




A Giant Metrewave Radio Telescope survey of radio-loud broad absorption line quasars

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ABSTRACT

A substantial fraction of quasars display broad absorption lines (BALs) in their rest-frame ultraviolet spectra. While the origin of BALs is thought to be related to the accretion disc wind, it remains unclear whether the observed ratio of BAL to non-BAL quasars is a result of orientation. We conducted observations of 48 BAL quasars and the same number of non-BAL quasars at 322 MHz using the Giant Metrewave Radio Telescope. Combined with previous flux measurements ranging from MHz to GHz frequencies, we compared continuum radio spectra between the two quasar groups. These data offer insights into low-frequency radio properties that have been difficult to investigate with previous observations only at GHz frequencies. Our results show that 73 ± 13 per cent of the BAL quasars exhibit steep or peaked spectra, a higher proportion than the 44 ± 14 per cent observed in the non-BAL quasars. In contrast, there are no discernible differences between the two quasar groups in the radio luminosity, peak frequency, and spectral index distributions of sources with steep or peaked spectra and sources with flat or inverted spectra. Generally, as the jet axis and line of sight become closer to parallel, quasars exhibit flat or inverted spectra rather than steep or peaked spectra. Therefore, these results suggest that BAL quasars are more frequently observed farther from the jet axis than non-BAL quasars. However, given that a certain proportion of BAL quasars exhibit flat or inverted spectra, more than the simple orientation scenario is required to elucidate the radio properties of BAL quasars.

Key words: galaxies: active – galaxies: evolution – galaxies: jets – radio continuum: galaxies – quasars: absorption lines – radiation mechanisms: non-thermal.

1 INTRODUCTION

Broad absorption line (BAL) quasars exhibit blueshifted absorption troughs in their ultraviolet spectra, which result from broad resonance lines (Lynds 1967; Weymann, Carswell & Smith 1981; Weymann et al. 1991). An active galactic nucleus (AGN) wind, accelerated by radiation pressure to a velocity of $\sim 0.1c$, is responsible for the absorption (Laor & Brandt 2002; Ganguly et al. 2007). The winds emanating from the accretion disc are the most potent absorber (e.g. Murray et al. 1995; Elvis 2000; Proga, Stone & Kallman 2000; Nomura et al. 2013). AGN winds are of significant importance as they provide substantial energy to their host galaxies (e.g. Borguet et al. 2013; Hamann et al. 2019; Choi et al. 2020, 2022), playing a pivotal role in regulating the coevolution of galaxies and supermassive black holes (Ciotti, Ostriker & Proga 2009; Farrah et al. 2012; Bischetti et al. 2023). Therefore, a thorough understanding of BAL quasars is imperative in a cosmological context.

BAL quasars fall into two categories based on the ionization levels of their absorption troughs. HiBAL quasars display high-ionization

troughs, such as C IV and Si IV, constituting 10–30 per cent of all quasars (e.g. Trump et al. 2006; Knigge et al. 2008; Gibson et al. 2009; Allen et al. 2011). LoBAL quasars, accounting for ~ 10 per cent of all BAL quasars, exhibit low-ionization troughs in addition to high-ionization troughs, such as Mg II and Al III. A small subset of LoBAL quasars, ~ 1 per cent of all BAL quasars, are referred to as FeLoBAL quasars, showing absorption from excited states of Fe II or Fe III (Trump et al. 2006). The cause of these observed proportions is still an enigmatic puzzle, with two prominent models proposed: an orientation scheme and an evolution scheme. The former suggests that all quasars have directional winds and that BAL detection depends on the object's inclination (Weymann et al. 1991; Goodrich & Miller 1995). In this scenario, the ratio of BAL to non-BAL quasars and the proportion of different types of BAL quasars depend on the number of quasars viewed from various angles (Elvis 2000). In contrast, the evolution scheme argues that the ratio of BAL to non-BAL quasars reflects the period during which quasars exhibit AGN winds. LoBAL quasars, in particular, are believed to be young, recently fuelled quasars (Voit, Weymann & Korista 1993; Canalizo & Stockton 2001; L  pari & Terlevich 2006; Chen et al. 2022; Lazarova et al. 2023; Peng et al. 2024). Ultimately, the question concerns whether BAL and non-BAL quasars share the same central engine.

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Previous studies have shown that jet activity is the main factor responsible for the radio emission observed in radio-loud BAL quasars, which is supported by high spatial resolution images obtained through very long baseline interferometry (VLBI; e.g. Jiang & Wang 2003; Liu et al. 2008; Bruni et al. 2013; Hayashi, Doi & Nagai 2013; Cegłowski, Kunert-Bajraszewska & Roskowiński 2015; Kunert-Bajraszewska et al. 2015). Because thermal disc winds and non-thermal jets arise from the same central engine, radio observations that detect non-thermal emission can provide valuable insights into the above-mentioned question. Previous investigations conducted at GHz frequencies have revealed differences between BAL and non-BAL quasars, with BAL quasars found to be less luminous than non-BAL quasars (Stocke et al. 1992; Becker et al. 2000, 2001; Shankar, Dai & Sivakoff 2008). Additionally, they exhibit steeper spectra (DiPompeo et al. 2011; Bruni et al. 2012), which supports the orientation scenario where BAL quasars are viewed from an edge-on perspective (DiPompeo, Brotherton & De Breuck 2012). However, morphological studies have suggested the presence of a significant proportion of BAL quasars, including polar BAL quasars, at all inclinations (Nair & Vivek 2022). Moreover, BAL quasars exhibiting significant radio variability, indicative of face-on objects, have been documented (Zhou et al. 2006; Ghosh & Punnsly 2007; DiPompeo et al. 2011; Cegłowski et al. 2017). Therefore, the simple orientation scenario cannot fully account for the radio characteristics of BAL quasars.

Thus far, several observational inquiries have also explored the overall radio spectral shape of BAL quasars, covering both radio-quiet (Barvainis & Lonsdale 1997) and radio-loud samples (Montenegro-Montes et al. 2008; Bruni et al. 2012; Tuccillo et al. 2017). Initially, there was a prevalent belief that most radio-loud BAL quasars displayed compact radio morphology (Becker et al. 2000, 2001). Their spectral characteristics were found to be typical of compact steep-spectrum (CSS) or GHz peaked-spectrum (GPS) sources (Montenegro-Montes et al. 2008), which are candidates for lobe-dominated young radio sources (O’Dea 1998). These findings were part of the basis for the evolution scheme of BAL quasars. However, when comparing them with non-BAL quasars, the fractions of sources suggesting a peaked spectrum were similar in the two samples (Bruni et al. 2012; Tuccillo et al. 2017).

Despite the efforts mentioned above, observations conducted at GHz frequencies are suboptimal for comprehending the true nature of objects located at high redshifts, where the ultraviolet absorption lines fall within the optical band, owing to their susceptibility to the orientation-dependent relativistic beaming effects of the jets. Based solely on high-frequency observations, it is impossible to discern the underlying cause of the radio weakness of BAL quasars, whether attributed to intrinsically weak jet activity in the central engine or weak relativistic beaming effects. Moreover, because of the limited low-frequency observations in the MHz range in the past, comparisons of the overall spectral shape for high-redshift sources were restricted to the most extreme cases, where radio spectra peak at high rest frequencies. Therefore, observations at lower frequencies play a crucial role in addressing these issues. By capturing the low-frequency extended emission, where relativistic effects are weak, we can trace the total amount of intrinsic jet activity from the central engines.

Recently, an all-sky survey conducted at 144 MHz (Shimwell et al. 2022) has illuminated that the detection of BAL in its optical spectra is uniform across a range of radio luminosities (Morabito et al. 2019), differing from the previous findings at GHz frequencies (e.g. Shankar et al. 2008). Furthermore, Morabito et al. (2019) have reported a potential difference in spectral indices by comparing the

144-MHz data with conventional 1.4-GHz data (Becker, White & Helfand 1995). Nevertheless, prior estimates of spectral indices based on the limited number of data points in the MHz regime are inaccurate, and the underlying causes of these discrepancies have yet to be discussed. Therefore, multifrequency data obtained at lower frequencies are imperative for capturing the overall spectral shape and determining the physical parameters at the same rest frequencies across all sources.

This paper presents the findings of a survey on BAL quasars and a comparison sample at 322 MHz using the Giant Metrewave Radio Telescope (GMRT). The study compares the low-frequency radio spectra of BAL quasars with those of non-BAL quasars. The samples are described in Section 2, while Section 3 explains the observations and data reduction. The results are presented in Section 4, along with a discussion of the origin of the radio properties in Section 5. The paper defines spectral index, α , as $f_\nu \propto \nu^\alpha$, where f_ν represents flux density at frequency, ν . We utilized the standard cosmological model with cold dark matter and a cosmological constant having $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$, which is supported by observational studies from the past decades (e.g. Planck Collaboration VI 2020).

2 SAMPLE

2.1 BAL quasar sample

We selected our targets from the quasar catalogue (Schneider et al. 2007) obtained from the fifth data release (DR5; Adelman-McCarthy et al. 2007) of the Sloan Digital Sky Survey (SDSS; York et al. 2000). Initially, we extracted our sample of BAL quasars from a subset of quasars, specifically those that have had their CIV BAL reported by Gibson et al. (2009). The definition of a BAL is a subject of debate, and various studies have addressed this issue (Hall et al. 2002; Ganguly et al. 2007; Knigge et al. 2008). Here, the traditional balnicity index (BI; Weymann et al. 1991) is a strict criterion, and some studies have suggested that it may underestimate the presence of BALs (Reichard et al. 2003; Knigge et al. 2008). Therefore, in this study, we adopted the modified balnicity index, BI_0 , proposed by Gibson et al. (2009), which is more lenient than BI.

To ensure that the blueshifted and high-velocity CIV absorption line was within the SDSS spectral bandpass, we limited our target range to sources with redshifts of $1.68 \leq z \leq 4.93$. Our identification of radio-loud quasars involved cross-referencing the optical positions from the SDSS with the Faint Images of the Radio Sky at Twenty centimeters (FIRST) survey (Becker et al. 1995), restricting our sample to sources with an integrated flux density greater than 10 mJy and located within 3 arcsec of the FIRST survey radio positions. We focused on objects within the right ascension range of 10–17 h to accommodate the allocated observing time. Our sample, detailed in Table 1, comprises 48 sources, 35 of which intersect with the sample in DiPompeo et al. (2011). The FIRST survey spatially resolved three sources in our sample; Fig. 1 presents their images. It is worth noting that three sources in our sample, b20 (J123954.15+373954.5), b34 (J141437.99+045537.4), and b36 (J143340.35+512019.3), are also classified as LoBAL quasars by Gibson et al. (2009), showing a BAL in their Al III line. Also, b34 shows a BAL in its Mg II line.

Subsequently, we identified a discrepancy in the redshift of b02 (100424.88+122922.2; $z = 2.64$) reported by Schneider et al. (2007) and Gibson et al. (2009), with the latter presenting a value of $z = 4.66$. Further analysis, based on a broader SDSS spectrum obtained during a different epoch (Lyke et al. 2020), suggested a redshift closer to that of Schneider et al., which we ultimately adopted. Assuming the

Table 1. BAL quasar sample for GMRT observation.

