al. 2002).

To derive q_{IR} for our sample, we followed the approach of Silpa et al. (2020), first estimating the 1400 MHz flux-density (S_{1400}) from the observed total 685 MHz flux-density (S_{685}) using:

$$S_{1400} = S_{685}(1400/685)^{\alpha_R} \quad (3)$$

where, α_R is the radio spectral index. The value for α_R is taken to be -0.7 for all sources. Using S_{1400} , we calculated the 1400 MHz luminosity for the sample as $L_{1400} = 4\pi D_L^2 S_{1400}(1+z)^{(-\alpha_R-1)}$. To calculate the total IR luminosities, Lyu et al. (2017) performed SED decomposition using AGN (Elvis et al. 1994; Xu et al. 2015), stellar, and star-forming galaxy templates (Rieke et al. 2009), and integrated the best-fit model over the $8\text{--}1000 \mu\text{m}$ range. We used the $8\text{--}1000 \mu\text{m}$ luminosities ($L_{\text{IR,host}}$) from Lyu et al. (2017), which account only for the host galaxy’s contribution minus the AGN, to calculate q_{IR} .

The sources that lie above the 3σ limit of the radio-IR correlation also have $q_{\text{IR}} < 1.8$ (see Table 3). This sug-

gests an AGN dominance in their radio emission. While the remaining 39 RQ sources lie on the correlation and within the 3σ limit, this does not rule out an AGN contribution in them (e.g. Wong et al. 2016). The coexistence of AGN and stellar emission is likely, as also suggested in Paper I for the smaller PG sub-sample. In the following section, we look at the relation between AGN jet power and accretion.

4.4. Relation between Radio Power & Accretion

In the current paper, the black hole masses (M_{BH}) and AGN bolometric luminosities (L_{bol}) have been obtained from Shanguan et al. (2018) and Lyu et al. (2017), respectively. The M_{BH} values are single-epoch virial estimates calculated using Equation 4 of Ho & Kim (2015), while the bolometric luminosities are derived as $L_{\text{bol}} = 5.29 L_{\text{IR,AGN}}$, with $L_{\text{IR,AGN}}$ being the AGN infrared luminosity from Lyu et al. (2017). The prefactor of 5.29 is derived from the intrinsic AGN SED template, calibrated by Xu et al. (2015) and adopted by Lyu et al. (2017) in defining the bolometric correction. The Eddington luminosity is computed using $L_{\text{Edd}}(L_{\odot}) = 3.2 \times 10^4 (M_{\text{BH}}/M_{\odot})$. The Eddington ratios $L_{\text{bol}}/L_{\text{Edd}}$ range from $0.01\text{--}3.59$ for the PG sample.

We find a significant ($\sim 3\sigma$) correlation ($r_s = 0.6$) between 685 MHz luminosity and black hole mass (left panel of Fig. 6). This could be interpreted as the radio jet power being closely related to the black hole mass, with more massive black holes producing the most powerful radio outflows, consistent with Best et al. (2005), and others. This correlation becomes tighter on invoking the dependence of the Eddington ratio, a proxy for the

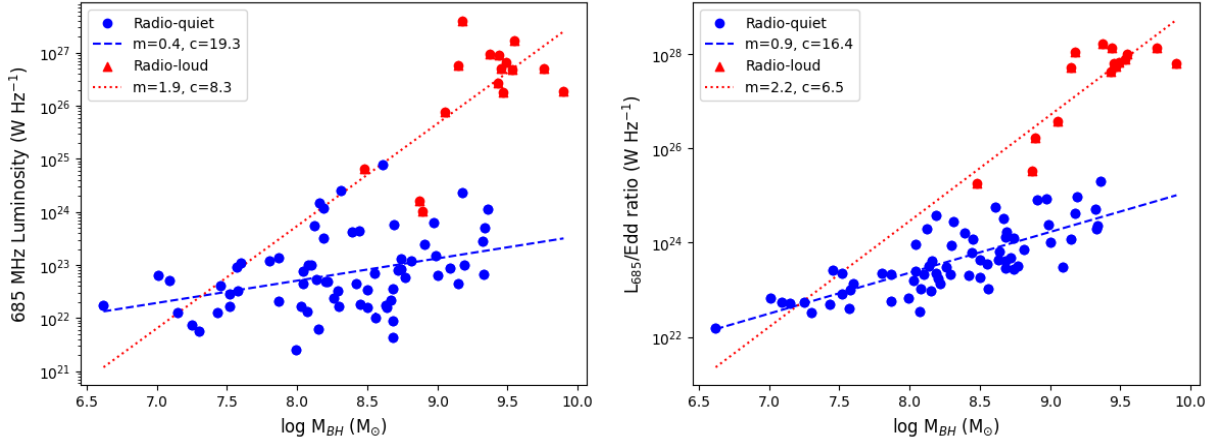


Figure 6. (Left) Total 685 MHz radio luminosities from the uGMRT versus logarithm of black hole masses for the PG quasars. The errors in 685 MHz radio luminosity are smaller than or comparable to the symbol size. The RL sources do not show any significant correlation. (Right) Ratio of 685 MHz luminosities to Eddington ratios versus black hole masses.

accretion rate (right panel of Fig. 6). We also note that RL AGN generally have higher M_{BH} and RQ AGN have lower M_{BH} , although with some overlap between the two populations, which suggests that the sources with low values of M_{BH} are less likely to possess powerful jets. This could favor the hypothesis that the jets are powered by black hole spins and that the observed correlation is resulting from a strong connection between M_{BH} and black hole spin (Laor 2000). However, there have been hints of a more slowly rotating population emerging at higher SMBH masses (Reynolds 2013, 2014). Our correlation becomes tighter on invoking the accretion rate dependence, which suggests that the RL/RQ divide could have both M_{BH} and accretion rate dependence, consistent with the findings of Lacy et al. (2001).

We carried out a partial correlation test between 685 MHz luminosity and Eddington ratio, controlling the influence of the black hole mass. Interestingly, a significant positive correlation is observed for the entire sample according to the Spearman rank correlation test ($r_s = 0.66$, $p_s = 1.8 \times 10^{-11}$). The RQ and RL sources separately also exhibit positive correlations (RQ: $r_s = 0.73$, $p_s = 3.3 \times 10^{-12}$; RL: $r_s = 0.59$, $p_s = 0.02$). The weaker correlation seen in RL quasars may arise from additional contributions of extended jet/lobe emission, whereas in RQ quasars the radio output predominantly traces the nuclear processes, leading to a comparatively tighter correlation.

Our analysis of the PG quasar sample at 685 MHz reveals a radio luminosity- M_{BH} correlation with a slope of 1.4, consistent with the slope of 1.4 ± 0.2 reported by Lacy et al. (2001) at 5 GHz. Including the Eddington ratio yields the best-fit relation, $\log L_{685 \text{ MHz}} = 1.9 \log M_{\text{BH}} + 1.0 \log (L/L_{\text{Edd}}) + 8.6$, which is also consistent with the slope of 1.9 ± 0.2 in Lacy et al. (2001).

Furthermore, we estimated the time-averaged jet kinetic power ($\bar{Q}$) using the relation given by Punsly et al. (2018)

$$\bar{Q} = 3.8 \times 10^{45} f L_{151}^{6/7} \text{ ergs s}^{-1} \quad (4)$$

where, L_{151} is the radio luminosity at 151 MHz in units of $10^{28} \text{ W Hz}^{-1} \text{ sr}^{-1}$ and $f = 15$ (Blundell & Rawlings 2000). We derived L_{151} using the following relations:

$$S_{151} = S_{685} (151/685)^{\alpha_R} \quad (5)$$

$$L_{151} = 4\pi D_L^2 S_{151} (1+z)^{(-\alpha_R-1)} \quad (6)$$

where, α_R is taken to be -0.7 for all sources and S_{685} is the total radio flux density listed in Table 1. The derived $\bar{Q}$ are presented in Table 3.

We find a significant positive correlation between jet power and M_{BH} for the entire sample (Figure 7, Table 2). Interestingly, the RQ and RL sources do not show different slopes here, compared to the 685 MHz luminosities versus black hole masses (left panel of Fig. 6). The jet powers of RQ and RL sources individually show a positive correlation with Eddington ratios (right panel of Fig. 7). However, the split between the RQ and RL sources is clearer here. This may be consistent with the RQ and RL sources following different relationships between jet power and accretion rates (see Section 5).

4.5. The Radio ‘Fundamental Plane’

The radio luminosity (L_R) is found to have a direct dependence on the mass of the black hole and X-ray luminosity (L_X), which is characterized as the black hole ‘fundamental plane’ (FP; Merloni et al. 2003). We used the 0.2–20 keV X-ray luminosities provided in Brandt et al. (2000); Laor & Behar (2008) taken from the

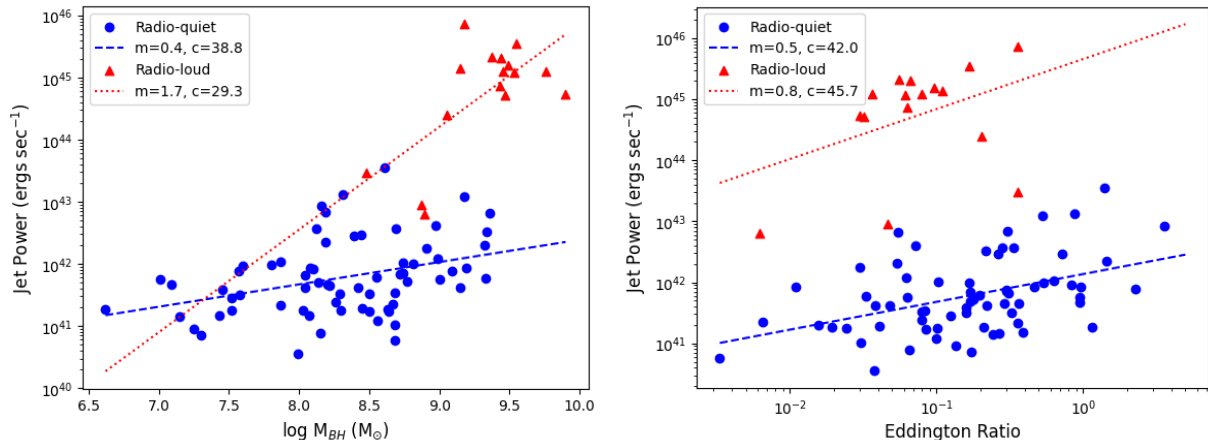


Figure 7. Jet kinetic power versus black hole masses (left) and Eddington ratios (right) for the PG sample. The RL sources in both the plots do not show any significant correlation (see Table 2).

ROSAT All-Sky Survey (RASS) with an effective angular resolution of $\sim 1.8'$. Figure 8 shows the correlation between L_R , L_X , and M_{BH} for the PG sample.

To model the dependence of L_R on L_X and M_{BH} , we performed linear regression using the `LinearRegression` routine from the `scikit-learn` Python package. The PG sample studied in this work defines the FP as: $\log L_R = 0.6 \log L_X + 1.1 \log M_{BH} - 11.3$. The RQ and RL sources show a dichotomy in the FP. The set of best-fit equations for RQ and RL sources are $\log L_R = 0.3 \log L_X + 0.3 \log M_{BH} + 8.5$ and $\log L_R = 0.8 \log L_X + 1.4 \log M_{BH} - 22.5$, respectively (see Figure 8). We discuss the radio ‘FP’ for the PG sources in the following section.

5. DISCUSSION

The radio-quiet PG quasars exhibit a significant correlation between 685 MHz luminosity and Eddington ratios. However, no such correlation is observed for the entire PG sample (see Table 2). Similarly, no correlation is found between radio-loudness and Eddington ratios for the PG quasar sample (see Table 2). Ho (2002) had reported an anti-correlation between the radio-loudness and the Eddington ratios for a sample of active galaxies. Since the Eddington ratio varies as mass accretion rate ($\dot{M}$), this anti-correlation implied that relative radio power increases with decreasing $\dot{M}$. Their study indicated that most of the weakly active nuclei in nearby galaxies are likely undergoing advection-dominated accretion. A similar anti-correlation was also reported by Sikora et al. (2007) for a sample comprising broad-line radio galaxies (BLRG), RL quasars, Seyferts, LINERS, FR I radio galaxies, and PG quasars.