ID	Source name (SDSS J)	z	M_i (mag)	BI (km s ⁻¹)	BI ₀ (km s ⁻¹)	Component	RA (J2000)	Dec. (J2000)	$f_{1.4}^{\text{FIRST}}$ (mJy)	$f_{1.4}^{\text{NVSS}}$ (mJy)	log L_5 (W Hz ⁻¹)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
b01	100109.42+114608.8	2.278	-27.1	716.1	3030.5	Total	—	—	23.8	23.6	27.5
	—	—	—	—	—	A	10 01 09.431 +11 46 08.71	13.7	—	—	27.2
	—	—	—	—	—	B	10 01 09.392 +11 45 55.13	10.1	—	—	27.1
b02	100424.88+122922.2	2.640	-25.8	4534.0 [†]	4534.0 [†]	—	10 04 24.872 +12 29 22.39	12.3	11.8	—	27.4
b03	104059.79+055524.4	2.443	-26.6	4120.3	4120.3	—	10 40 59.802 +05 55 24.78	42.2	39.1	—	27.8
b04	104452.41+104005.9	1.882	-27.9	2463.3	3283.9	—	10 44 52.417 +10 40 05.91	17.2	13.1	—	27.0
b05	105416.51+512326.0	2.341	-27.2	337.5	1056.2	—	10 54 16.528 +51 23 26.21	33.9	35.6	—	27.7
b06	110206.66+112104.9	2.351	-27.7	0.0	75.3	—	11 02 06.657 +11 21 04.74	83.1	80.8	—	28.1
b07	110531.42+151215.9	2.063	-27.0	4556.4	4556.4	—	11 05 31.490 +15 12 17.55	12.3	11.4	—	27.0
b08	112241.46+303534.9	1.810	-28.6	0.1	0.1	—	11 22 41.467 +30 35 34.88	10.0	9.5	—	26.7
b09	112938.47+440325.0	2.212	-27.8	0.0	806.5	—	11 29 38.475 +44 03 25.05	42.0	42.3	—	27.7
b10	113152.56+584510.2	2.262	-26.8	2.5	925.3	—	11 31 52.546 +58 45 10.26	12.8	13.2	—	27.2
b11	113445.83+431858.0	2.184	-26.9	4443.4	4443.4	—	11 34 45.834 +43 18 57.87	28.0	25.2	—	27.5
b12	115901.75+065619.0	2.191	-26.6	1675.4	1675.4	—	11 59 01.713 +06 56 18.91	160.1	158.3	—	28.2
b13	115944.82+011206.9	2.000	-28.4	0.0	937.9	—	11 59 44.832 +01 12 06.87	268.5	275.6	—	28.3
b14	121323.94+010414.7	2.829	-26.0	1551.0	1551.0	—	12 13 23.934 +01 04 14.82	22.9	27.5	—	27.8
b15	121539.66+090607.4	2.723	-28.0	116.3	116.3	—	12 15 39.670 +09 06 07.48	49.8	49.1	—	28.1
b16	122848.21-010414.5	2.655	-28.1	17.1	17.1	—	12 28 48.190 -01 04 14.27	30.8	29.1	—	27.8
b17	123411.73+615832.6	1.946	-26.9	4907.9	4907.9	—	12 34 11.747 +61 58 32.40	24.0	22.7	—	27.2
b18	123511.59+073330.7	3.035	-27.9	0.0	93.5	—	12 35 11.609 +07 33 30.80	11.3	12.9	—	27.6
b19	123717.44+470807.0	2.271	-27.3	868.7	868.7	—	12 37 17.438 +47 08 07.05	80.2	90.9	—	28.0
b20	123954.15+373954.5	1.841	-25.5	959.3	959.3	Total	—	—	18.5	16.2	27.0
	—	—	—	—	—	A	12 39 54.149 +37 39 54.45	10.7	—	—	26.8
	—	—	—	—	—	B	12 39 55.205 +37 39 42.20	4.3	—	—	26.4
	—	—	—	—	—	C	12 39 52.533 +37 40 15.77	3.5	—	—	26.3
b21	125243.85+005320.1	1.693	-27.1	94.6	94.6	—	12 52 43.860 +00 53 20.17	12.8	15.4	—	26.7
b22	130332.05+014407.4	2.109	-26.2	0.0	136.0	—	13 03 32.061 +01 44 07.41	38.0	34.7	—	27.5
b23	130448.06+130416.5	2.568	-27.3	4.8	4.8	—	13 04 48.050 +13 04 16.67	50.0	56.5	—	28.0
b24	130756.73+042215.5	3.022	-28.7	879.0	879.0	—	13 07 56.723 +04 22 15.50	14.9	15.8	—	27.7
b25	133004.34+605949.7	1.734	-26.2	72.1	72.1	Total	—	—	28.5	38.3	27.1
	—	—	—	—	—	A	13 30 04.335 +60 59 49.93	18.1	—	—	26.9
	—	—	—	—	—	B	13 30 03.250 +60 59 52.71	10.4	—	—	26.7
b26	133701.39-024630.3	3.064	-27.9	0.0	2.3	—	13 37 01.399 -02 46 29.89	44.8	45.1	—	28.2
b27	135550.30+361627.6	1.855	-26.3	0.0	604.4	—	13 55 50.294 +36 16 27.55	10.7	15.3	—	26.8
b28	135910.45+563617.4	2.248	-27.9	56.2	156.9	—	13 59 10.410 +56 36 17.01	17.9	16.8	—	27.3
b29	135910.77+400218.6	2.013	-26.8	432.9	432.9	—	13 59 10.774 +40 02 18.66	15.0	14.0	—	27.1
b30	140126.15+520834.6	2.972	-28.0	80.3	80.3	—	14 01 26.163 +52 08 34.63	37.1	30.4	—	28.1
b31	140501.12+041535.7	3.215	-27.1	12.5	12.5	—	14 05 01.114 +04 15 35.87	1055.9	933.0	—	29.7
b32	141313.63+411637.8	2.616	-28.4	1053.3	1053.3	—	14 13 13.622 +41 16 37.91	26.7	28.7	—	27.7
b33	141334.38+421201.7	2.817	-27.9	0.0	1446.9	—	14 13 34.404 +42 12 01.76	18.7	16.8	—	27.7
b34	141437.99+045537.4	1.851	-26.1	2015.1	2201.2	—	14 14 37.977 +04 55 37.22	11.8	14.4	—	26.8
b35	141736.05+372825.9	2.554	-26.1	0.0	177.3	—	14 17 36.045 +37 28 26.04	25.8	23.5	—	27.7
b36	143340.35+512019.3	1.863	-26.9	1085.7	1085.7	—	14 33 40.387 +51 20 19.70	12.6	13.0	—	26.9
b37	144434.80+003305.3	2.036	-26.5	0.0	163.0	—	14 44 34.816 +00 33 05.49	13.2	10.5	—	27.0
b38	145910.13+425213.2	2.967	-28.2	87.1	87.1	—	14 59 10.134 +42 52 13.20	13.7	15.0	—	27.6
b39	150332.93+440120.6	2.050	-27.0	1405.1	1405.1	—	15 03 32.948 +44 01 20.63	11.2	10.8	—	27.0
b40	150823.71+334700.7	2.208	-27.6	663.5	663.5	—	15 08 23.730 +33 47 00.63	132.0	131.3	—	28.2
b41	151630.30-005625.5	1.921	-27.0	0.0	517.0	—	15 16 30.350 -00 56 24.67	25.5	25.8	—	27.2
b42	153729.54+583224.6	3.059	-26.8	0.0	1432.0	—	15 37 29.553 +58 32 24.79	14.2	14.5	—	27.7
b43	155429.40+300118.9	2.693	-28.4	574.8	574.8	—	15 54 29.403 +30 01 19.04	41.2	40.5	—	28.0
b44	160354.15+300208.6	2.030	-27.7	0.0	480.0	—	16 03 54.159 +30 02 08.88	54.2	54.1	—	27.6
b45	162453.47+375806.6	3.381	-28.4	900.5	900.5	—	16 24 53.470 +37 58 06.65	56.4	55.6	—	28.5
b46	162559.90+485817.5	2.724	-28.4	3447.9	3447.9	—	16 25 59.905 +48 58 17.50	25.5	26.0	—	27.8
b47	162656.74+295328.0	2.312	-26.9	283.4	283.4	—	16 26 56.741 +29 53 28.02	11.3	13.4	—	27.2
b48	165543.24+394519.9	1.753	-27.2	3635.3	3635.3	—	16 55 43.235 +39 45 19.91	10.2	9.2	—	26.7

Note. Columns are as follows: (1) object ID; (2) SDSS source name; (3), (4) redshift and i -band absolute magnitude from the SDSS quasars catalogue DR5 (Schneider et al. 2007); (5), (6) balnicity index, BI, and modified balnicity index, BI₀, of C IV absorption line, respectively (Gibson et al. 2009), where BI and BI₀ of b02 indicated by [†] were measured based on the estimated redshift of $z = 4.66$ (see text for details); (7) name of each component if multiple radio source is associated; (8), (9) radio positions; (10) flux density at 1.4 GHz from the FIRST survey; (11) flux density at 1.4 GHz from the NVSS (Condon et al. 1998); (12) log specific luminosity at rest 5 GHz calculated by flux density at 1.4 GHz assuming a spectral index of $\alpha = -0.7$. For quasars associated with multiple radio sources, we provide information on each source. The reference for columns (7)–(9) is Becker et al. (1995).

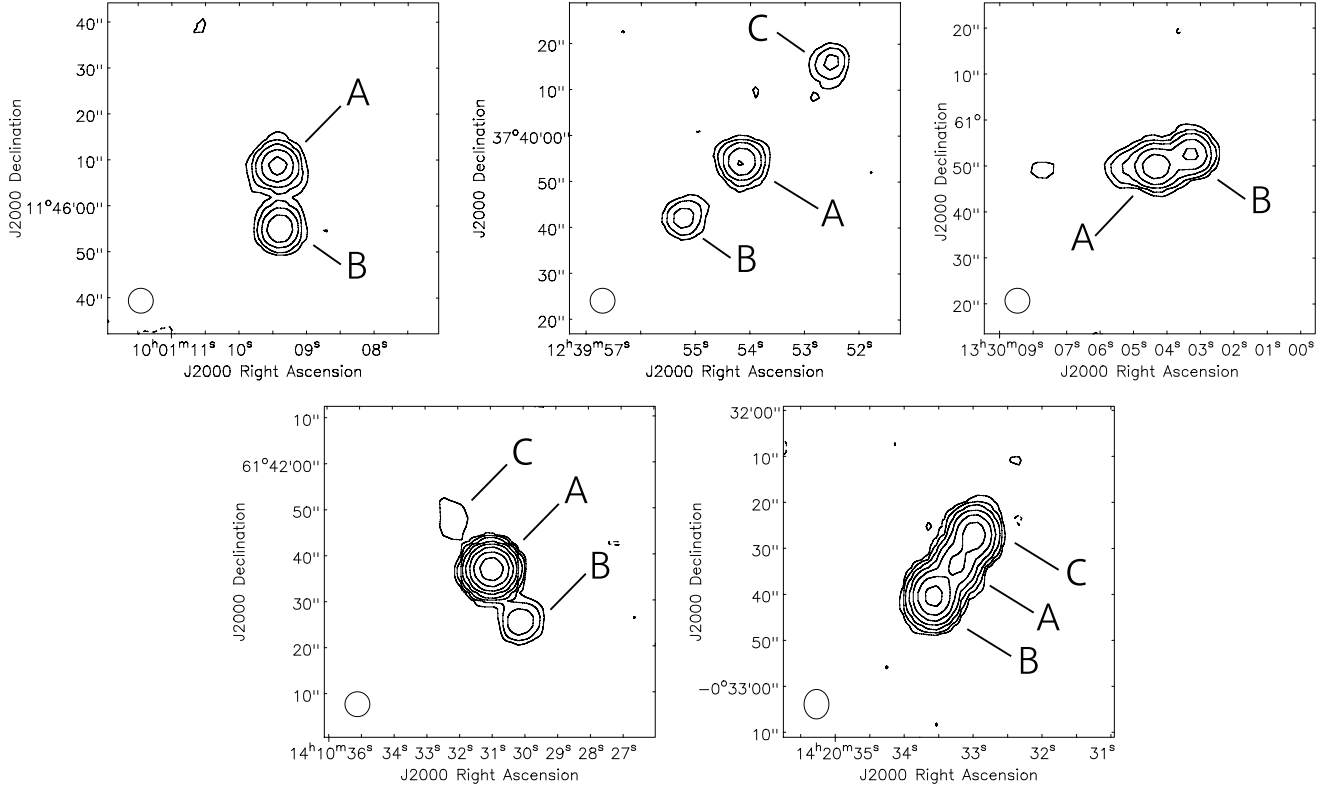


Figure 1. Radio images at 1.4 GHz for b01 (J100109+114608), b20 (J123954+373954), b25 (J133004+605949), n24 (J141031+614136), and n27 (J142033+003233) from top left to bottom right, all of which are resolved BAL quasars, provided by the FIRST survey. The optical position of the quasar corresponds to the component A in each image. From top left to bottom right, the contour levels commence at 520, 546, 479, 494, and 394 $\mu\text{Jy beam}^{-1}$ (equivalent to the 3σ noise level of the image) and are then multiplied by a factor of 2.

redshift of $z = 2.64$, we detected no C IV absorption from this source; hence, the BI and BI₀ presented in Table 1 should be 0. However, the source displayed potential BALs in Al III and Mg II, indicating the characteristics of a LoBAL quasar. Despite this issue, we could not acquire GMRT observational data for this source due to radio frequency interference (RFI). Even in statistical analyses that do not require GMRT data, we provide both examinations, considering and excluding this specific object.

2.2 Non-BAL quasar sample

To establish a comparison group, we created a non-BAL quasar sample where each object was paired with objects in the BAL quasar sample based on each physical quantity. The criterion for selection comprises a redshift of 10 per cent of the corresponding BAL quasar within the range of $1.68 \leq z \leq 4.93$, a flux density at 1.4 GHz of 20 per cent of the BAL quasar, and an *i*-band magnitude within ± 1.0 of the BAL quasar. In addition, we tried to select objects that could be observed using the same phase calibrators as the BAL sample to minimize the total observation time. Table 2 lists the resulting non-BAL quasar sample, which contains two sources that the FIRST survey resolved; Fig. 1 also shows their images. Additionally, we visually inspected the SDSS spectra of the non-BAL quasar sample in the rest-frame wavelength range of 1400–1600 Å. We confirmed they were free from significant broad absorption of Si IV or C IV. We note, however, that we inadvertently incorporated a source, n24 (J141031.00+614136.9), that displays a BAL in Al III at 1857.4 Å in our sample. We present both analyses, incorporating and excluding this object.

Fig. 2 depicts the distributions of redshift, specific luminosity at 5 GHz with a spectral index of $\alpha = -0.7$, and *i*-band absolute magnitude for both the BAL and non-BAL quasar samples. The Kolmogorov–Smirnov (KS) and Wilcoxon rank sum (RS) tests indicate no notable distinctions between the distributions of the two samples. Consequently, we can deduce that the two samples exhibit homogeneity, except for BALs.

2.3 Flux variability

The primary objective of this investigation is to examine the radio spectra of quasars using new GMRT observations and previous flux measurements. Generally, quasars display variations in flux density at radio wavelengths (Hufnagel & Bregman 1992; Barvainis et al. 2005; Hovatta et al. 2007), which may affect the data collected at different epochs. To assess this impact on the samples, we compared the 1.4-GHz flux density measurements acquired from the FIRST survey with those obtained from the NRAO VLA Sky Survey (NVSS; Condon et al. 1998). Fig. 3 depicts the comparison of the integrated flux densities. To evaluate the extent of flux density variability, we utilized the index introduced by Zhou et al. (2006), given by

$$V = \frac{|f_1 - f_2|}{\sqrt{\sigma_1^2 + \sigma_2^2}}, \quad (1)$$

where f_i and σ_i denote the flux density and measurement error for the *i*th epoch data, respectively. The errors in flux density are the rms of the thermal noise and calibration uncertainty, which were assumed to be 5 per cent. When comparing data acquired from different array configurations, objects with a high-resolution peak flux density

Table 2. Non-BAL quasar sample for GMRT observation.

ID	Source name (SDSS J)	z	M_i (mag)	Compo- nent	RA (J2000)	Dec. (J2000)	$f_{1.4}^{\text{FIRST}}$ (mJy)	$f_{1.4}^{\text{NVSS}}$ (mJy)	$\log L_5$ (W Hz ⁻¹)
(1)	(2)	(3)	(4)	(7)	(5)	(6)	(7)	(8)	(9)
n01	103808.94+464249.1	1.924	−26.9	—	10 38 08.950	+46 42 49.46	12.2	12.4	26.9
n02	111048.93+045608.0	2.208	−26.8	—	11 10 48.963	+04 56 07.13	65.2	74.2	27.9
n03	111336.10+494034.7	2.466	−27.6	—	11 13 36.087	+49 40 34.63	28.7	27.4	27.7
n04	111434.01+041434.0	1.719	−26.0	—	11 14 34.018	+04 14 33.97	17.1	18.7	26.9
n05	112854.24+035341.4	1.829	−26.9	—	11 28 54.258	+03 53 41.05	19.8	20.3	27.0
n06	113017.37+073212.9	2.647	−28.9	—	11 30 17.371	+07 32 13.09	31.6	27.6	27.8
n07	113716.36+371046.4	2.027	−27.3	—	11 37 16.365	+37 10 46.67	10.3	9.5	26.9
n08	113854.52+394553.6	2.159	−27.2	—	11 38 54.533	+39 45 53.62	21.2	19.7	27.3
n09	115534.50+575156.4	1.967	−26.4	—	11 55 34.509	+57 51 56.49	23.9	24.2	27.2
n10	121911.23−004345.5	2.293	−27.7	—	12 19 11.247	−00 43 45.42	94.5	104.5	28.1
n11	123215.09+554049.4	2.307	−26.3	—	12 32 15.115	+55 40 49.53	11.1	32.2	27.2
n12	123545.38−033610.9	2.375	−26.6	—	12 35 45.391	−03 36 10.79	10.2	11.3	27.2
n13	123856.09−005930.8	1.844	−27.3	—	12 38 56.101	−00 59 30.89	14.0	15.5	26.9
n14	124409.64+554823.4	1.768	−25.9	—	12 44 09.639	+55 48 23.49	10.2	10.5	26.7
n15	125321.59−032315.7	1.771	−26.6	—	12 53 21.602	−03 23 15.96	26.7	30.0	27.1
n16	131003.35+535348.2	3.278	−27.2	—	13 10 03.352	+53 53 48.16	14.5	13.1	27.8
n17	131926.27+143439.9	2.541	−27.6	—	13 19 26.285	+14 34 39.88	59.3	60.0	28.0
n18	133754.41+451239.1	2.758	−28.3	—	13 37 54.428	+45 12 39.32	25.8	29.7	27.8
n19	134253.64+390223.6	1.723	−26.2	—	13 42 53.653	+39 02 23.68	13.4	13.4	26.8
n20	134303.25+502832.0	1.962	−26.6	—	13 43 03.252	+50 28 32.16	39.9	40.9	27.5
n21	134520.40+324112.5	2.255	−27.7	—	13 45 20.421	+32 41 12.59	14.6	14.9	27.2
n22	140637.60+141530.0	2.926	−27.3	—	14 06 37.619	+14 15 30.19	40.9	41.8	28.1
n23	140909.74+071226.1	2.734	−27.1	—	14 09 09.748	+07 12 26.26	11.7	10.5	27.4
n24	141031.00+614136.9	2.246	−27.0	Total	—	—	125.0	98.2	28.2
	—	—	—	A	14 10 30.992	+61 41 36.89	118.4	—	28.1
	—	—	—	B	14 10 30.113	+61 41 25.51	4.9	—	26.8
	—	—	—	C	14 10 32.179	+61 41 48.03	1.8	—	26.3
n25	141846.20+482308.2	2.193	−26.2	—	14 18 46.211	+48 23 08.23	12.8	11.1	27.1
n26	142009.33+392738.5	2.295	−26.9	—	14 20 09.377	+39 27 38.77	38.4	38.1	27.7
n27	142033.25−003233.3	2.682	−27.3	Total	—	—	77.6	77.0	28.2
	—	—	—	A	14 20 33.238	−00 32 33.54	16.4	—	27.6
	—	—	—	B	14 20 33.569	−00 32 40.42	38.5	—	27.9
	—	—	—	C	14 20 32.982	−00 32 27.06	22.7	—	27.7
n28	142326.05+325220.3	1.905	−29.3	—	14 23 26.073	+32 52 20.34	8.2	8.1	26.7
n29	142352.38+031125.8	1.884	−26.9	—	14 23 52.396	+03 11 26.08	55.8	52.8	27.5
n30	142921.87+540611.2	3.013	−26.5	—	14 29 21.891	+54 06 10.95	1165.4	1028.3	29.6
n31	143243.29+410327.9	1.970	−27.8	—	14 32 43.322	+41 03 28.04	261.7	261.9	28.3
n32	143708.18+040534.3	2.025	−27.5	—	14 37 08.201	+04 05 34.65	16.5	15.3	27.1
n33	143737.06+094847.7	2.162	−26.8	—	14 37 37.042	+09 48 47.81	181.2	191.5	28.3
n34	144752.46+582420.3	2.983	−28.1	—	14 47 52.441	+58 24 20.39	33.2	32.8	28.0
n35	145627.72+414944.2	2.668	−26.5	—	14 56 27.731	+41 49 44.43	13.2	12.1	27.5
n36	145924.24+340113.1	2.790	−28.3	—	14 59 24.251	+34 01 13.11	21.7	22.2	27.7
n37	151258.36+352533.2	2.236	−26.7	—	15 12 58.373	+35 25 33.32	47.5	53.6	27.7
n38	152314.87+381402.0	3.159	−27.9	—	15 23 14.870	+38 14 02.13	47.7	51.9	28.3
n39	154644.24+311711.3	2.122	−26.3	—	15 46 44.250	+31 17 11.47	12.7	14.0	27.1
n40	154935.74+314338.2	1.815	−25.8	—	15 49 35.725	+31 43 38.38	11.0	9.9	26.8
n41	155816.63+502953.7	1.900	−26.5	—	15 58 16.632	+50 29 53.77	16.7	16.9	27.0
n42	160911.26+374635.7	2.412	−26.4	—	16 09 11.287	+37 46 36.42	22.7	25.9	27.5
n43	161920.20+375502.7	2.966	−26.7	—	16 19 19.962	+37 55 02.77	18.9	19.9	27.8
n44	162004.73+351554.6	2.960	−27.6	—	16 20 04.690	+35 15 54.93	50.0	57.3	28.2
n45	165137.53+400219.0	2.343	−28.5	—	16 51 37.565	+40 02 18.71	43.9	43.1	27.8
n46	165508.72+373244.6	2.092	−26.6	—	16 55 08.724	+37 32 44.77	9.5	8.8	26.9
n47	074927.90+415242.3	3.111	−28.9	—	07 49 27.911	+41 52 42.20	15.2	15.5	27.8
n48	095537.94+333503.9	2.477	−28.6	—	09 55 37.936	+33 35 03.97	36.6	33.0	27.8

Note. Columns are as follows: (1) object ID; (2) SDSS source name; (3), (4) redshift and i -band absolute magnitude from SDSS DR5 (Adelman-McCarthy et al. 2007); (5) name of each component if multiple radio source is associated; (6), (7) radio positions; (8) flux density at 1.4 GHz from the FIRST survey; (9) Flux density at 1.4 GHz from the NVSS (Condon et al. 1998). (10) Log specific luminosity at rest 5 GHz calculated by flux density at 1.4 GHz assuming spectral index of $\alpha = -0.7$. For quasars associated with multiple radio sources, we provide information on each source. The reference for columns (5)–(7) is Becker et al. (1995).