The sample studied in Ho (2002) included sources spanning a much broader range of activity, our work focuses on the PG quasars, which are optically se-

lected and, therefore, are unlikely to host an advection-dominated accretion flow (ADAF) disk (e.g., Narayan & Yi 1994). When comparing our results with those of Sikora et al. (2007), we observe that their sample includes 43 PG sources, which, when considered separately, also show a negative correlation between radio-loudness and Eddington ratios (at the 2σ level). However, when all the 87 PG sources are considered, we find no such correlation. This could likely be because the already weak and scattered trends are further diluted by the large dispersion introduced by the remaining sources.

Franceschini et al. (1998) found a positive correlation between M_{BH} and 5 GHz radio luminosity for 13 nearby weakly active galaxies, with the functional form of the correlation arising naturally due to an ADAF. Laor (2000) derived the black hole masses from the $H\beta$ FWHM values and the optical continuum luminosity for all 87 $z < 0.5$ PG sources (Boroson & Green 1992) and found an increasing trend of 5 GHz radio luminosity with M_{BH} . However, when they included 29 nearby galaxies in their sample, they found that the tight relation of Franceschini et al. (1998) was not supported by their data. Lacy et al. (2001) combined the quasars from the FIRST Bright Quasar Survey (FBQS) with the PG sample and studied the correlation between M_{BH} and the 5 GHz radio luminosity. They found a continuous variation of radio luminosity with M_{BH} . They reported that the correlation becomes marginally tighter on invoking the dependence on the accretion rate, which is based on the radio-optical correlation studies (e.g., Serjeant et al. 1998; Willott et al. 1999). They suggested a new scheme to “unify” RL and RQ sources in which radio luminosity would depend on M_{BH} and accretion rate. Our uGMRT study of the PG quasar sample is

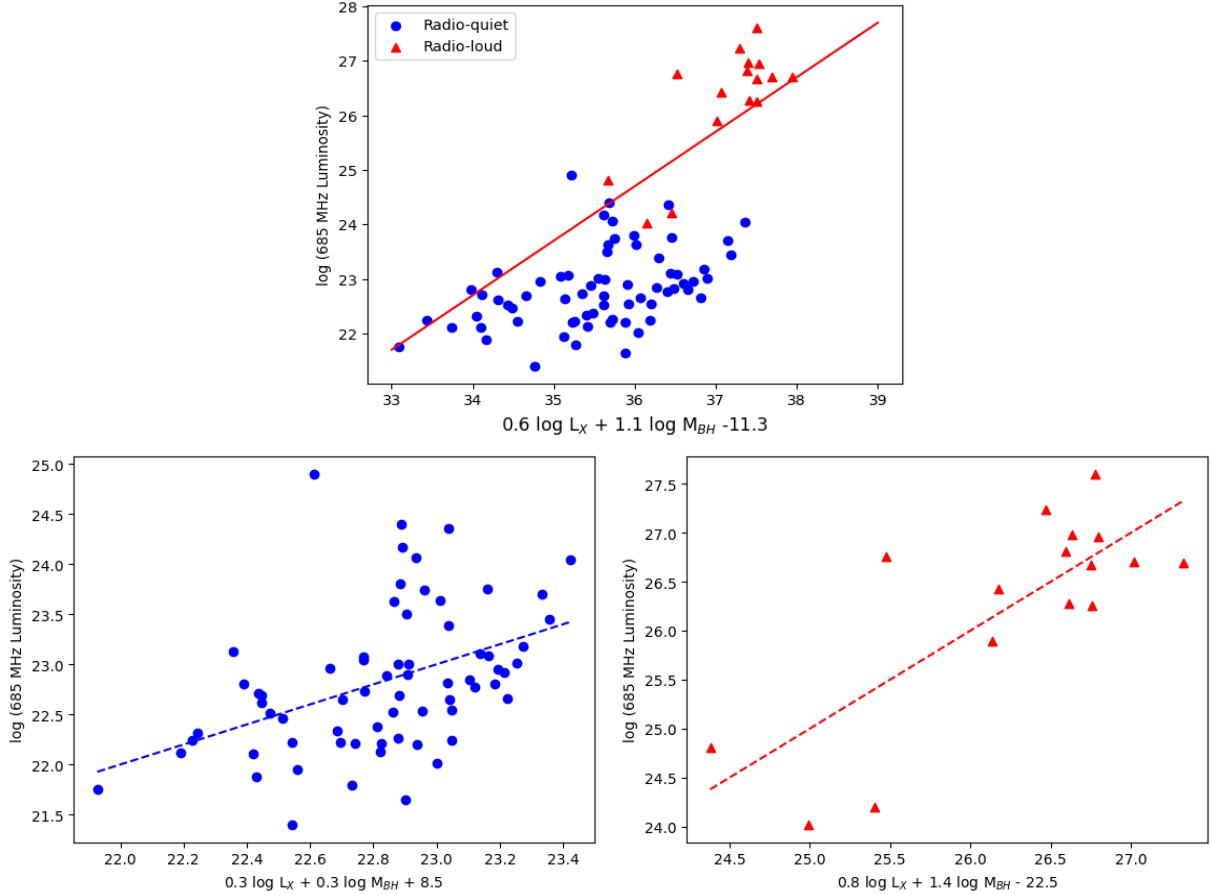


Figure 8. The ‘fundamental plane’ of black hole activity for the complete sample (top), RQ (left), and RL (right) sources separately. The x-axis is defined following the best-fit parameters respectively.

consistent with the findings of [Laor \(2000\)](#) and [Lacy et al. \(2001\)](#).

5.1. Signatures of Episodic AGN Activity

7 of the 16 RL sources exhibit morphological signatures such as X-shaped lobes, hybrid morphology, or strongly bent jets, which may be consistent with either environmental effects or episodes of restarted AGN activity (also see [Baghel et al. 2023, 2024](#)). In particular, the misaligned northern radio lobe in PG 1704+608 suggests a change in the direction of the jet, as reported by [Vaddi et al. \(2019\)](#); [Baghel et al. \(2023\)](#). A clear discontinuity in the surface brightness between the inner jets and the larger lobes in PG 1004+130 is indicative of restarted AGN activity with two distinct episodes, as proposed by [Ghosh et al. \(2023\)](#) and [Baghel et al. \(2023\)](#) based on spectral index imaging and polarization. Re-activation is suggested to be one of the possible explanations for the peculiar morphology of PG 1100+772 ([Marecki 2012](#); [Fernini 2007](#); [Baghel et al. 2023](#)).

All RL sources in our sample, except PG 1100+772, PG 1704+608, and PG 2251+113, exhibit flat or in-

verted spectrum cores, consistent with synchrotron self-absorbed jet bases. PG 1100+772 and PG 1704+608 show very steep spectrum cores ($\alpha \sim -1$), while PG 2251+113 yields an ultra-steep spectral index of ~ -3 when using the 5 GHz flux from [Kellermann et al. \(1989\)](#). Consequently, we adopt a spectral index of -0.7 for this source, as reported by [Baghel et al. \(2024\)](#). The presence of steep-spectrum cores in these RL sources suggests that restarted activity on small spatial scales cannot be ruled out. All three sources suggest ‘relic’ emission from past episodes of AGN activity ([Roettiger et al. 1994](#); [Kharb et al. 2016](#)). Additionally, three radio-quiet sources: PG 1612+261, PG 1613+658, and PG 1700+518, also exhibit very steep-spectrum cores ($\alpha_R < -1$), further suggesting that small-scale restarted activity may not be exclusive to RL quasars.

5.2. Origin of radio emission in RQ quasars

In radio-loud sources, the radio emission is primarily powered by relativistic jets (e.g., [Bridle & Perley 1984](#)). In contrast, the origin of radio emission in RQ sources remains an open question, with possibilities ranging from

weak jets and AGN winds to star formation and coronal activity (e.g., Kellermann et al. 1989, 1994; White et al. 2017; Zakamska et al. 2016; Hwang et al. 2018; Silpa et al. 2020; Baldi et al. 2022; Chen et al. 2023).

The PG quasars occupy four different quadrants in the α_R versus q_{IR} plot (see right panel of Figure 5). The top-right quadrant denotes flat/inverted spectrum radio emission of stellar origin, most likely arising from thermal free-free emission around HII regions or other stellar-related thermal processes. The bottom-right quadrant represents steep-spectrum radio emission of stellar origin, most likely produced by starburst-driven winds and/or star formation. The top-left quadrant corresponds to flat/inverted spectrum radio emission of AGN origin, arising from synchrotron self-absorbed jet bases, coronal emission, or thermal free-free emission from the accretion disk or torus. The bottom-left quadrant represents steep-spectrum AGN-related radio emission, produced by jets or AGN winds.

All RL sources lie in the left quadrants, consistent with the presence of jets. All except PG 1100+772, PG 1704+608, and PG 2251+113 lie in the top-left quadrant. These three sources, which lie in the bottom-left quadrant, are candidate restarted AGN (see Section 4). Of the 33 RQ sources, 17 lie in the right quadrants (indicative of stellar origin) and 16 in the left quadrants (indicative of an AGN origin), as also observed in the radio-IR correlation plot (Figure 5). Of the 17, one source (PG 1426+015) exhibits a flat/inverted spectrum, most likely arising from stellar-related thermal processes, while the rest show steep-spectrum stellar-origin emission, likely driven by starburst winds. Four of the 16 AGN-origin sources exhibit a flat/inverted spectrum, likely from the bases of small-scale or frustrated jets or coronal activity. The remaining 12 sources have steep-spectrum emission arising from AGN jets or winds. Additionally, two sources (PG 0804+761 and PG 1416–129) lie on the flat-steep division and belong to the AGN dominant category.

Therefore, the radio emission in $\simeq 48\%$ (16/33) of the RQ sample, for which we obtained α_R values, is AGN-dominated, while the remaining $\simeq 52\%$ (17/33) shows contributions from both AGN and stellar-related activity. A plausible breakdown of the physical processes at play in these sources is outlined here: $\simeq 75\%$ (12/16) of the AGN-dominated sources host jets or AGN winds, and $\simeq 25\%$ (4/16) are likely powered by either jet/wind bases, coronal activity, or AGN thermal processes. $\simeq 94\%$ (16/17) of the star-formation-dominated sources host starburst-driven winds, while one source (1/17 $\simeq 6\%$) is likely driven by stellar thermal pro-

cesses, with AGN activities potentially co-existing (also see Silpa et al. 2020).

5.3. Potential causes of the RL-RQ divide

In the 685 MHz luminosity versus black hole mass planes (left panel of Figure 6), RL and RQ sources appear to form a continuous distribution, with RL sources occupying the higher end and RQ sources the lower end, suggesting a possible unification of these classes in terms of black hole activity (e.g., Franceschini et al. 1998; Laor 2000; Lacy et al. 2001). Based on the partial correlation test (Section 4.4), when the influence of black hole mass is taken into account, the positive correlation observed between 685 MHz luminosity and Eddington ratio strengthens for both RQ and RL quasars separately, indicating that the Eddington ratio, which serves as a proxy for accretion rate, plays a dominant role in driving the RL–RQ dichotomy (e.g., Lacy et al. 2001).

It is worth considering the possibility that the RL–RQ transition in quasars may be linked to changes in the accretion state of the disk. In a previous study of the changing-look quasar PG 0007+106, a.k.a. III Zw 2 (Silpa et al. 2021), it was suggested that shifts in accretion mode could lead to variations in jet activity, potentially turning jets on or off (e.g., Baghel et al. 2023, 2024). If this analogy holds, RQ AGN might correspond to the soft state, characterized by suppressed jets and possibly strong winds, while RL AGN could be in the hard state, where jet launching is more efficient and powerful outflows are produced (Fender et al. 2004). The correlation we observe between 685 MHz radio luminosities and Eddington ratios, especially after controlling for black hole masses, further suggests that accretion state transitions could play a role in driving the RL–RQ dichotomy (e.g., Körding et al. 2006; Sikora et al. 2007; Silpa & Kharb 2022). This would also be consistent with the different relations observed between jet power and Eddington ratios for the RQ and RL sources seen in Figure 7. Additionally, the ‘magnetic flux paradigm’ that suggests the accumulation of large-scale magnetic flux near the black hole in magnetically arrested disks (MADs) can lead to the launching of powerful relativistic jets (Tchekhovskoy 2015; Sikora 2016; van Velzen & Falcke 2013), could hold true.