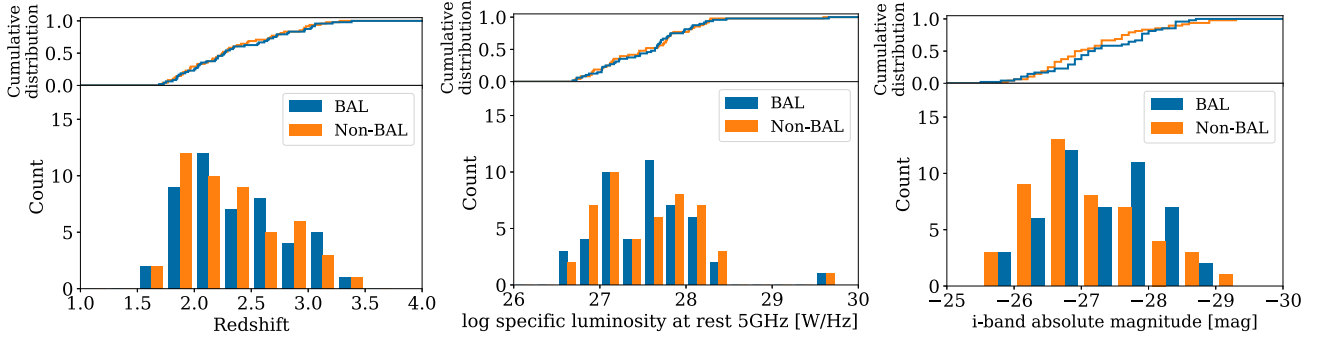


Figure 2. Comparison of the characteristics of the BAL and non-BAL quasar samples: redshift z , specific radio luminosity at rest 5.0 GHz, $L_{5.0}$, and i -band absolute magnitude, M_i , from left to right. Each panel shows the distribution of the two samples, represented in blue and orange, respectively, in terms of both number and cumulative frequency. We have applied two statistical tests, the KS and RS tests, to evaluate the likelihood that the two distributions do not originate from different parent populations. The KS test yields a test statistic of $D_{KS} = 0.0833, 0.0833, \text{ and } 0.1875$ for $z, L_{5.0}, \text{ and } M_i$, respectively, with corresponding probabilities of $p = 0.996, 0.996, \text{ and } 0.368$. The RS test gives a test statistic of $Z_{RS} = 1194, 1162, \text{ and } 1018$ for $z, L_{5.0}, \text{ and } M_i$, respectively, with corresponding probabilities of $p = 0.764, 0.945, \text{ and } 0.326$. These p -values indicate the probability of obtaining a result equal to or more extreme than the observed result, assuming the null hypothesis that the two samples are drawn from the same parent population.

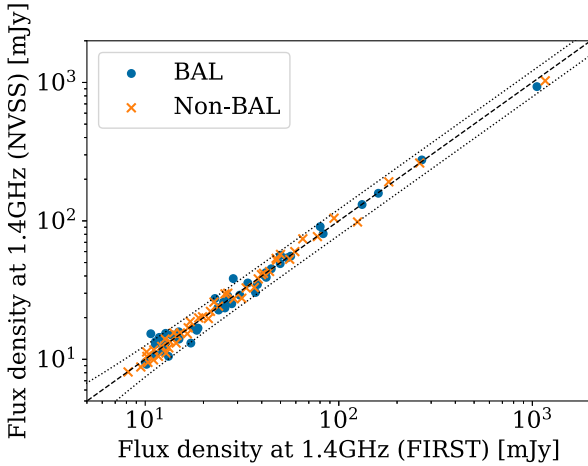


Figure 3. Flux density distribution at 1.4 GHz obtained from the FIRST survey and the NVSS. Circles and Crosses indicate BAL and non-BAL quasars, respectively. The dashed line indicates where the two survey fluxes are equal, and the dotted lines show the 3σ variation of the sources around the line of equal flux. Two BAL quasars that appear to lie well above the line may have a second object contaminating the NVSS flux density and are likely not variable.

greater than the integrated flux density at a lower resolution are considered potential variable objects.

We have identified two candidates, b04 (J104452.41+104005.9) and n24 (J141031.00+614136.9), representing significant variability of $V > 3$, with $V = 3.57$ and 3.52 , respectively. While we acknowledge that only two epochs of observations may not be sufficient to provide conclusive evidence regarding the stability or variability of the targets, we present both analyses, encompassing and omitting these candidates for variable sources.

3 OBSERVATIONS AND DATA REDUCTION

3.1 New 322-MHz observation

We conducted the new GMRT observations between 2013 May 16 and 19 under project code 24_006. To reduce the impact of ionospheric variations, we initiated the observations in the early evening

and continued throughout the night as a contiguous block lasting 10 h. During the observations, we utilized the default parameters of the 306-MHz band of the legacy GMRT system, with a 32-MHz wide intermediate frequency centred at 322 MHz for both LL and RR polarizations. We collected the data using 256 spectral channels, each with a width of 12.5 kHz. We monitored the flux and bandpass calibrator, 3C 286, every 3–4 h, and we observed each target for 6–8 min scans at two different hour angles. Additionally, we observed phase calibrators approximately every 30 min, with a typical angular separation of 6 deg and a maximum separation of 13.5 deg between targets and each calibrator. Please refer to Table 3 for an overview of the observations.

We processed the data using the Common Astronomy Software Applications (CASA; McMullin et al. 2007) package, with reference to the calibration and imaging pipeline developed by Ishwara-Chandra et al. (2020). We started with an initial delay correction using the CASA task `gaincal` with a bright calibrator, 3C 286. We then performed amplitude and phase bandpass calibration using the same calibrator. Next, the flux density scale was determined using the formula from Perley & Butler (2017), with 3C 286 as the calibrator. Finally, we calibrated the antenna-based amplitude and phase time variations using phase calibrators. We identified and flagged RFI in the time and frequency domains at each stage using the `rflag` and `tcrop` modes of the CASA task `flagdata`. Unfortunately, as a result of significant scintillation of the ionosphere, we could not achieve proper phase calibration for three BAL quasars (b01, b02, and b18) and one non-BAL quasar (n10). Because of the absence of low-frequency flux measurements potentially affecting the statistical outcomes, we present both analyses, inclusive and exclusive of these objects. These sources requiring careful consideration in subsequent statistical analyses are listed in Table 4.

We utilized the CASA task `tclean` equipped with widefield imaging mode and multiterm multifrequency synthesis capabilities to carry out imaging processes. First, we reduced the size of the data set by averaging the data to 32 channels, each 2 MHz wide. In order to resolve the antenna-based amplitude and phase corrections for Stokes I , self-calibration was executed. Initially, we performed phase-only calibration to the data with $u-v$ length greater than $2 \text{ k}\lambda$ against a basic point source model of $\sim 1 \times 1 \text{ deg}^2$, obtained from the FIRST survey (Becker et al. 1995) utilizing the Montage Image Mosaic Engine (Jacob et al. 2009). Subsequently, we gradually integrated short baselines and resolved radio sources, followed by several

Table 3. Observation summary.

Date	Phase calibrator	Observed targets
2013 May 16	1131+4514	b05, b09, b11, n01, n03, n08
	1338+3851	b20, b29, b32, b33, b35, n18, n19, n26, n28, n31
	1531+3533	b40, n35, n36, n37, n38
	1653+3945	b45, b48, n45, n46
2013 May 17	0753+4231	n47
	1123+0530	b03, b04, b06, b07, b12, b13, b14, b15, n02, n04, n05, n06
	1308−0950	b26
	1419+0628	b31, b34, b37, n23, n27, n29, n32, n33
	1510−0543	b41
2013 May 18	1252+5634	b19, n09, n11, n14, n16
	1313+6735	b10, b17, b25, b28
	3C 286	b27, n21
	1411+5212	b30, b36, n20, n25, n30
	1449+6316	b42, n24, n34
	1545+4751	b38, b39, b46, n41
2013 May 19	0958+3224	n48
	1021+2159	b01, b02
	1156+3128	b08, n07
	1242−0446	b16, b18 , b21, b22, n10 , n12, n13, n15
	1347+1217	b23, b24, n17, n22
	1602+3326	b43, b44, b47, n39, n40, n42, n43, n44

Note. IDs in the ‘observed targets’ column are object IDs in Tables 1 and 2. Targets whose flux measurements were not made due to severe RFI are indicated in bold.

Table 4. Annotation of objects requiring consideration in statistical analyses.

ID	Comments
b01	RFI in the 322-MHz data; source with multicomponents
b02	RFI in the 322-MHz data; no C IV BAL but potential presence of Al III BAL
b04	Candidate exhibiting variability
b11	No detection at both 150 and 322 MHz
b18	RFI in the 322-MHz data
b20	Source with multicomponents
b25	Source with multicomponents
n10	RFI in the 322-MHz data
n24	Candidate exhibiting variability; source with multicomponents; no C IV BAL but potential presence of Al III BAL
n27	Source with multicomponents
n32	No detection at both 150 and 322 MHz

rounds of widefield imaging and phase and amplitude calibration. Ultimately, we generated final images using a Briggs weighting of $\text{robust} = 0.5$ (Briggs 1995), encompassing a field of view as large as $2.5 \times 2.5 \text{ deg}^2$ to include probable strong sources positioned beyond the primary lobe. The typical synthesized beam size for the resulting images was ~ 11 and $\sim 8 \text{ arcsec}$ for the major and minor axes, respectively.

To determine the flux densities of our targets, we used the CASA task *IMFIT*, which fits an elliptical Gaussian component within a small box enclosing the radio source. We estimated the flux density errors by taking the rms of a calibration uncertainty and the error provided by *IMFIT*, which contains thermal noise and fitting errors. To be conservative, we assumed a calibration uncertainty of 10 per cent (e.g. Chandra, Ray & Bhatnagar 2004). The typical rms noise level obtained from *IMFIT* was approximately $0.5 \text{ mJy beam}^{-1}$, consistent with the previous snapshot survey observations made using the legacy GMRT system (e.g. Prescott et al. 2016).

3.2 Archival data

We additionally used data points from previous publications to determine the overall spectral shape.

For 144-MHz data, we initially endeavoured to utilize data obtained from the second data release of the LOFAR Two-metre Sky Survey (LoTSS-DR2; Shimwell et al. 2022). This survey observes at a frequency centred on 144 MHz and has a spatial resolution of 6 arcsec. Although the survey’s catalogue tables provide error estimates, these estimations only reflect thermal noise and do not account for the uncertainty associated with amplitude calibration. Therefore, we calculated the flux density error by taking the rms of thermal noise and amplitude calibration error. The latter was assumed to be 10 per cent of the flux density measurement (Shimwell et al. 2022). As the survey observations are still ongoing, flux density measurements are not accessible for some sources. For such sources, we relied on the flux density at 147.5 MHz provided by the TIFR GMRT Sky Survey (TGSS; Intema et al. 2017), whose spatial resolution is 25 arcsec. We directly utilized the flux measurement errors listed in the survey’s catalogue, which account for thermal noise and amplitude calibration errors. The TGSS did not detect some sources that LoTSS has yet to observe. For these sources, we estimated the thermal noise from the image cutouts provided by the TGSS and adopted 5σ as an upper limit.