Using a sample of 208 radio AGN, of which 141 were RQ and 67 RL, derived from multi-wavelength surveys of GOODS-N, GOODS-S, and COSMOS/UltraVISTA, Wang et al. (2024) have reported that the ‘fundamental plane’ differs significantly between RQ and RL AGN, indicating a strong dependence on radio-loudness. Our findings are consistent with Wang et al. (2024). In our work, the RL and RQ PG sources follow dis-

tinct FP relations with significantly different coefficients, reinforcing the dichotomy. The radio emission in RQ sources may have contributions from both star-formation-related processes and AGN-driven activity, potentially affecting their position on the FP.

The observed radio-X-ray correlation in this work, also reported by Brinkmann et al. (2000) using ROSAT and FIRST observations for a sample of 843 AGN, suggests that both radio and X-ray emissions are likely driven by the same underlying physical mechanisms, primarily involving the central black hole and the accretion disk. The anti-correlation found between the spectral index and the Eddington ratio indicates that sources with higher Eddington ratios have a steeper slope, while those with lower Eddington ratios exhibit a flatter slope (e.g., Laor et al. 2019). This suggests the dominance of optically thin synchrotron emission in the former, which can be explained by the presence of strong radio outflows (Ghosh et al. 2025). In sources with lower Eddington ratios, either coronal emission is dominant (e.g., Behar et al. 2018) or the synchrotron self-absorbed bases of jets, which require very long baseline interferometry (VLBI) to resolve them.

6. CONCLUSIONS

Results from uGMRT 685 MHz observations of 87 PG quasars are presented in this paper. Low-frequency radio emission is detected in all sources except for the RQ quasars, PG 0043+039, PG 1121+422, and PG 1552+085. Below are our primary findings.

1. Morphological signs of jet disruption, misalignment, and steep spectrum cores observed at 685 MHz in some RL quasars point to episodic or restarted jet activity. The dichotomy observed between RL and RQ PG quasars with the VLA at 5 GHz persists at 685 MHz observations with the uGMRT. The detection of additional diffuse radio emission, including potential relics from previous episodes of AGN activity, often missed in higher-frequency observations due to sensitivity limitations, does not significantly alter the RL–RQ division.
2. We find an empirical division in the 685 MHz luminosities: sources with $\log_{10}(L_{685 \text{ MHz}}/\text{W Hz}^{-1}) < 23.5$ can be classified as RQ, while those with $\log_{10}(L_{685 \text{ MHz}}/\text{W Hz}^{-1}) > 25.5$ can be classified as RL. Sources with luminosities, $23.5 \leq \log_{10}(L_{685 \text{ MHz}}/\text{W Hz}^{-1}) \leq 25.5$, are intermediate. The radio sizes display the RQ–RL divide as well with RQ sources typically having sizes $\lesssim 30$ kpc, with only 16 ($\sim 22\%$) RQ sources having sizes

between 30 and 100 kpc where there is an overlap with RL quasar sizes. One RQ quasar with a size of ~ 98 kpc, PG 1216+069, is clearly a misclassified RL quasar with an appropriately large 685 MHz luminosity and an inverted core spectral index.

3. We did not find a difference in the minimum-energy magnetic field (B_{min}) strengths of the radio cores of RL and RQ quasars, with the exception of the RL quasar PG 1226+023 or 3C 273. However, different assumptions of source volume and volume filling factors may be valid for the two AGN classes. High resolution X-ray observations that can resolve the X-ray core and a radio-to-X-ray flux density comparison are needed to obtain independent magnetic field strengths and thereby test the ‘magnetic flux paradigm’ for RL and RQ AGN.
4. The distribution of PG quasars in the (685 MHz – 5 GHz) α_R – q_{IR} plane reveals four distinct quadrants. RL quasars occupy the AGN-dominated quadrants consistent with jet activity, while RQ sources are split nearly evenly between AGN-related and star-formation-related quadrants. This is also consistent with the findings in the 685 MHz radio–IR correlation. The AGN-related emission in RQ sources may arise in weak jets or coronal emission.
5. The RL and RQ PG quasars follow distinct ‘fundamental plane’ relations constructed using 685 MHz radio luminosity, with significantly different coefficients for the two populations. This supports the idea that the coupling between radio emission, black hole mass, and accretion differs between the two populations. This is also observed in the relation between jet power and Eddington ratios of the RQ and RL classes. The deviation of RQ sources from the RL-defined plane might reflect additional radio contribution from star formation, or differences in the accretion disk states.
6. Overall, our results suggest that accretion rates and supermassive black hole masses are likely to be influential in the RL–RQ divide. Additionally, magnetic field strengths at the black holes can be important and need to be estimated.

7. ACKNOWLEDGMENTS

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Table 1. PG sample properties and uGMRT observation details for 65 sources. The peak flux density corresponds to the compact core component and is therefore equivalent to the core flux density.

Quasar	Redshift	Host galaxy* morphology (from NED)	radio-loudness** (R)	Classification by Radio	uGMRT Phase cal IAU name	685 MHz peak flux density S_{685}^{peak} (mJy beam $^{-1}$)	685 MHz total flux density S_{685} (mJy)	rms noise (μ Jy beam $^{-1}$)	Angular size ($''$)	Linear size (kpc)
PG 0003+158	0.45090	-	180	RL	0022+002	102.2	1192.6 $\pm$ 10.3	864.8	47.3	264.2
PG 0003+199	0.02578	S0/a	0.27	RQ	2330+110	11	12 $\pm$ 1	31.7	5.2	2.6
PG 0007+106	0.08934	-	200	RL	2330+110	56	95 $\pm$ 6	33.5	84.4	135.3
PG 0026+129	0.14520	-	1.1	RQ	0022+002	7.0	12.0 $\pm$ 0.7	67.0	11.4	27.9
PG 0049+171	0.06400	-	0.32	RQ	0119+321	1.8	2.0 $\pm$ 0.2	64.2	4.6	5.4
PG 0050+124	0.05890	Sa;Sbrst	0.33	RQ	0059+001	9.5	11.0 $\pm$ 1.0	34.5	4.3	4.7
PG 0052+251	0.15445	Sb	0.24	RQ	0119+321	2.3	2.9 $\pm$ 0.2	53.0	10.4	26.8
PG 0157+001	0.16311	Bulge/disc	2.1	RQ	0059+001	39.2	42.5 $\pm$ 3.9	27.3	6.4	17.1
PG 0804+761	0.10000	E3	0.6	RQ	0410+769	2.4	3.1 $\pm$ 0.2	25.5	27.7	49.0
PG 0838+770	0.13230	S	≤ 0.11	RQ	0410+769	0.55	0.80 $\pm$ 0.06	19.2	16.5	37.4
PG 0844+349	0.06400	Sp(d)	0.027	RQ	0741+312	0.24	1.70 $\pm$ 0.04	36.2	17.7	21.0
PG 0921+525	0.05299	-	1.5	RQ	0834+555	8.2	13.9 $\pm$ 0.8	30.1	17.9	12.1
PG 0923+129	0.02915	S0?	2.1	RQ	0842+185	12	14 $\pm$ 1	27.8	10.1	5.7
PG 0923+201	0.19270	E1	0.14	RQ	0842+185	0.35	0.79 $\pm$ 0.04	22.9	17.0	52.5
PG 0934+013	0.05034	SBab	0.38	RQ	0943-083	1.2	2.1 $\pm$ 0.1	23.3	8.5	8.0
PG 0947+396	0.20554	S	0.25	RQ	1035+564	0.98	1.3 $\pm$ 0.1	19.8	9.1	29.4
PG 0953+414	0.23410	-	0.44	RQ	0834+555	0.66	0.69 $\pm$ 0.07	20.0	5.0	18.0
PG 1001+054	0.16012	-	0.50	RQ	0943-083	0.66	2.3 $\pm$ 0.1	73.3	7.5	20.0
PG 1004+130	0.24074	E2	230	RL	1120+143	24.9	2106.9 $\pm$ 2.5	61.3	143.5	526.0
PG 1011-040	0.05831	SB(r)b: pec	0.097	RQ	0943-083	1.2	1.6 $\pm$ 0.1	22.7	8.7	9.4
PG 1012+008	0.18674	E	0.50	RQ	0943-083	5.1	5.4 $\pm$ 0.5	21.6	23.3	70.1
PG 1022+519	0.04459	SB0/a	0.23	RQ	0834+555	1.3	1.6 $\pm$ 0.1	19.2	5.9	5.0
PG 1048+342	0.16707	E	≤ 0.1	RQ	1227+365	0.33	0.25 $\pm$ 0.04	27.9	3.7	10.2 ^a
PG 1048-090	0.34530	-	380	RL	1130-148	38.7	3692.7 $\pm$ 3.9	220.8	91.9	434.6
PG 1049-005	0.35895	-	0.25	RQ	1130-148	1.5	1.8 $\pm$ 0.2	72.1	13.3	64.5
PG 1100+772	0.31150	-	320	RL	1313+675	659.4	4325.7 $\pm$ 65.9	124.3	32.3	142.5
PG 1103-006	0.42374	-	270	RL	1130-148	183.3	1720.9 $\pm$ 18.3	77.4	57.4	309.0
PG 1114+445	0.14373	S	0.13	RQ	1227+365	0.90	1.70 $\pm$ 0.09	24.3	11.8	28.6
PG 1115+407	0.15481	-	0.17	RQ	1227+365	0.98	2.2 $\pm$ 0.1	25.5	11.2	28.8
PG 1116+215	0.17564	E2	0.72	RQ	1120+143	8.1	8.2 $\pm$ 0.8	36.9	4.5	12.9
PG 1119+120	0.05020	SABa	0.15	RQ	1120+143	3.2	5.4 $\pm$ 0.3	29.1	8.1	7.7
PG 1126-041	0.05980	S	0.17	RQ	1130-148	1.9	2.4 $\pm$ 0.2	26.2	5.3	5.9
PG 1149-110	0.04870	-	0.88	RQ	1130-148 3	6.8	7.7 $\pm$ 0.7	30.1	9.1	4.4
PG 1151+117	0.17565	-	≤ 0.07	RQ	1120+143	0.45	0.51 $\pm$ 0.06	44.4	5.4	15.6 ^a
PG 1202+281	0.16501	E1	0.19	RQ	3C286	2.0	2.1 $\pm$ 0.2	33.5	10.1	27.5
PG 1211+143	0.08090	-	0.13	RQ	1254+116	4.7	6.5 $\pm$ 0.5	155.3	5.3	7.8
PG 1216+069	0.33130	E	1.7	RQ	1150-003	1.94	4.7 $\pm$ 0.2	33.1	21.3	97.8
PG 1226+023	0.15834	-	1100	RL	1150-003	35878	70105.0 $\pm$ 3587.8	3214	36.6	96.2
PG 1229+204	0.06301	SB0	0.11	RQ	1254+116	1.9	2.5 $\pm$ 0.2	28.71	5.2	6.0
PG 1244+026	0.04818	E/S0	0.53	RQ	1254+116	2.9	3.1 $\pm$ 0.3	26.48	5.7	5.1
PG 1259+593	0.47619	-	≤ 0.1	RQ	1400+621	0.16	0.19 $\pm$ 0.03	27.1	5.6	32.3 ^a
PG 1302-102	0.27840	E4(?)	190	RL	1351-148	410.5	461.7 $\pm$ 41.0	96.7	19.4	79.2
PG 1307+085	0.15384	E1?	0.1	RQ	1330+251	0.87	1.20 $\pm$ 0.09	36.8	8.4	21.5
PG 1309+355	0.18295	Sab	180	RL	3C286	62.8	86.4 $\pm$ 6.3	47.8	16.8	50.0
PG 1310-108	0.03427	-	0.095	RQ	1248-199	0.74	0.87 $\pm$ 0.08	30.64	4.9	3.2
PG 1322+659	0.16800	S	0.098	RQ	1400+621	0.63	0.71 $\pm$ 0.07	29.4	18.4	50.8
PG 1341+258	0.08656	-	0.12	RQ	1330+251	0.30	0.36 $\pm$ 0.04	23.9	4.3	6.7
PG 1351+236	0.05500	-	0.26	RQ	1330+251	2.1	3.0 $\pm$ 0.2	23.4	4.4	4.6
PG 1351+640	0.08820	-	0.26	RQ	1400+621	34.2	35.6 $\pm$ 3.4	33.2	15.7	24.9
PG 1352+183	0.15147	E	0.11	RQ	3C286	0.26	0.20 $\pm$ 0.04	31.0	5.2	13.3 ^a
PG 1354+213	0.30046	E	≤ 0.08	RQ	3C286	0.35	0.30 $\pm$ 0.05	34.0	5.2	22.6 ^a
PG 1402+261	0.16400	SBb	0.23	RQ	3C286	1.63	1.7 $\pm$ 0.2	33.3	9.0	24.5 ^a
PG 1404+226	0.09800	-	0.47	RQ	1330+251	2.8	2.9 $\pm$ 0.3	20.2	3.9	6.8
PG 1411+442	0.08960	E4	0.13	RQ	3C286	2.50	2.7 $\pm$ 0.3	31.8	8.2	13.2
PG 1415+451	0.11371	-	0.17	RQ	3C286	1.57	1.8 $\pm$ 0.2	32.5	6.3	12.6
PG 1416-129	0.1289	-	1.1	RQ	1351-148	2.2	2.7 $\pm$ 0.2	34.3	14.3	31.5
PG 1425+267	0.36361	-	540	RL	3C286	36.8	675.4 $\pm$ 3.7	36.8	279.9	1369.4
PG 1426+015	0.08657	E/S0	0.28	RQ	1445+099	2.0	2.6 $\pm$ 0.2	24.3	4.9	7.6
PG 1427+480	0.22063	E	≤ 0.16	RQ	1400+621	0.37	0.46 $\pm$ 0.05	30.1	13.9	47.8
PG 1435-067	0.12600	-	0.069	RQ	1445+099 1	0.47	1.0 $\pm$ 0.7	56.9	11.0	23.9
PG 1440+356	0.07906	S	0.37	RQ	3C286	7.31	7.7 $\pm$ 0.7	54.1	14.0	20.1
PG 1444+407	0.26791	E1(?)	≤ 0.08	RQ	3C286	2.79	2.8 $\pm$ 0.3	34.5	6.4	25.4 ^a
PG 1448+273	0.06500	-	0.23	RQ	3C 286	5.3	5.3 $\pm$ 0.5	27.0	5.2	6.2
PG 1501+106	0.03642	E	0.36	RQ	1445+099	3.7	5.1 $\pm$ 0.4	204.3	5.4	3.7
PG 1512+370	0.37053	-	190	RL	1609+266	37.5	1627.3 $\pm$ 3.8	77.6	79.2	329.2
PG 1519+226	0.13609	-	0.9	RQ	1609+266	0.30	0.32 $\pm$ 0.05	36.9	6.3	14.6
PG 1534+580	0.03023	E1?, S0	0.7	RQ	1400+621	7.7	7.9 $\pm$ 0.8	28.5	21.6	12.5
PG 1535+547	0.03893	-	0.14	RQ	1400+621	1.6	1.6 $\pm$ 0.2	33.4	18.0	13.3
PG 1543+489	0.39982	S	0.63	RQ	1400+621	4.3	4.4 $\pm$ 0.4	39.6	14.8	76.7
PG 1545+210	0.26430	-	420	RL	1609+266	40.5	1186.1 $\pm$ 4.0	145.0	81.8	321.2
PG 1612+261	0.13095	-	2.8	RQ	1609+266	27.8	30.3 $\pm$ 2.8	33.7	15.9	35.7
PG 1613+658	0.12109	E2	0.94	RQ	1400+621	8.2	8.5 $\pm$ 0.8	87.5	34.9	73.2
PG 1617+175	0.11460	-	0.39	RQ	1609+266	8.1	8.2 $\pm$ 0.8	34.7	2.7	5.5 ^a
PG 1626+554	0.13360	-	0.11	RQ	1400+621	0.41	0.44 $\pm$ 0.05	28.5	11.3	25.8 ^a
PG 1700+518	0.28900	Sbrst	2.4	RQ	1634+627	37.2	44.0 $\pm$ 3.7	40.2	18.7	78.2
PG 1704+608	0.37152	-	620	RL	1634+627	63.8	5844.9 $\pm$ 6.4	137.7	73.0	362.4
PG 2130+099	0.06298	(R)Sa	0.32	RQ	2148+069	7.5	8.7 $\pm$ 0.7	24.44	4.2	4.9
PG 2112+059	0.45900	-	0.32	RQ	2130+050	5.1	5.2 $\pm$ 0.5	56.3	5.3	30.1
PG 2209+184	0.07000	-	54	RL	2148+069	93	97 $\pm$ 9	95.5	5.5	7.0
PG 2214+139	0.06576	-	0.052	RQ	2148+069	0.94	0.93 $\pm$ 0.10	25.5	0.8	1.0 ^a
PG 2233+134	0.32571	E	0.28	RQ	2130+050	1.2	1.4 $\pm$ 0.1	22.8	18.5	84.2
PG 2251+113	0.32550	-	370	RL	2212+018	1228	2548.3 $\pm$ 122.8	246.3	19.3	87.6
PG 2304+042	0.04200	-	0.25	RQ	2330+110	1.0	1.1 $\pm$ 0.1	32.1	5.8	4.6
PG 2308+098	0.43330	-	190	RL	2212+018	51.1	1278.6 $\pm$ 5.1	93.4	117.0	638.0

* E=elliptical; S0=lenticular; S=spiral; Sbrst=starburst; pec=peculiar; ?=uncertainty; a,b represent the tightness of the spiral arms; A,B represent bars; (r) represents inner ring. ** Radio-loudness parameter taken from (Kellermann et al. 1994). a: unresolved sources. Undetected sources: PG 0043+039, PG 1121+422, PG 1552+085

Table 2. Results on the correlation studies of 685 MHz luminosity with other physical properties. The values represent the correlation coefficients with respective p-values in brackets. A correlation is considered significant at the $\sim 99.7\%$ confidence level ($p < 0.001$, $\simeq 3\sigma$).

Parameters	Spearman Rank			Kendall-tau		
	Full sample	RQ	RL	Full Sample	RQ	RL
Spectral index - Edd ratio	-0.4 (0.0006)	-0.4 (0.008)	-0.5 (0.05)	-0.3 (0.0009)	-0.3 (0.008)	-0.4 (0.06)
Radio-loudness - Edd ratio	0.09 (0.4)	0.2 (0.2)	-0.2 (0.5)	0.05 (0.6)	0.1 (0.1)	-0.1 (0.4)
685 MHz total luminosity - Edd ratio	0.1 (0.3)	0.4 (0.0005)	0.4 (0.1)	0.1 (0.2)	0.3 (0.0005)	0.3 (0.1)
685 MHz total luminosity - M_{BH}	0.6 (1.8×10^{-10})	0.4 (0.001)	0.4 (0.1)	0.4 (1.9×10^{-9})	0.3 (0.002)	0.2 (0.2)
685 MHz total luminosity/Edd. ratio - M_{BH}	0.9 (2.2×10^{-25})	0.8 (3.9×10^{-15})	0.6 (0.008)	0.7 (2.3×10^{-19})	0.6 (2.7×10^{-12})	0.5 (0.003)
685 MHz total luminosity - L_X	0.6 (9.2×10^{-10})	0.5 (1.2×10^{-5})	0.6 (0.02)	0.4 (3.9×10^{-9})	0.4 (1.8×10^{-5})	0.4 (0.03)
685 MHz total luminosity - L_{IR}	0.6 (4.5×10^{-9})	0.6 (8.9×10^{-8})	0.5 (0.1)	0.4 (6.4×10^{-8})	0.5 (3.7×10^{-7})	0.2 (0.2)
Jet Power - M_{BH}	0.6 (1.8×10^{-10})	0.4 (0.001)	0.4 (0.1)	0.4 (1.9×10^{-9})	0.3 (0.002)	0.2 (0.2)
Jet Power - Eddington Ratio	0.1 (0.3)	0.4 (0.0004)	0.4 (0.1)	0.1 (0.2)	0.3 (0.0005)	0.3 (0.1)

Table 3. Summary of physical properties of PG quasars. The spectral index (α_R) has been calculated using the peak flux densities at 685 MHz (this work) and 5 GHz (Kellermann et al. 1994).