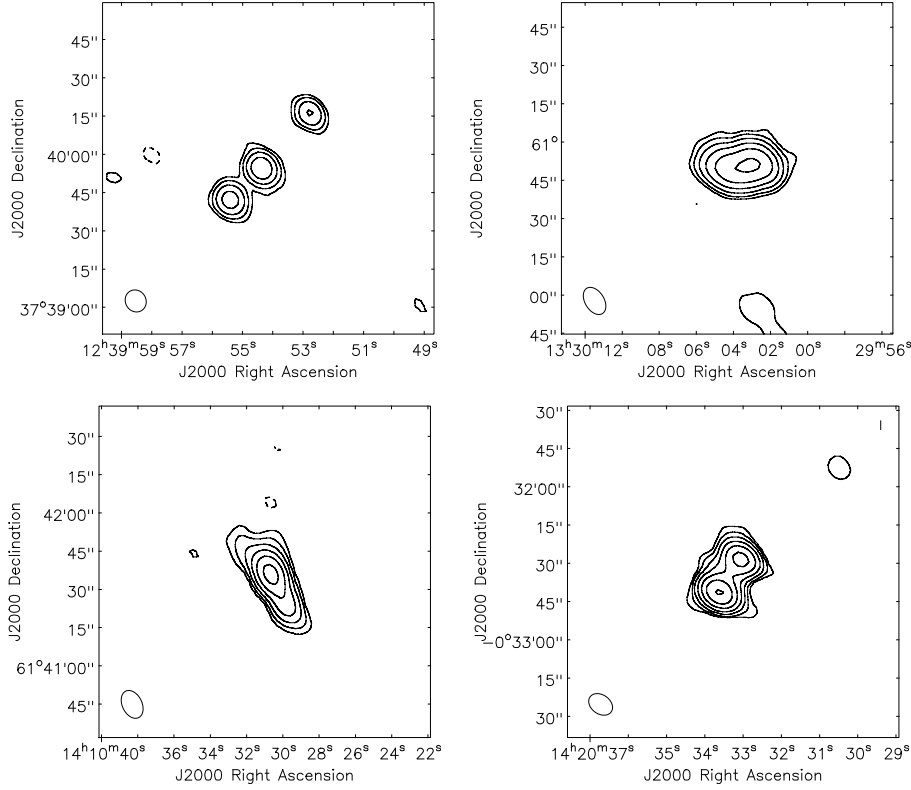


Figure 4. Radio images at 322 MHz for b20 (J123954+373954), b25 (J133004+605949), n24 (J141031+614136), and n27 (J142033–003233) from top left to bottom right, whose contour levels commence at 1.7, 1.0, 1.4, and 2.2 mJy beam^{−1} (equivalent to the 3 σ noise level of the image), respectively, and are then multiplied by a factor of 2.

For GHz-frequency data, we acquired flux density measurements at 1.4 and 3.0 GHz from the FIRST survey and the VLA Sky Survey (VLASS; Lacy et al. 2020), respectively. These surveys have an angular resolution of 5.0 and 2.5 arcsec, respectively. We calculated the flux density error by taking the square root of the sum of the squares of thermal noise from the catalogues and a 5 percent amplitude calibration error (Lacy et al. 2019). As Gordon et al. (2021) recommend, we corrected the catalogue values by multiplying them by 1/0.87 in our analysis due to a systematic underestimation of the flux density measurements.

In addition to the data mentioned above, where flux measurements at the same frequency are provided for all objects in the samples, the following archive data were also utilized to evaluate the overall spectral shape of targets: the LOFAR LBA Sky Survey (LoLSS) at 54 MHz with a resolution of 15 arcsec (de Gasperin et al. 2023); the VLA Low-Frequency Sky Survey (VLSS) at 74 MHz with a resolution of 80 arcsec (Cohen et al. 2007); the GaLactic and Extragalactic All-sky Murchison Widefield Array (GLEAM) survey at 200 MHz with a resolution of 120 arcsec (Hurley-Walker et al. 2017); the Texas Survey at 365 MHz with a resolution of 20 arcsec (Douglas et al. 1996); the Rapid ASKAP Continuum Survey (RACS) at 887.5 MHz with a resolution of 25 arcsec (Hale et al. 2021); and the Cosmic Lens All-Sky Survey (CLASS) at 8.4 GHz, with a resolution of 0.2 arcsec (Myers et al. 2003). As these data are not available for all objects in the samples, a statistical comparison of spectral indices including them was not performed. If the flux error in the catalogue did not consider calibration uncertainty, we estimated the error by calculating the rms of the thermal noise and amplitude calibration error as described in the source paper. Furthermore, we also utilized prior flux measurements carried out by VLA specifically

for BAL quasars, as documented in studies by DiPompeo et al. (2011), Montenegro-Montes et al. (2008), and Bruni et al. (2012).

4 RESULTS

4.1 Flux measurement and spectral indices

We found that the images of all targets at all bands are consistent with those from the FIRST survey (Fig. 1), and we did not detect any new components. Our GMRT observations have revealed that all targets, except those shown in Fig. 4, are point sources. Tables 5 and 6 show the results of the GMRT observations and prior all-sky surveys, including the corresponding spectral indices and radio luminosities. Please see Figs 5 and 6 for the radio spectra of the BAL and non-BAL quasar samples, respectively. As described in Section 3.1, RFI prevented us from measuring the flux density at 322 MHz for three BAL quasars (b01, b02, and b18) and one non-BAL quasar (n10). In addition, we did not detect one source from each group at this frequency (b11 and n32), which was also undetected at 144 MHz; thus, we could not establish constraints on their low-frequency spectral index between 144 and 322 MHz. Table 4 summarizes the objects requiring careful consideration in subsequent statistical analyses.

4.2 Spectral classification

To classify the overall spectral shape, we fitted the observed spectra with the following function,

$$\log f_\nu = \log f_p + b - \sqrt{b^2 + c^2(\log \nu - \log \nu_p)^2}, \quad (2)$$

Table 5. Flux densities, spectral indices, and radio luminosities of the BAL quasar sample.