Quasar	$L_{\text{IR,host}}^a$ ($10^{11} L_\odot$)	$\log L_X^b$ (erg s^{-1})	$\log M_{\text{BH}}^c$ ($M_\odot$)	Edd. h ratio λ	L_{5000} (total) ($10^{28} \text{ erg s}^{-1} \text{ Hz}^{-1}$)	α_R	L_{1400} ($\times 10^{22}$ W Hz^{-1})	L_{151} ($\times 10^{22}$ $\text{W Hz}^{-1} \text{ sr}^{-1}$)	$\bar{Q}$ ($\times 10^{41}$ erg s^{-1})	q_{IR}
PG 0003+158	0.50	45.55	9.45	0.08	1.4×10^5	0.12	3.0×10^4	1.2×10^4	1.2×10^4	-1.8
PG 0003+199	0.02	43.80	7.52	0.21	5.5	-0.65	1.1	0.4	1.8	1.3
PG 0007+106	0.48	44.49	8.87	0.05	5.4×10^3	0.50	96.8	36.6	89.8	0.7
PG 0026+129	-	44.70	8.12	0.28	236.8	-1.8	33.8	12.8	36.4	-
PG 0049+171	0.03	44.05	8.45	0.02	5.9	-0.50	1.1	0.4	2.0	1.4
PG 0050+124	2.93	44.18	7.57	2.26	21.5	-0.84	5.5	2.1	7.7	2.7
PG 0052+251	0.71	44.93	8.99	0.06	38.9	-0.9	9.2	3.5	12.0	1.9
PG 0157+001	17.49	44.23	8.31	0.87	468.8	-0.98	151.0	57.1	131.5	2.1
PG 0804+761	0.13	44.78	8.55	0.20	54.0	-0.5	4.3	1.6	6.2	1.5
PG 0838+770	1.30	44.16	8.29	0.16	*	-	2.0	0.8	3.2	2.8
PG 0844+349	0.14	43.99	8.03	0.10	-	-	1.0	0.4	1.8	2.2
PG 0921+525	0.02	43.52	7.45	0.16	11.3	-0.7	2.5	1.5	3.9	1.0
PG 0923+129	0.22	43.69	7.52	0.12	20.6	-	1.7	0.6	2.9	2.1
PG 0923+201	0.31	43.69	9.33	0.03	20.7	-	4.0	1.5	5.8	1.9
PG 0934+013	0.25	43.73	7.15	0.24	3.2	-0.90	0.8	0.3	1.4	2.5
PG 0947+396	1.94	44.72	8.81	0.17	29.1	-0.7	7.4	2.8	9.9	2.4
PG 0953+414	-	44.98	8.74	0.30	229.4	-	5.1	1.9	7.1	-
PG 1001+054	0.09	42.74	7.87	0.63	46.4	-	8.2	3.1	10.8	1.1
PG 1004+130	1.42	44.48	9.43	0.06	5.6×10^4	0.02	1.6×10^4	6.2×10^3	7.3×10^3	-1.0
PG 1011-040	0.28	42.60	7.43	0.27	2.3	-0.59	0.8	0.3	1.5	2.6
PG 1012+008	0.90	44.06	8.39	0.26	78.2	-0.97	25.6	9.7	28.7	1.6
PG 1022+519	0.20	43.66	7.25	0.14	1.7	-	0.5	0.2	0.9	2.6
PG 1048+342	0.88	44.22	8.50	0.08	0.6	-	1.0	0.4	1.7	3.0
PG 1048-090	0.36	45.16	9.37	0.06	1.7×10^5	0.2	5.7×10^4	2.2×10^4	2.1×10^4	-2.2
PG 1049-005	0.45	44.78	9.34	0.22	132.4	-	30.1	11.4	33.0	2.5
PG 1100+772	3.80	45.24	9.44	0.07	1.4×10^5	-1.08	5.5×10^4	2.1×10^4	2.1×10^4	-1.1
PG 1103-006	-	44.90	9.49	0.10	1.8×10^5	-0.4	4.0×10^4	1.5×10^4	1.6×10^4	-
PG 1114+445	0.12	43.87	8.72	0.17	10.3	-0.8	4.8	1.8	6.9	1.4
PG 1115+407	2.22	44.33	7.80	0.54	-	-	7.2	2.7	9.7	2.5
PG 1116+215	-	44.83	8.69	0.34	194.2	-0.7	34.5	13.0	37.1	-
PG 1119+120	0.36	43.48	7.58	0.32	5.7	-	2.0	0.8	3.2	2.3
PG 1126-041	0.60	42.32	7.87	0.36	4.4	-	1.2	0.5	2.1	2.7
PG 1149-110	0.30	43.83	8.04	0.05	14.9	-0.96	2.7	0.9	3.8	2.1
PG 1151+117	-	44.43	8.68	0.08	**	-	2.1	1.0	4.1	-
PG 1202+281	0.87	44.70	8.74	0.10	50.9	-0.6	7.8	2.9	10.4	2.1
PG 1211+143	0.09	44.54	8.10	0.46	2.4×10^3	-0.70	6.0	2.3	8.3	-
PG 1216+069	-	45.10	9.36	0.06	945.6	0.47	67.9	25.7	66.3	-
PG 1226+023	6.32	45.67	9.18	0.36	2.1×10^6	-0.2	2.4×10^5	9.1×10^4	7.3×10^4	-1.6
PG 1229+204	0.26	44.00	8.26	0.08	6.4	-0.93	1.4	0.5	2.4	2.3
PG 1244+026	0.16	43.58	6.62	1.15	4.6	-0.92	1.0	0.4	1.9	2.2
PG 1259+593	-	44.53	9.09	0.30	14.1	-	5.4	2.1	7.6	-
PG 1302-102	4.89	45.09	9.05	0.20	1.3×10^5	+0.3	4.7×10^3	1.8×10^3	2.5×10^3	0.03
PG 1307+085	0.03	44.59	9.00	0.06	18.7	-	4.0	1.5	5.7	0.9
PG 1309+355	0.66	43.89	8.48	0.36	4.0×10^3	-0.1	391.9	148.3	297.8	0.2
PG 1310-108	0.04	43.30	7.99	0.04	0.7	-	0.1	0.06	0.4	2.4
PG 1322+659	0.99	44.68	8.42	0.22	12.6	-	2.7	1.0	4.2	2.6
PG 1341+258	0.22	43.83	8.15	0.06	0.9	-	0.4	0.1	0.8	2.8
PG 1351+236	0.50	43.11	8.67	0.006	3.7	-	1.3	0.4	1.7	2.6
PG 1351+640	1.59	43.53	8.97	0.07	236.6	-0.3	38.4	14.5	40.7	1.6
PG 1352+183	-	44.38	8.56	0.10	13.0	-	0.6	0.2	1.2	-
PG 1354+213	1.07	44.60	8.77	0.18	**	-	3.6	1.3	5.3	2.5
PG 1402+261	1.63	44.44	8.08	0.97	37.2	-	6.1	2.3	8.4	2.4
PG 1404+226	0.21	43.77	7.01	0.95	22.2	-0.58	3.9	1.5	5.7	1.7
PG 1411+442	0.06	42.72	8.20	0.29	11.3	-0.8	3.0	1.1	4.6	1.3
PG 1415+451	0.54	43.99	8.14	0.17	11.8	-	3.3	1.2	4.9	2.2
PG 1416-129	0.14	44.65	9.19	0.01	136.3	-0.5	6.2	2.3	8.5	1.4
PG 1425+267	2.73	44.21	9.90	0.03	3.7×10^4	0.05	1.2×10^4	4.4×10^3	5.4×10^3	-0.6
PG 1426+015	0.51	44.58	9.15	0.04	21.0	-0.38	2.7	1.0	4.2	2.3
PG 1427+480	1.26	44.30	8.22	0.37	2.1	-	3.0	1.1	4.6	2.6
PG 1435-067	0.02	44.28	8.50	0.08	6.9	-0.4	2.1	0.8	3.3	1.1
PG 1440+356	1.46	44.54	7.60	0.83	23.9	-1.2	6.7	2.5	9.1	2.4
PG 1444+407	0.66	44.55	8.44	0.72	25.0	-	26.3	9.9	29.3	1.4
PG 1448+273	0.23	43.86	7.09	0.95	9.8	-0.80	3.1	1.2	4.7	1.9
PG 1501+106	0.20	43.65	8.64	0.02	4.7	-1.00	1.0	0.4	1.7	2.3
PG 1512+370	0.28	45.03	9.53	0.06	1.0×10^5	+0.3	2.9×10^4	1.1×10^4	1.2×10^4	-2.0
PG 1519+226	0.3555	44.24	8.07	0.39	62.7	-	0.8	0.3	1.5	2.7
PG 1534+580	0.05	43.54	8.30	0.02	4.1	-0.7	1.0	0.4	1.8	1.7
PG 1535+547	0.03	<41.76	7.30	0.17	1.7	-	0.3	0.1	0.7	1.9
PG 1543+489	18.57	44.40	8.16	3.59	364.1	-	89.9	34.0	84.3	2.3
PG 1545+210	-	45.14	9.47	0.03	1.1×10^5	-0.1	1.1×10^4	4.1×10^3	5.2×10^3	-
PG 1612+261	1.39	44.53	8.19	0.31	195.9	-1.4	71.0	26.9	68.8	1.3
PG 1613+658	3.57	44.89	9.32	0.05	100.0	-1.2	17.0	6.4	20.2	2.3
PG 1617+175	0.06	44.15	8.91	0.03	32.4	-	14.7	5.6	17.8	0.6
PG 1626+554	-	44.48	8.63	0.04	6.8	-0.1	1.07	0.4	1.9	-
PG 1700+518	8.82	42.90	8.61	1.39	1.3×10^3	-1.5	481.0	181.9	348.9	1.3
PG 1704+608	6.09	44.64	9.55	0.17	3.6×10^5	-1.0	1.0×10^5	3.9×10^4	3.5×10^4	-1.2
PG 2112+059	1.87	43.87	9.18	0.53	388.4	-0.96	137.6	52.0	121.4	1.1
PG 2130+099	0.50	44.35	8.04	0.31	18.1	-0.88	4.7	1.8	6.7	2.0
PG 2233+134	1.21	44.42	8.19	1.44	108.3	-0.7	19.1	7.2	22.4	1.8
PG 2209+184	0.16	43.94	8.89	0.006	3.1×10^3	-	63.5	24.0	62.5	0.4
PG 2214+139	0.10	42.63	8.68	0.03	2.3	-	0.5	0.2	1.0	2.3
PG 2251+113	0.51	44.09	9.15	0.11	1.2×10^5	-0.7***	3.5×10^4	1.3×10^4	1.4×10^4	-1.8
PG 2304+042	0.001	43.89	8.68	0.003	3.1	0.05	0.3	0.1	0.6	0.6
PG 2308+098	-	45.35	9.76	0.04	1.2×10^5	+0.3	3.0×10^4	1.1×10^4	1.2×10^4	-

The sources in boldface are from Paper I. The spectral index, L_{1400} , L_{151} , $\bar{Q}$, and q_{IR} were recalculated for these sources using the methodology described in Section 4.2. ^a 8 – 1000 μm host galaxy IR luminosity from Lyu et al. (2017)

^b 0.2 – 20 keV luminosity from Laor & Behar (2008)

^c BH mass from Shangguan et al. (2018)

^d Eddington Ratio ($L_{\text{bol}}/L_{\text{Edd}}$) estimated using M_{BH} and L_{bol} from Lyu et al. (2017)

^e 5 GHz total luminosity from Kellermann et al. (1989) at 18'' resolution

* Flux of -0.02 mJy reported in Kellermann et al. (1989)

** Flux of 0.0 mJy reported in Kellermann et al. (1989)

*** The spectral index for this source, when calculated using the 5 GHz flux from Kellermann et al. (1989), yielded an ultra-steep value of approximately -3. Therefore, the spectral index adopted here is taken from Baghel et al. (2024).

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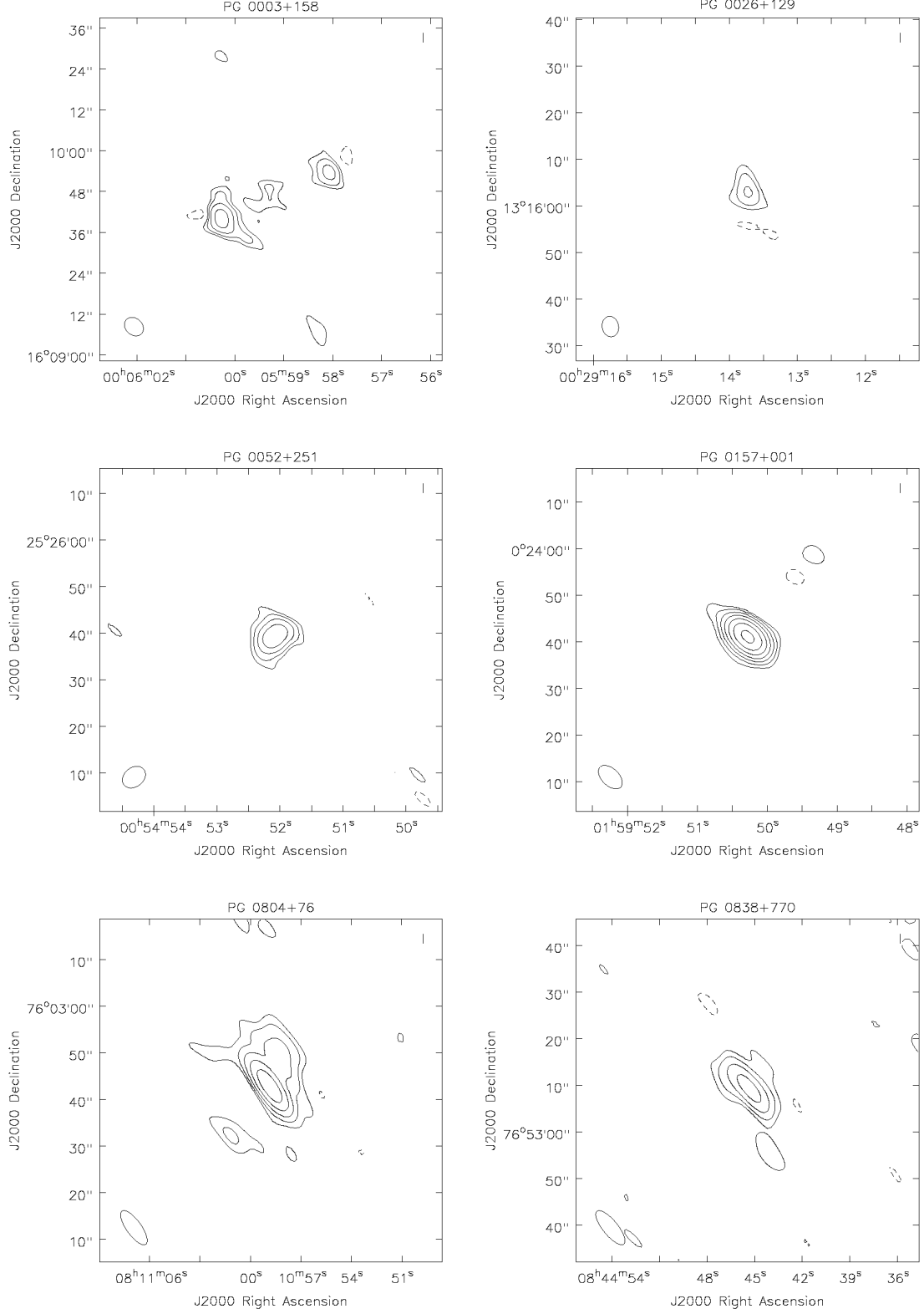


Figure 9. uGMRT 685 MHz radio contour images of PG 0003+158 (RL), PG 0026+129, PG 0052+251, PG 0157+001, PG 0804+761, and PG 0838+770. The contour levels are $3\sigma \times (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 516)$.

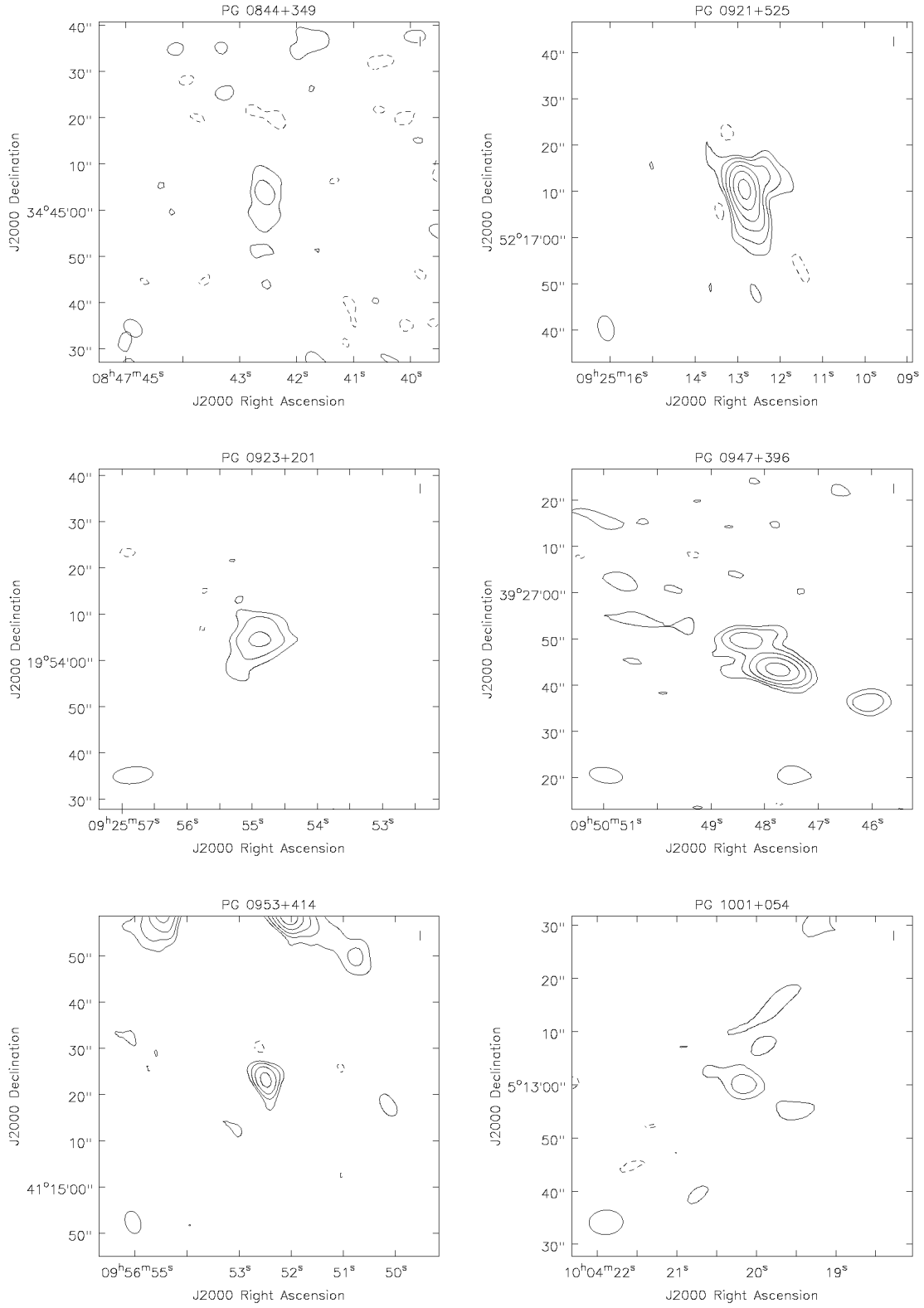


Figure 10. uGMRT 685 MHz radio contour images of PG 0844+349, PG 0921+525, PG 0923+201, PG 0947+396, PG 0953+414, and PG 1001+054. The contour levels are $3\sigma \times (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 516)$.

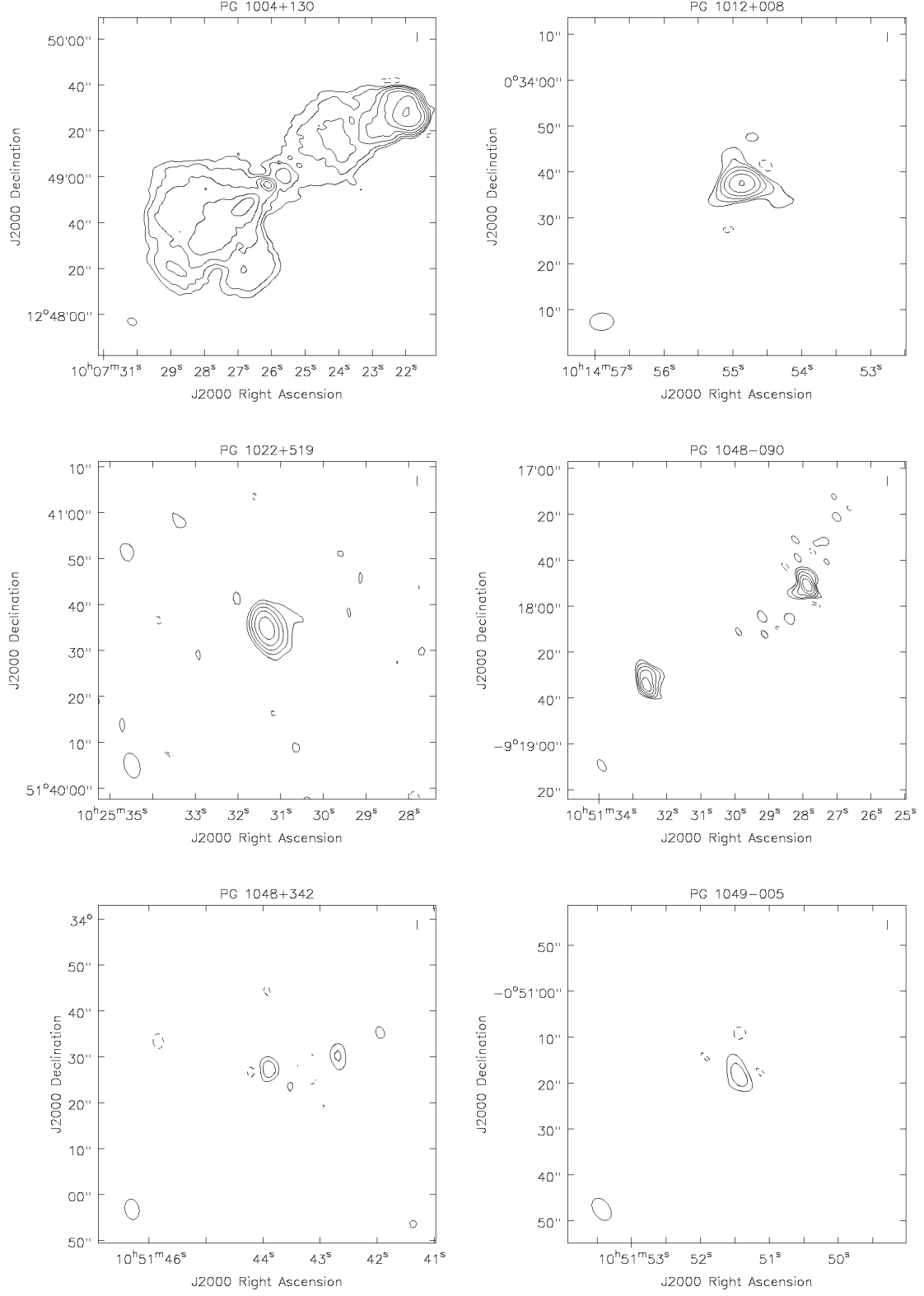


Figure 11. uGMRT 685 MHz radio contour images of PG 1004+130 (RL), PG 1012+008, PG 1022+519, PG 1048-090 (RL), PG 1048+342, PG 1049-005. The contour levels are $3\sigma \times (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 516)$.

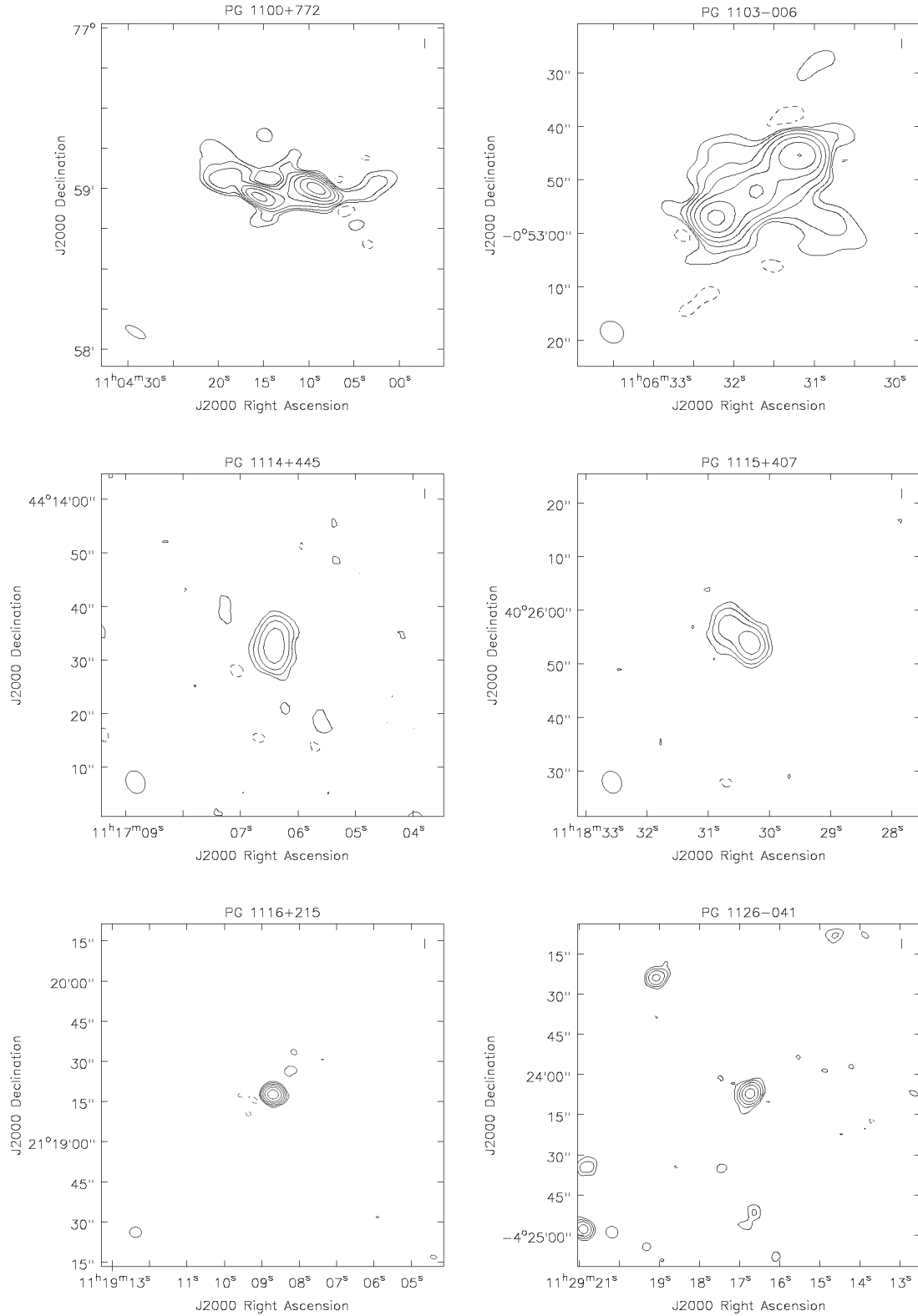


Figure 12. uGMRT 685 MHz radio contour images of PG 1100+772 (RL), PG 1103-006 (RL), PG 1114+445, PG 1115+407, PG 1116+215, and PG 1126-041. The contour levels are $3\sigma \times (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 516)$.