ID	Component	$f_{0.144}$ (mJy)	$f_{0.322}$ (mJy)	$f_{1.4}$ (mJy)	$f_{3.0}$ (mJy)	α_{low}	α_{mid}	α_{high}	$\log L_{0.7}$ (W Hz ⁻¹)	$\log L_3$ (W Hz ⁻¹)	$\log L_7$ (W Hz ⁻¹)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
b01	Total	112.1 ± 12.6 [†]	—	23.8 ± 1.2	23.0 ± 1.1	—	—	−0.04 ± 0.09	—	—	27.5
	A	—	—	13.7 ± 0.7	17.9 ± 0.6	—	—	0.35 ± 0.08	—	—	27.3
	B	—	—	10.1 ± 0.5	5.1 ± 0.4	—	—	−0.90 ± 0.12	—	—	27.0
b02	—	—	—	12.3 ± 0.6	9.9 ± 0.4	—	—	−0.29 ± 0.09	—	—	27.4
b03	—	174.2 ± 17.9 [†]	174.1 ± 17.5	42.2 ± 2.1	18.7 ± 0.7	0.00 ± 0.18	−0.96 ± 0.15	−1.07 ± 0.08	28.4	28.0	27.7
b04	—	< 50.3 [†]	12.7 ± 1.8	17.2 ± 0.9	6.4 ± 0.3	> −1.76	0.21 ± 0.20	−1.29 ± 0.09	< 27.2	27.1	26.8
b05	—	81.9 ± 8.4	66.9 ± 6.7	33.9 ± 1.7	20.1 ± 0.7	−0.25 ± 0.18	−0.46 ± 0.15	−0.68 ± 0.08	28.0	27.8	27.6
b06	—	< 20.9 [†]	6.9 ± 1.2	83.1 ± 4.2	59.6 ± 1.8	> −1.43	1.70 ± 0.24	−0.44 ± 0.08	< 27.3	27.7	28.0
b07	—	58.4 ± 7.1 [†]	47.4 ± 4.8	12.3 ± 0.6	7.2 ± 0.3	−0.27 ± 0.20	−0.92 ± 0.15	−0.70 ± 0.09	27.7	27.2	26.9
b08	—	3.5 ± 0.4	5.6 ± 0.6	10.0 ± 0.5	13.2 ± 0.5	0.61 ± 0.19	0.39 ± 0.16	0.36 ± 0.08	26.5	26.8	26.9
b09	—	9.9 ± 1.0	17.1 ± 2.2	42.0 ± 2.1	45.6 ± 1.4	0.68 ± 0.20	0.61 ± 0.18	0.11 ± 0.08	27.2	27.6	27.7
b10	—	56.9 ± 5.9	39.7 ± 4.1	12.8 ± 0.7	7.4 ± 0.3	−0.45 ± 0.18	−0.77 ± 0.15	−0.72 ± 0.09	27.8	27.4	27.1
b11	—	< 21.0 [†]	< 15.1	28.0 ± 1.4	20.0 ± 0.7	—	> 0.42	−0.44 ± 0.08	< 27.4	< 27.4	27.4
b12	—	797.3 ± 79.9 [†]	546.1 ± 54.7	160.1 ± 8.0	86.4 ± 2.7	−0.48 ± 0.18	−0.83 ± 0.15	−0.81 ± 0.08	28.9	28.4	28.1
b13	—	340.2 ± 34.3 [†]	1144.9 ± 114.7	268.5 ± 13.4	164.6 ± 5.0	1.55 ± 0.18	−0.99 ± 0.15	−0.64 ± 0.08	28.8	28.5	28.2
b14	—	< 16.4 [†]	14.3 ± 1.6	22.9 ± 1.2	23.7 ± 0.8	> −0.17	0.32 ± 0.16	0.05 ± 0.08	< 27.6	27.7	27.8
b15	—	< 27.0 [†]	15.2 ± 1.7	49.8 ± 2.5	53.0 ± 1.6	> −0.74	0.81 ± 0.16	0.08 ± 0.08	< 27.7	27.9	28.1
b16	—	< 19.5 [†]	26.5 ± 4.6	30.8 ± 1.5	19.1 ± 0.6	> 0.39	0.10 ± 0.24	−0.63 ± 0.08	< 27.7	27.8	27.7
b17	—	7.2 ± 0.7	18.4 ± 1.9	24.0 ± 1.2	19.3 ± 0.6	1.17 ± 0.18	0.18 ± 0.15	−0.28 ± 0.08	27.0	27.3	27.2
b18	—	< 26.1 [†]	—	11.3 ± 0.6	5.4 ± 0.3	—	—	−0.97 ± 0.11	—	—	27.5
b19	—	56.5 ± 5.7	65.2 ± 6.5	80.2 ± 4.0	86.7 ± 2.6	0.18 ± 0.18	0.14 ± 0.15	0.10 ± 0.08	27.9	28.0	28.0
b20	Total	93.4 ± 9.4	64.0 ± 6.6	18.5 ± 1.0	8.2 ± 0.8	−0.47 ± 0.18	−0.85 ± 0.15	−1.06 ± 0.15	27.7	27.2	26.8
	A	27.0 ± 2.7	27.6 ± 3.0	10.7 ± 0.6	4.2 ± 0.3	0.03 ± 0.18	−0.65 ± 0.16	−1.21 ± 0.10	27.3	26.9	26.6
	B	33.8 ± 3.4	22.4 ± 2.5	4.3 ± 0.3	1.8 ± 0.3	−0.51 ± 0.19	−1.12 ± 0.17	−1.12 ± 0.23	27.2	26.6	26.2
	C	32.6 ± 3.3	14.0 ± 1.7	3.5 ± 0.2	2.1 ± 0.3	−1.05 ± 0.20	−0.95 ± 0.18	−0.66 ± 0.22	27.1	26.5	26.2
b21	—	< 19.2 [†]	6.7 ± 1.4	12.8 ± 0.7	13.8 ± 0.5	> −1.35	0.44 ± 0.28	0.10 ± 0.08	< 26.7	26.8	26.8
b22	—	< 27.9 [†]	33.8 ± 3.6	38.0 ± 1.9	17.9 ± 0.6	> 0.24	0.08 ± 0.15	−0.98 ± 0.08	< 27.5	27.6	27.4
b23	—	< 22.9 [†]	14.2 ± 1.6	50.0 ± 2.5	38.0 ± 1.2	> −0.61	0.86 ± 0.16	−0.36 ± 0.08	< 27.6	27.8	27.9
b24	—	30.0 ± 5.0 [†]	26.7 ± 2.7	14.9 ± 0.8	12.2 ± 0.4	−0.15 ± 0.25	−0.40 ± 0.15	−0.26 ± 0.08	28.0	27.8	27.6
b25	Total	158.4 ± 15.9	99.7 ± 10.0	28.5 ± 1.4	26.5 ± 2.6	−0.58 ± 0.18	−0.85 ± 0.15	−0.10 ± 0.15	27.8	27.3	27.2
	A	101.4 ± 10.2	48.4 ± 4.9	18.1 ± 0.9	20.3 ± 0.7	−0.92 ± 0.18	−0.67 ± 0.15	0.15 ± 0.08	27.5	27.1	27.0
	B	57.0 ± 5.7	51.3 ± 5.2	10.4 ± 0.5	6.2 ± 0.3	−0.13 ± 0.18	−1.09 ± 0.15	−0.68 ± 0.10	27.5	26.9	26.6
b26	—	< 21.4 [†]	5.8 ± 1.1	44.8 ± 2.2	71.5 ± 2.2	> −1.67	1.39 ± 0.26	0.61 ± 0.08	< 27.7	27.8	28.2
b27	—	< 28.3 [†]	10.4 ± 1.3	10.7 ± 0.6	13.2 ± 0.5	> −1.28	0.02 ± 0.18	0.27 ± 0.09	< 27.0	26.9	26.9
b28	—	68.5 ± 6.9	51.7 ± 5.2	17.9 ± 0.9	11.8 ± 0.4	−0.35 ± 0.18	−0.72 ± 0.15	−0.54 ± 0.08	27.9	27.5	27.2
b29	—	35.3 ± 3.5	26.2 ± 2.8	15.0 ± 0.8	14.7 ± 0.6	−0.37 ± 0.18	−0.38 ± 0.15	−0.03 ± 0.08	27.4	27.2	27.1
b30	—	8.0 ± 0.8	21.1 ± 2.3	37.1 ± 1.9	41.6 ± 1.3	1.21 ± 0.19	0.38 ± 0.16	0.15 ± 0.08	27.5	27.9	28.1
b31	—	1674.6 ± 167.7 [†]	1356.7 ± 135.7	1055.9 ± 52.8	1056.6 ± 32.1	−0.27 ± 0.18	−0.17 ± 0.15	0.00 ± 0.08	29.8	29.7	29.6
b32	—	27.9 ± 2.8	28.7 ± 9.5	26.7 ± 1.3	44.4 ± 1.4	0.03 ± 0.43	−0.05 ± 0.44	0.67 ± 0.08	27.8	27.7	27.8
b33	—	8.8 ± 0.9	17.5 ± 2.0	18.7 ± 0.9	13.5 ± 0.5	0.85 ± 0.19	0.05 ± 0.16	−0.43 ± 0.08	27.4	27.7	27.6
b34	—	< 46.5 [†]	19.8 ± 2.2	11.8 ± 0.6	6.2 ± 0.4	> −1.09	−0.35 ± 0.16	−0.84 ± 0.11	< 27.3	26.9	26.7
b35	—	2.0 ± 0.3	4.5 ± 1.3	25.8 ± 1.3	11.2 ± 0.4	0.99 ± 0.40	1.19 ± 0.39	−1.09 ± 0.08	26.7	27.4	27.5
b36	—	43.1 ± 4.5	50.1 ± 5.0	12.6 ± 0.6	4.9 ± 0.4	0.19 ± 0.18	−0.94 ± 0.15	−1.23 ± 0.12	27.5	27.1	26.6
b37	—	59.0 ± 9.8 [†]	36.1 ± 3.7	13.2 ± 0.7	12.0 ± 0.5	−0.63 ± 0.25	−0.68 ± 0.15	−0.12 ± 0.08	27.6	27.2	27.1
b38	—	4.5 ± 0.5	8.4 ± 1.5	13.7 ± 0.7	19.0 ± 0.7	0.77 ± 0.26	0.33 ± 0.24	0.43 ± 0.08	27.2	27.5	27.7
b39	—	28.8 ± 2.9	24.0 ± 2.4	11.2 ± 0.6	8.9 ± 0.4	−0.23 ± 0.18	−0.52 ± 0.15	−0.30 ± 0.09	27.4	27.1	27.0
b40	—	135.6 ± 13.6	185.4 ± 18.5	132.0 ± 6.6	88.5 ± 2.7	0.39 ± 0.18	−0.23 ± 0.15	−0.52 ± 0.08	28.3	28.2	28.1
b41	—	48.7 ± 8.9 [†]	55.8 ± 6.5	25.5 ± 1.3	21.2 ± 0.7	0.17 ± 0.28	−0.53 ± 0.17	−0.24 ± 0.08	27.6	27.4	27.2
b42	—	12.3 ± 1.2	10.0 ± 1.5	14.2 ± 0.7	40.9 ± 1.3	−0.26 ± 0.22	0.24 ± 0.20	1.39 ± 0.08	27.6	27.6	27.8
b43	—	40.9 ± 4.1	44.7 ± 4.5	41.2 ± 2.1	44.9 ± 1.4	0.11 ± 0.18	−0.06 ± 0.15	0.11 ± 0.08	28.0	28.0	28.0
b44	—	13.8 ± 1.4	56.5 ± 5.9	54.2 ± 2.7	42.4 ± 1.3	1.75 ± 0.18	−0.03 ± 0.15	−0.32 ± 0.08	27.5	27.7	27.6
b45	—	36.7 ± 3.7	50.8 ± 5.1	56.4 ± 2.8	34.9 ± 1.1	0.40 ± 0.18	0.07 ± 0.15	−0.63 ± 0.08	28.2	28.4	28.4
b46	—	41.9 ± 4.4	44.6 ± 4.5	25.5 ± 1.3	14.4 ± 0.5	0.08 ± 0.18	−0.38 ± 0.15	−0.74 ± 0.08	28.0	27.9	27.7
b47	—	2.0 ± 0.3	2.4 ± 0.6	11.3 ± 0.6	6.1 ± 0.3	0.21 ± 0.34	1.06 ± 0.31	−0.80 ± 0.09	26.5	27.0	27.0
b48	—	15.0 ± 1.5	25.7 ± 2.6	10.2 ± 0.5	4.7 ± 0.3	0.67 ± 0.18	−0.63 ± 0.15	−1.02 ± 0.11	27.1	26.8	26.5

Note. Columns are as follows: (1) object ID; (2) subcomponent name of the sources; (3)–(6) flux densities at 144 MHz, 322 MHz, 1.4 GHz, and 3.0 GHz, respectively; (7)–(9) spectral indices between neighbouring bands; (10)–(12) log-specific luminosity at rest 700 MHz, 3 GHz, and 7.0 GHz calculated by interpolating the obtained flux densities. References for columns (3), (5), and (6) are Shimwell et al. (2022), Becker et al. (1995), and Gordon et al. (2021), respectively. Data in column (3) indicated by [†] were obtained from the TGSS at 147.5 MHz (Intema et al. 2017).

Table 6. Flux densities, spectral indices, and radio luminosities of the non-BAL quasar sample.