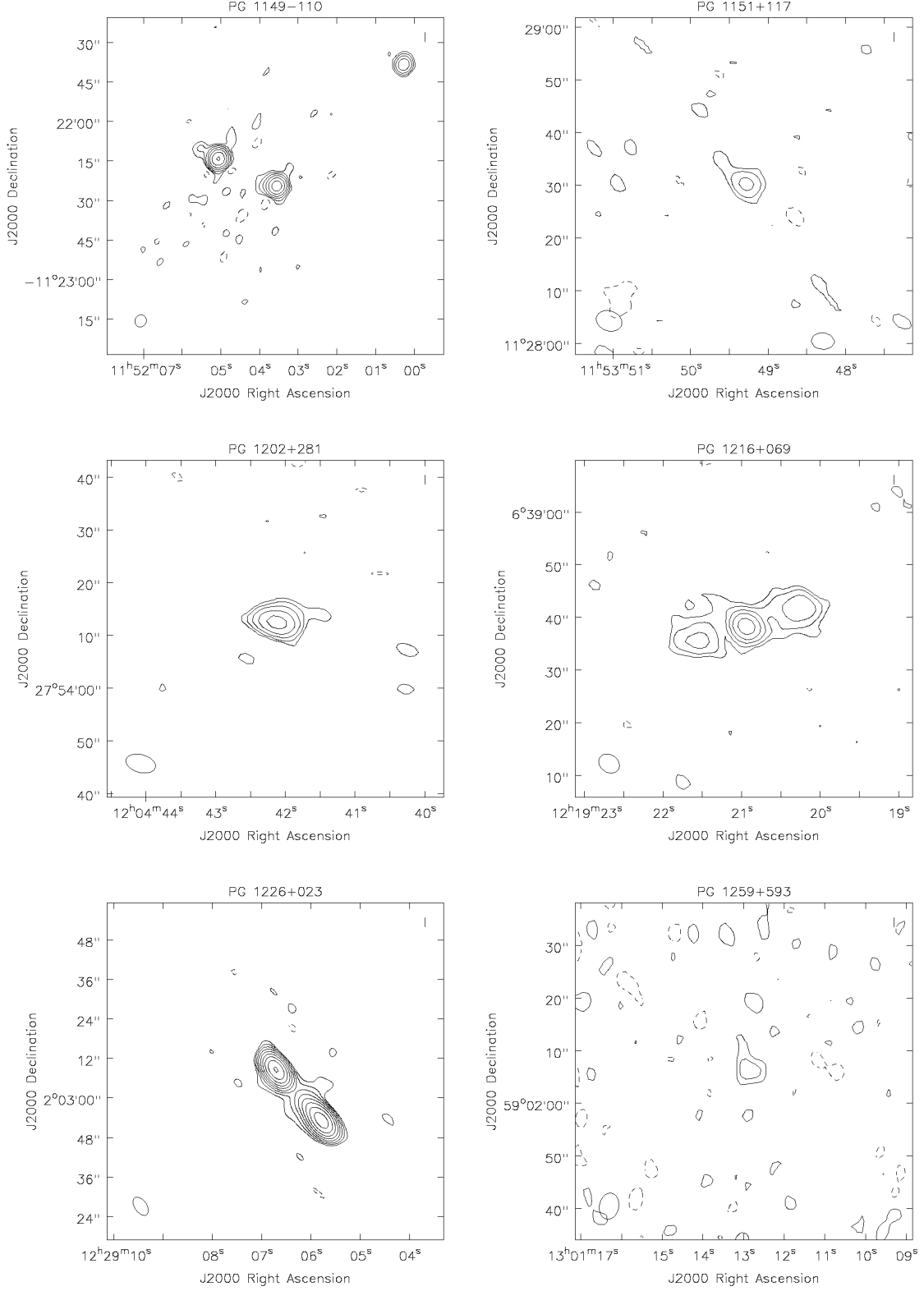


Figure 13. uGMRT 685 MHz radio contour images of PG 1149-110, PG 1151+117, PG 1202+281, PG 1216+069, PG 1226+023 (RL), and PG 1259+593. The contour levels are $3\sigma \times (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 516)$.

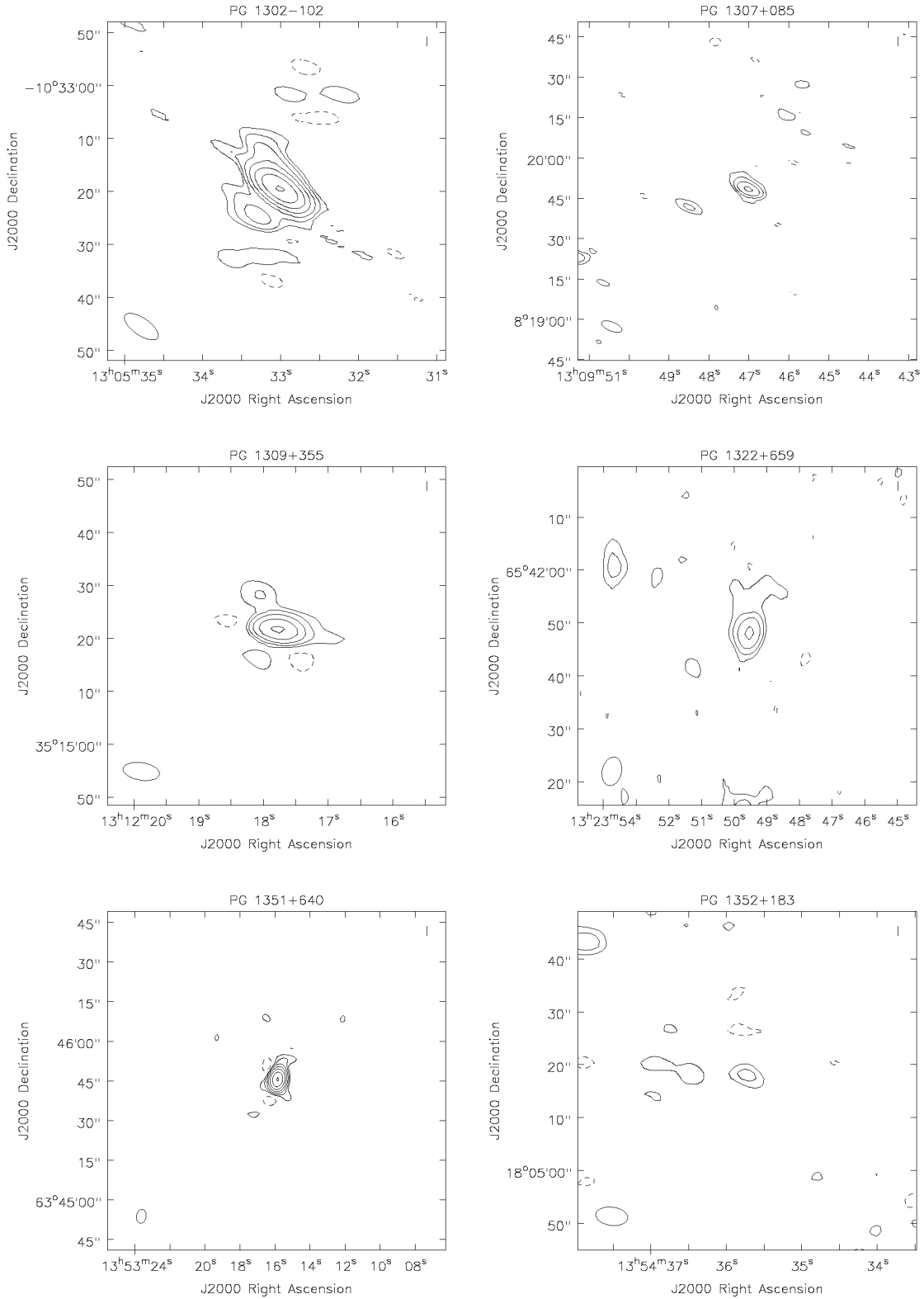


Figure 14. uGMRT 685 MHz radio contour images of PG 1302-102 (RL), PG 1307+085, PG 1309+355 (RL), PG 1322+659, PG 1351+640, and PG 1352+183. The contour levels are $3\sigma \times (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 516)$.

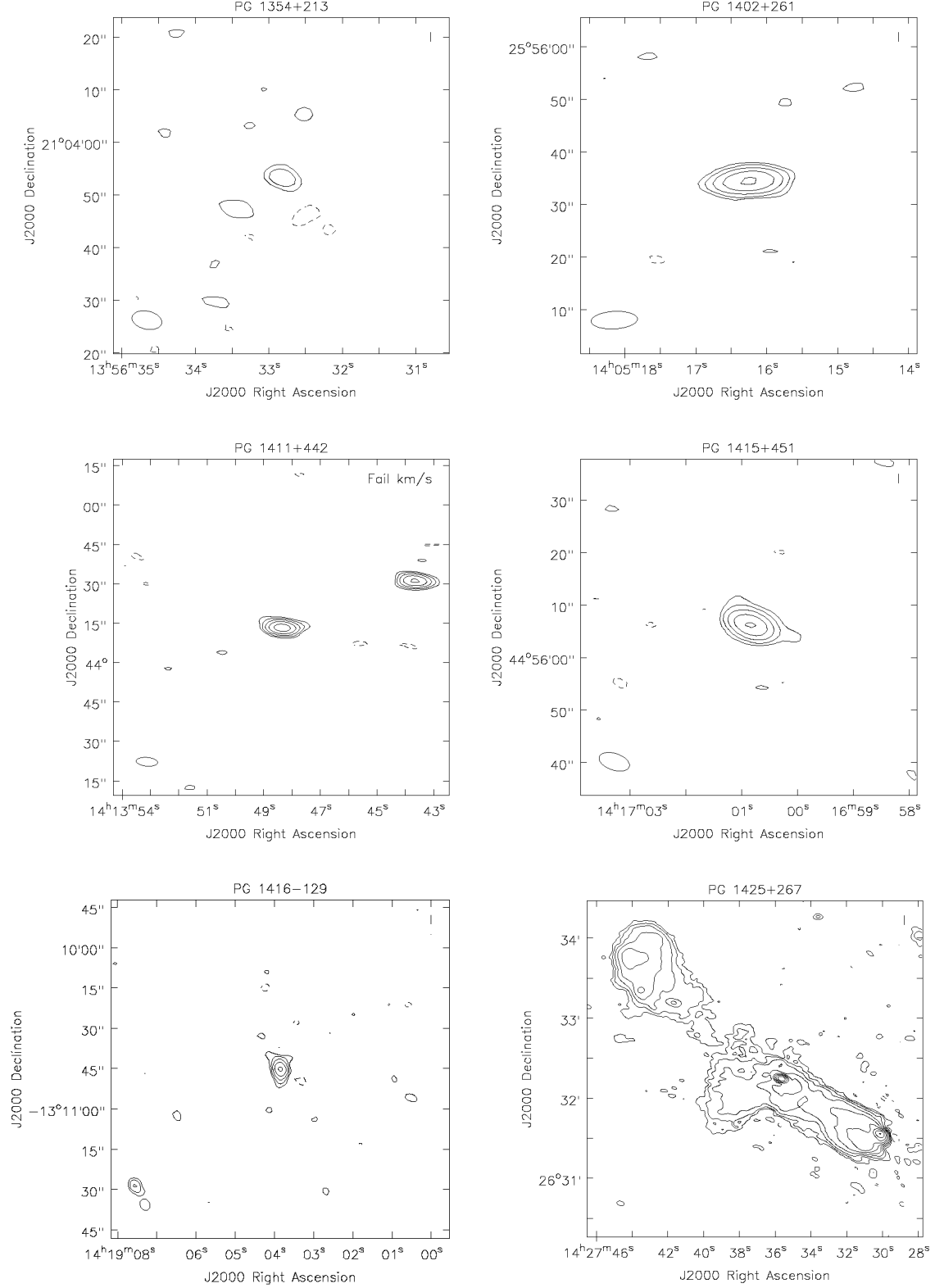


Figure 15. uGMRT 685 MHz radio contour images of PG 1354+213, PG 1402+261, PG 1411+442, PG 1415+451, PG 1416-129, and PG 1425+267 (RL). The contour levels are $3\sigma \times (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 516)$.

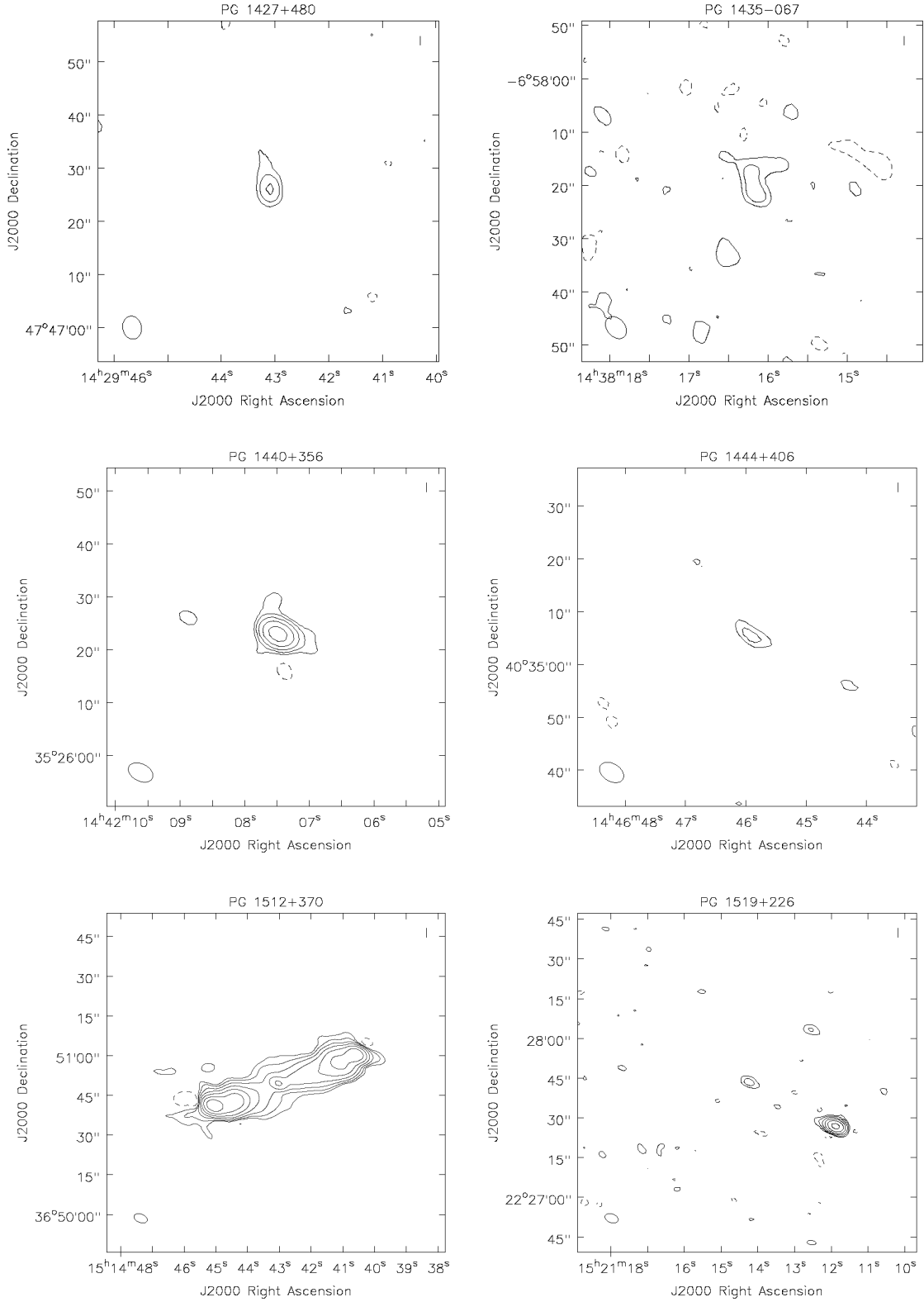


Figure 16. uGMRT 685 MHz radio contour images of PG 1427+480, PG 1435-067, PG 1440+356, PG 1444+406, PG 1512+370 (RL), and PG 1519+226 (the source is the weak one at the centre of the image). The contour levels are $3\sigma \times (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 516)$.

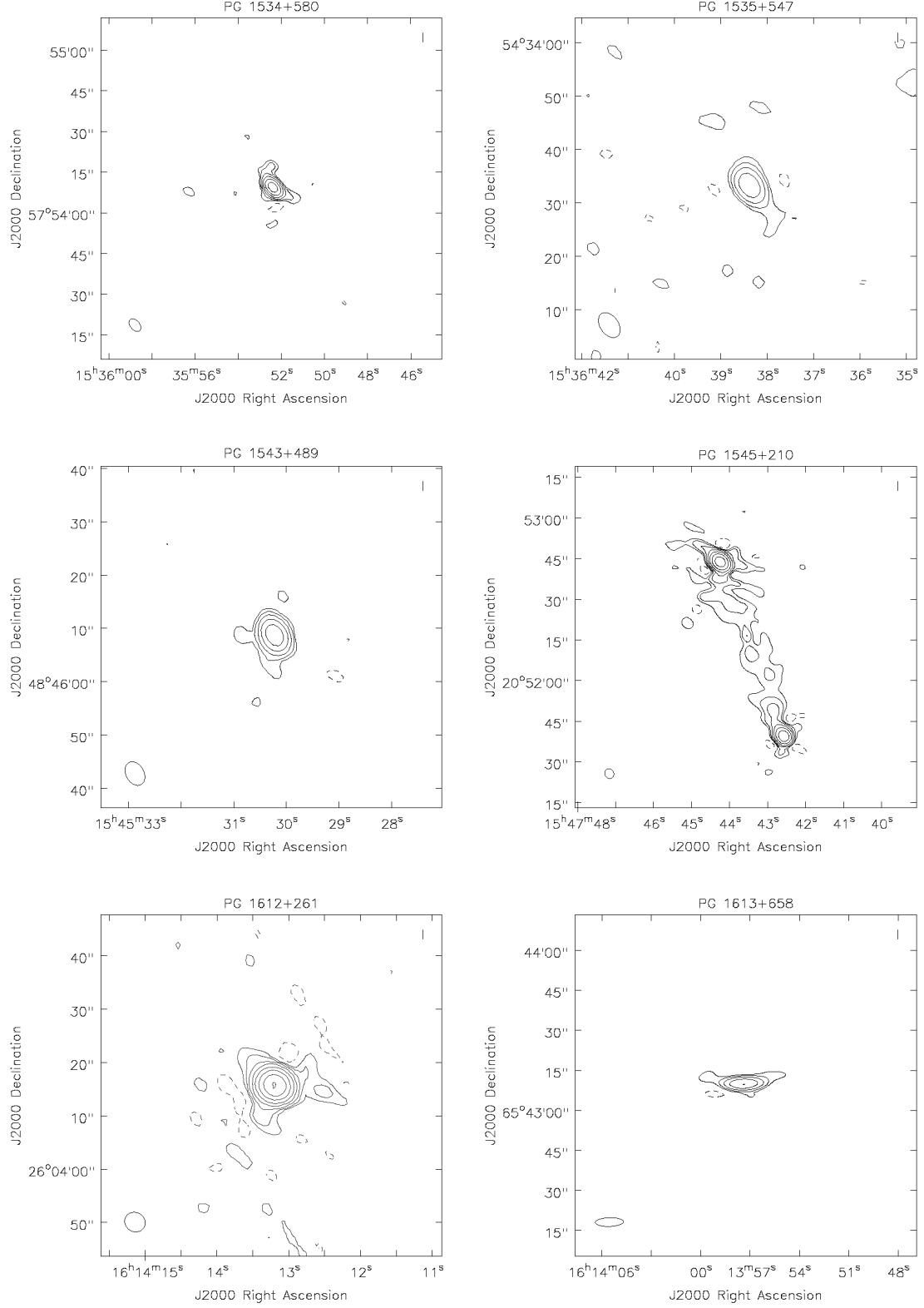


Figure 17. uGMRT 685 MHz radio contour images of PG 1543+580, PG 1535+547, PG 1543+489, PG 1545+210 (RL), PG 1612+261, and PG 1613+658. The contour levels are $3\sigma \times (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 516)$.

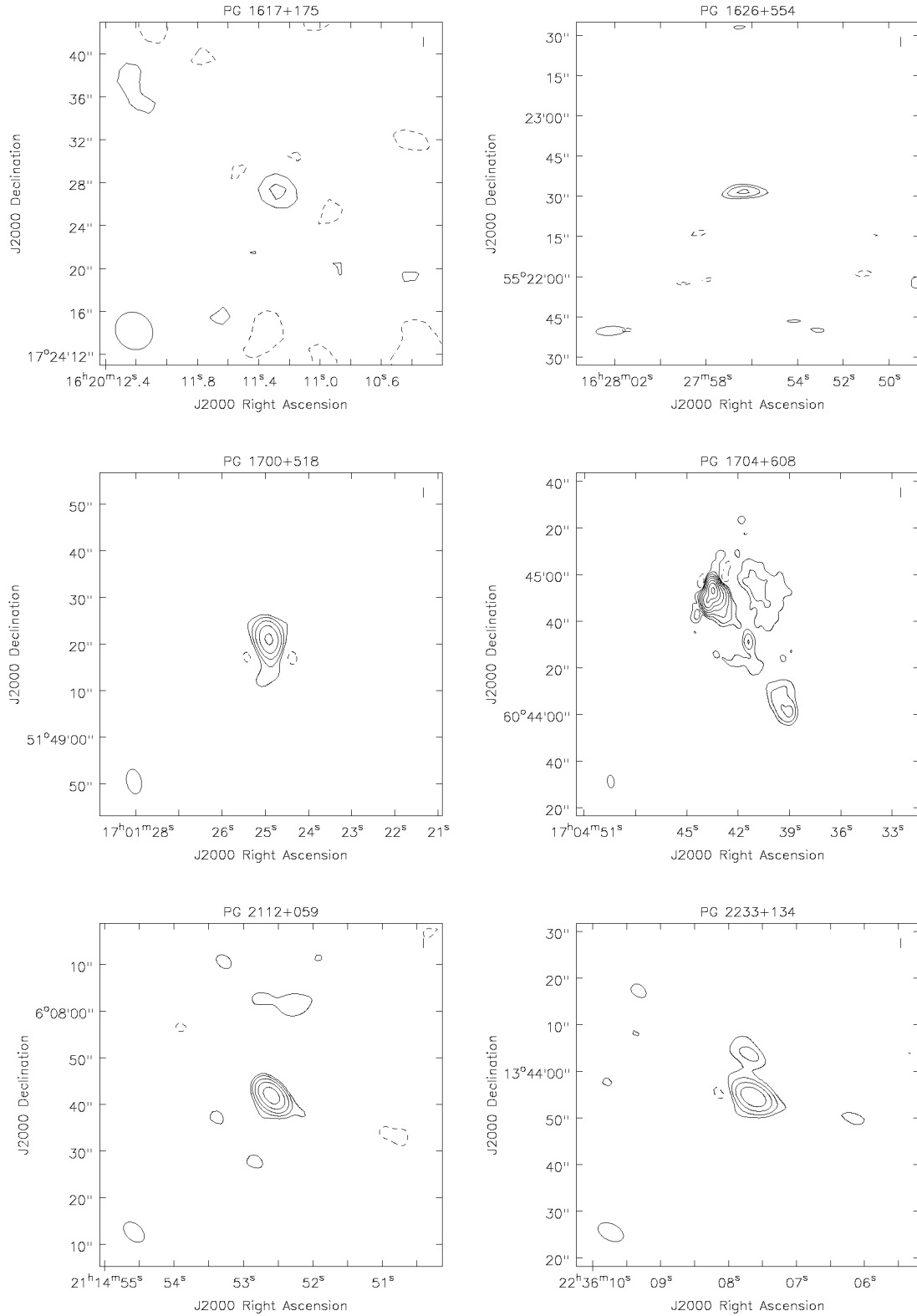


Figure 18. uGMRT 685 MHz radio contour images of PG 1617+175, PG 1626-554, PG 1700+518, PG 1704+068 (RL), PG 2112+059, and PG 2233+134. The contour levels are $3\sigma \times (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 516)$.

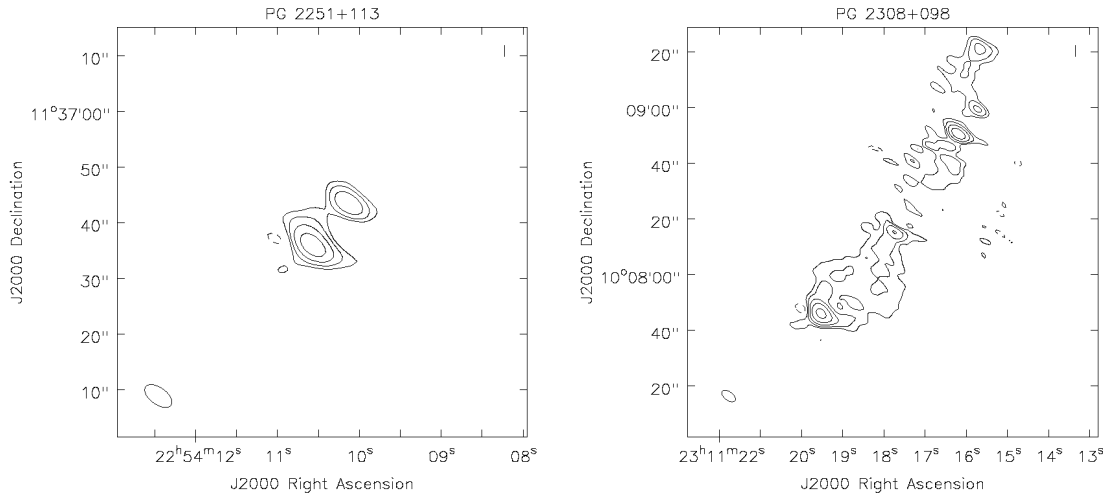


Figure 19. uGMRT 685 MHz radio contour images of PG 2251+113 (RL) and PG 2308+098 (RL). The contour levels are $3\sigma \times (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 516)$.

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