ID	Compo- nent	$f_{0.144}$ (mJy)	$f_{0.322}$ (mJy)	$f_{1.4}$ (mJy)	$f_{3.0}$ (mJy)	α_{low}	α_{mid}	α_{high}	$\log L_{0.7}$ (W Hz ⁻¹)	$\log L_3$ (W Hz ⁻¹)	$\log L_7$ (W Hz ⁻¹)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
n01	–	37.8 ± 3.8	28.9 ± 3.1	12.2 ± 0.6	10.0 ± 1.0	−0.33 ± 0.18	−0.59 ± 0.08	−0.26 ± 0.15	27.4	27.0	26.9
n02	–	95.0 ± 10.6 [†]	89.7 ± 9.1	65.2 ± 3.3	73.3 ± 7.3	−0.07 ± 0.19	−0.22 ± 0.08	0.15 ± 0.15	28.0	27.9	27.9
n03	–	66.2 ± 6.7	59.9 ± 6.0	28.7 ± 1.4	33.3 ± 3.3	−0.12 ± 0.18	−0.50 ± 0.08	0.19 ± 0.15	28.0	27.8	27.7
n04	–	< 24.4 [†]	11.9 ± 1.7	17.1 ± 0.9	13.0 ± 1.3	> −0.92	0.25 ± 0.10	−0.35 ± 0.15	< 26.9	26.9	26.9
n05	–	< 16.1 [†]	15.8 ± 1.8	19.8 ± 1.0	10.2 ± 1.1	> −0.02	0.15 ± 0.09	−0.87 ± 0.15	< 27.0	27.1	26.9
n06	–	< 16.2 [†]	12.7 ± 1.4	31.6 ± 1.6	68.6 ± 6.9	> −0.31	0.62 ± 0.08	1.02 ± 0.15	< 27.5	27.7	28.0
n07	–	6.8 ± 0.8	7.0 ± 0.8	10.3 ± 0.5	6.8 ± 0.7	0.03 ± 0.21	0.26 ± 0.09	−0.56 ± 0.16	26.8	26.9	26.9
n08	–	15.1 ± 1.5	26.3 ± 2.7	21.2 ± 1.1	23.9 ± 2.4	0.69 ± 0.18	−0.15 ± 0.08	0.16 ± 0.15	27.4	27.4	27.4
n09	–	18.5 ± 1.9	20.5 ± 2.2	23.9 ± 1.2	31.8 ± 3.2	0.13 ± 0.18	0.11 ± 0.08	0.37 ± 0.15	27.2	27.3	27.4
n10	–	77.7 ± 9.4 [†]	–	94.5 ± 4.7	65.1 ± 6.5	–	–	−0.49 ± 0.15	–	–	28.0
n11	–	13.4 ± 1.3	16.9 ± 1.7	11.1 ± 0.6	13.2 ± 1.3	0.29 ± 0.18	−0.29 ± 0.08	0.23 ± 0.15	27.3	27.2	27.2
n12	–	< 15.8 [†]	5.3 ± 1.1	10.2 ± 0.5	7.8 ± 0.8	> −1.39	0.44 ± 0.14	−0.34 ± 0.15	< 27.2	27.1	27.1
n13	–	< 17.1 [†]	5.2 ± 0.9	14.0 ± 0.7	23.6 ± 2.4	> −1.53	0.68 ± 0.13	0.68 ± 0.15	< 26.7	26.9	27.1
n14	–	20.6 ± 2.1	16.2 ± 1.7	10.2 ± 0.5	9.0 ± 0.9	−0.30 ± 0.18	−0.31 ± 0.08	−0.17 ± 0.15	27.0	26.8	26.7
n15	–	78.2 ± 9.4 [†]	74.1 ± 8.3	26.7 ± 1.3	17.8 ± 0.3	−0.07 ± 0.21	−0.69 ± 0.08	−0.53 ± 0.07	27.7	27.3	27.1
n16	–	63.3 ± 6.4	45.9 ± 5.1	14.5 ± 0.7	8.5 ± 0.9	−0.40 ± 0.19	−0.79 ± 0.08	−0.69 ± 0.15	28.4	28.0	27.7
n17	–	27.9 ± 5.5 [†]	62.6 ± 6.3	59.3 ± 3.0	37.2 ± 3.7	1.03 ± 0.28	−0.04 ± 0.08	−0.61 ± 0.15	27.8	28.0	27.9
n18	–	13.6 ± 1.5	27.5 ± 2.8	25.8 ± 1.3	22.4 ± 2.3	0.88 ± 0.18	−0.04 ± 0.08	−0.19 ± 0.15	27.6	27.8	27.8
n19	–	18.6 ± 1.9	26.5 ± 4.0	13.4 ± 0.7	8.2 ± 0.9	0.44 ± 0.23	−0.46 ± 0.11	−0.65 ± 0.15	27.1	26.9	26.7
n20	–	60.3 ± 6.1	67.1 ± 6.9	39.9 ± 2.0	25.0 ± 2.5	0.13 ± 0.18	−0.35 ± 0.08	−0.61 ± 0.15	27.7	27.6	27.4
n21	–	6.5 ± 0.8	5.3 ± 0.9	14.6 ± 0.7	7.4 ± 0.8	−0.26 ± 0.26	0.70 ± 0.12	−0.89 ± 0.15	26.9	27.1	27.1
n22	–	218.0 ± 22.9 [†]	147.3 ± 14.8	40.9 ± 2.0	20.5 ± 2.1	−0.50 ± 0.19	−0.87 ± 0.08	−0.91 ± 0.15	28.8	28.3	28.0
n23	–	< 40.1 [†]	10.1 ± 1.2	11.7 ± 0.6	7.2 ± 0.8	> −1.76	0.10 ± 0.09	−0.65 ± 0.16	< 27.8	27.4	27.3
n24	Total	85.6 ± 8.6	89.9 ± 9.2	125.0 ± 6.3	163.9 ± 16.4	0.06 ± 0.18	0.22 ± 0.08	0.36 ± 0.15	28.0	28.2	28.3
	A	44.5 ± 4.5	55.9 ± 5.6	118.4 ± 5.9	161.2 ± 16.1	0.28 ± 0.18	0.51 ± 0.08	0.41 ± 0.15	27.8	28.1	28.2
	B	29.4 ± 2.9	22.4 ± 2.4	4.9 ± 0.3	2.7 ± 0.7	−0.34 ± 0.18	−1.04 ± 0.08	−0.77 ± 0.37	27.5	27.0	26.6
	C	11.7 ± 1.2	11.5 ± 1.9	1.8 ± 0.2	< 0.8	−0.02 ± 0.24	−1.27 ± 0.13	< −1.02	27.2	26.6	< 26.2
n25	–	0.9 ± 0.2	2.4 ± 0.5	12.8 ± 0.7	13.6 ± 1.4	1.17 ± 0.34	1.14 ± 0.14	0.07 ± 0.15	26.2	27.0	27.2
n26	–	114.3 ± 11.5	75.1 ± 8.0	38.4 ± 1.9	23.8 ± 2.4	−0.52 ± 0.18	−0.46 ± 0.08	−0.63 ± 0.15	28.1	27.8	27.6
n27	Total	485.8 ± 49.0	285.2 ± 28.7	77.6 ± 3.9	35.4 ± 3.5	−0.68 ± 0.18	−0.89 ± 0.08	−1.03 ± 0.15	28.9	28.4	28.1
	A	–	72.0 ± 7.7	16.4 ± 0.8	15.5 ± 1.6	–	−1.01 ± 0.08	−0.07 ± 0.15	–	27.8	27.5
	B	–	138.8 ± 14.0	38.5 ± 1.9	10.1 ± 1.1	–	−0.87 ± 0.08	−1.75 ± 0.15	–	28.1	27.7
	C	–	74.3 ± 7.6	22.7 ± 1.1	9.8 ± 1.0	–	−0.81 ± 0.08	−1.11 ± 0.15	–	27.9	27.5
n28	–	5.6 ± 0.6	5.7 ± 0.8	8.2 ± 0.4	18.5 ± 1.9	0.02 ± 0.22	0.24 ± 0.10	1.07 ± 0.15	26.6	26.8	27.0
n29	–	52.4 ± 8.7 [†]	66.6 ± 6.7	55.8 ± 2.8	67.6 ± 6.8	0.31 ± 0.25	−0.12 ± 0.08	0.25 ± 0.15	27.6	27.6	27.7
n30	–	4122.7 ± 412.4	2750.9 ± 275.5	1165.4 ± 58.3	691.8 ± 69.2	−0.50 ± 0.18	−0.58 ± 0.08	−0.68 ± 0.15	30.1	29.7	29.5
n31	–	281.5 ± 28.2	447.6 ± 44.8	261.7 ± 13.1	143.4 ± 14.4	0.58 ± 0.18	−0.37 ± 0.08	−0.79 ± 0.15	28.5	28.4	28.2
n32	–	< 39.7 [†]	< 4.0	16.5 ± 0.8	92.6 ± 9.3	–	> 0.97	2.26 ± 0.15	< 27.6	< 27.0	27.7
n33	–	315.5 ± 32.4 [†]	357.5 ± 35.8	181.2 ± 9.1	151.9 ± 15.4	0.16 ± 0.18	−0.46 ± 0.08	−0.23 ± 0.15	28.6	28.4	28.3
n34	–	4.0 ± 0.4	10.5 ± 1.1	33.2 ± 1.7	35.9 ± 3.6	1.21 ± 0.18	0.79 ± 0.08	0.10 ± 0.15	27.2	27.8	28.0
n35	–	12.3 ± 1.2	10.7 ± 1.5	13.2 ± 0.7	9.2 ± 0.9	−0.17 ± 0.21	0.14 ± 0.10	−0.48 ± 0.15	27.4	27.4	27.4
n36	–	37.2 ± 3.8	25.1 ± 2.6	21.7 ± 1.1	38.3 ± 3.9	−0.49 ± 0.18	−0.10 ± 0.08	0.75 ± 0.15	27.9	27.8	27.8
n37	–	45.9 ± 4.6	48.9 ± 5.0	47.5 ± 2.4	45.7 ± 4.6	0.08 ± 0.18	−0.02 ± 0.08	−0.05 ± 0.15	27.8	27.8	27.8
n38	–	42.6 ± 4.3	38.8 ± 3.9	47.7 ± 2.4	50.2 ± 5.0	−0.12 ± 0.18	0.14 ± 0.08	0.07 ± 0.15	28.2	28.2	28.2
n39	–	10.8 ± 1.1	13.5 ± 1.7	12.7 ± 0.6	14.2 ± 1.4	0.28 ± 0.20	−0.05 ± 0.09	0.15 ± 0.15	27.1	27.1	27.2
n40	–	2.8 ± 0.3	3.2 ± 0.6	11.0 ± 0.6	9.5 ± 1.0	0.15 ± 0.28	0.84 ± 0.13	−0.20 ± 0.15	26.3	26.8	26.8
n41	–	10.0 ± 1.0	14.3 ± 1.4	16.7 ± 0.8	7.5 ± 0.8	0.44 ± 0.18	0.11 ± 0.08	−1.05 ± 0.15	27.0	27.1	26.8
n42	–	136.0 ± 13.6	80.2 ± 8.1	22.7 ± 1.1	16.1 ± 1.6	−0.66 ± 0.18	−0.86 ± 0.08	−0.45 ± 0.15	28.2	27.7	27.5
n43	–	113.5 ± 11.4	70.2 ± 7.1	18.9 ± 1.0	11.9 ± 1.2	−0.60 ± 0.18	−0.89 ± 0.08	−0.61 ± 0.15	28.5	28.0	27.7
n44	–	196.3 ± 19.8	113.7 ± 11.6	50.0 ± 2.5	74.2 ± 7.5	−0.68 ± 0.18	−0.56 ± 0.08	0.52 ± 0.15	28.7	28.3	28.2
n45	–	2.8 ± 0.4	7.2 ± 1.2	43.9 ± 2.2	50.6 ± 5.1	1.18 ± 0.28	1.23 ± 0.12	0.19 ± 0.15	26.8	27.6	27.8
n46	–	30.3 ± 3.1	31.6 ± 3.4	9.5 ± 0.5	7.9 ± 0.8	0.06 ± 0.18	−0.82 ± 0.08	−0.23 ± 0.15	27.5	27.1	26.9
n47	–	< 25.8 [†]	7.5 ± 1.0	15.2 ± 0.8	13.3 ± 1.4	> −1.59	0.48 ± 0.09	−0.17 ± 0.15	< 27.9	27.6	27.7
n48	–	15.6 ± 1.6	11.8 ± 1.3	36.6 ± 1.8	61.4 ± 6.2	−0.34 ± 0.19	0.77 ± 0.08	0.68 ± 0.15	27.4	27.6	27.9

Note. Columns are as follows: (1) object ID; (2) subcomponent name of the sources; (3)–(6) flux densities at 144 MHz, 322 MHz, 1.4 GHz, and 3.0 GHz, respectively; (7)–(9) spectral indices between neighbouring bands; (10)–(12) Log specific luminosity at rest 700 MHz, 3 GHz, and 7.0 GHz calculated by interpolating the obtained flux densities. References for columns (3), (5), and (6) are Shimwell et al. (2022), Becker et al. (1995), and Gordon et al. (2021), respectively. Data in column (3) indicated by [†] were obtained from the TGSS at 147.5 MHz (Intema et al. 2017).

where f_p and ν_p are the peak flux density and peak frequency, while b and c represent purely numerical values without conveying direct physical information (Dallacasa et al. 2000; Tinti et al. 2005). For objects with spectra lacking significant curvature, we employed a simple power-law model, whereas a double power-law model was used for objects with convex downward spectra. Figs 5 and 6 also show fitting results. If the estimated peak frequency was below the

observed frequency range, the upper limit of ν_p was set by the minimum observed frequency.

Based on the fitting results, we classified the radio spectra of the objects into steep/peaked or flat/inverted spectra. Following Dallacasa et al. (2000), for sources fitted with a power law or hyperbolic function, we identified spectra with a spectral index, α , smaller than -0.5 in the optically thin region above the peak

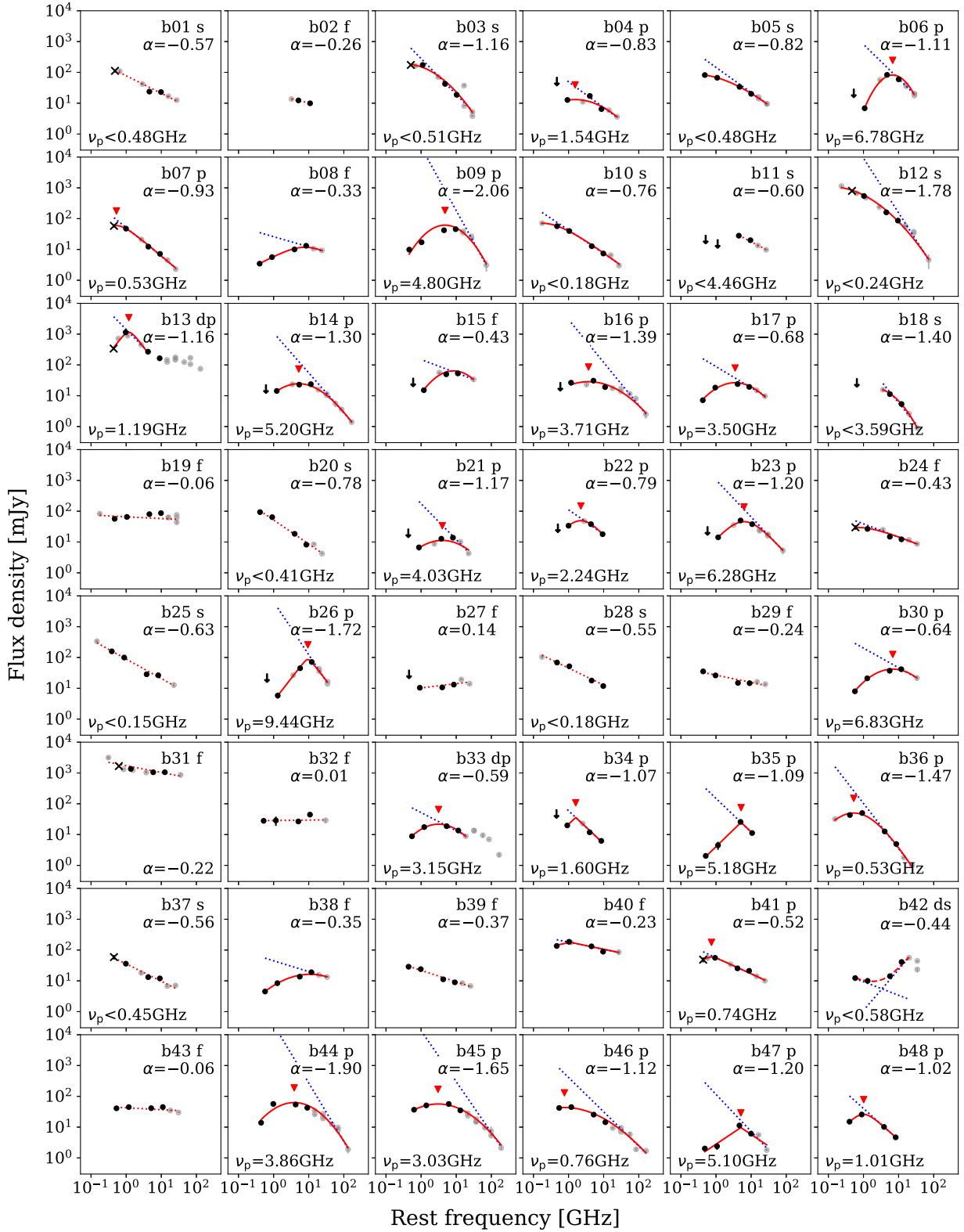


Figure 5. Radio spectra of the BAL quasar sample. Although error bars are illustrated for each measurement result, in most cases, they are substantially smaller than the data points and concealed by the markers. Black circles represent data obtained by LoTSS (Shimwell et al. 2022), the FIRST survey (Becker et al. 1995), VLASS (Lyke et al. 2020), and our GMRT observations, employed in the computation of spectral indices. Crosses and down arrows, respectively, indicate the flux measurement and its upper limit obtained from the TGSS (Intema et al. 2017). Grey circles show additional data only utilized for estimating overall spectral shapes (see Section 3.2 for details). The results of fitting with a hyperbola, power law, and double power law are illustrated as red solid, dotted, and dashed lines, respectively. The blue dotted lines represent the power-law fitting for the data within the optically thin regime. The spectral indices, α , given at each panel were obtained from the fit. The spectral classification is denoted to the right of the object name in each panel (see Section 4.2 for more details). As for sources with a steep/peaked spectrum, the estimated peak frequency, ν_p , is denoted by a red triangle, and its value is provided in each panel.

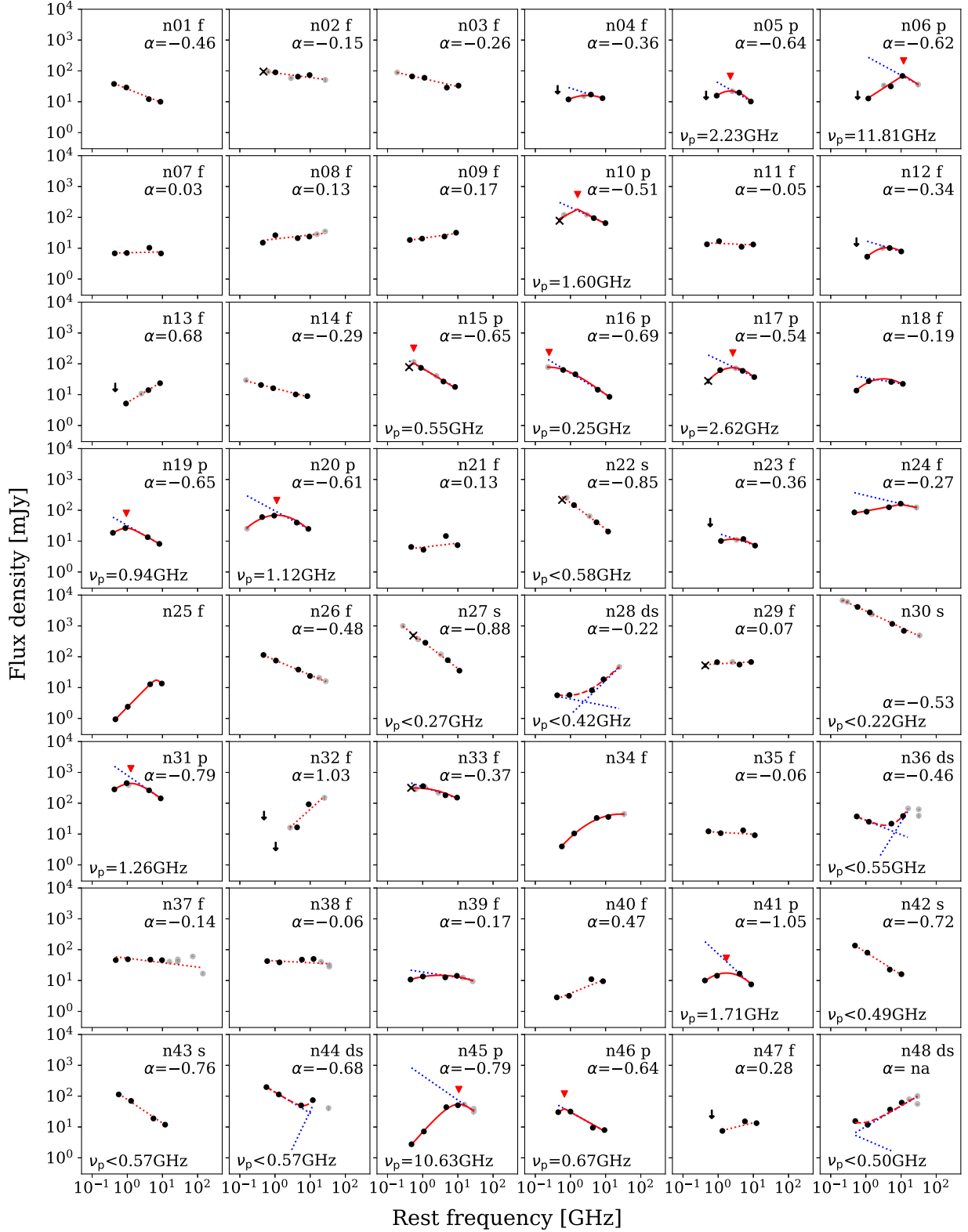


Figure 6. Radio spectra of the non-BAL quasar sample. Same as Fig. 5. In the case of n48, because the fitting with the double power law did not converge, $\alpha = -0.8$ was set as the spectral index for its low-frequency component.

frequency as steep or peaked spectra (denoted as ‘s’ or ‘p’ in Figs 5 and 6, respectively). In contrast, spectra with $\alpha > -0.5$ were classified as flat/inverted spectra (denoted as ‘f’ in Figs 5 and 6). If the number of data points in the optically thin regime was insufficient

to confirm $\alpha < -0.5$, we classified them as flat/inverted spectra. Our classification was based on the low-frequency component for sources with two components in their spectra. This focus aligns with the main objective of this study, aiming to scrutinize low-frequency

Table 7. Spectral classification of the BAL and non-BAL quasar samples.

ID	Method	α	Spectral type	S_p (mJy)	ν_p (GHz)	L_{bol} (W)	ID	Method	α	Spectral type	S_p (mJy)	ν_p (GHz)	L_{bol} (W)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
b01	P	−0.57	s	> 112	< 0.48	< 36.3	n01	P	−0.46	f	—	—	—
b02	P	−0.26	f	—	—	—	n02	P	−0.15	f	—	—	—
b03	H	−1.16	s	> 174	< 0.51	< 36.6	n03	P	−0.26	f	—	—	—
b04	H	−0.83	p	13	1.54	35.7	n04	H	−0.36	f	—	—	—
b05	H	−0.82	s	> 82	< 0.48	< 36.2	n05	H	−0.64	p	22	2.23	36.1
b06	H	−1.11	p	82	6.78	37.4	n06	H	−0.62	p	70	11.81	37.7
b07	H	−0.93	p	59	0.53	36.0	n07	P	0.03	f	—	—	—
b08	H	−0.33	f	—	—	—	n08	P	0.13	f	—	—	—
b09	H	−2.06	p	62	4.80	37.0	n09	P	0.17	f	—	—	—
b10	H	−0.76	s	> 57	< 0.18	< 35.6	n10	H	−0.51	p	183	1.60	37.1
b11	P	−0.60	p	> 28	< 4.46	< 36.6	n11	P	−0.05	f	—	—	—
b12	H	−1.78	s	> 797	< 0.24	< 36.8	n12	H	−0.34	f	—	—	—
b13	H	−1.16	dp	1139	1.19	37.6	n13	P	0.68	f	—	—	—
b14	H	−1.30	p	25	5.20	36.9	n14	P	−0.29	f	—	—	—
b15	H	−0.43	f	—	—	—	n15	H	−0.65	p	107	0.55	36.1
b16	H	−1.39	p	29	3.71	36.8	n16	H	−0.69	p	78	0.25	36.3
b17	H	−0.68	p	27	3.50	36.4	n17	H	−0.54	p	75	2.62	37.0
b18	H	−1.40	s	> 11	< 3.59	< 36.5	n18	H	−0.19	f	—	—	—
b19	P	−0.06	f	—	—	—	n19	H	−0.65	p	27	0.94	35.7
b20	P	−0.78	s	> 93	< 0.41	< 35.9	n20	H	−0.61	p	69	1.12	36.3
b21	H	−1.17	p	11	4.03	35.9	n21	P	0.13	f	—	—	—
b22	H	−0.79	p	49	2.24	36.6	n22	P	−0.85	s	> 218	< 0.58	< 37.0
b23	H	−1.20	p	46	6.28	37.2	n23	H	−0.36	f	—	—	—
b24	H	−0.43	f	—	—	—	n24	H	−0.27	f	—	—	—
b25	P	−0.63	s	> 158	< 0.15	< 35.7	n25	H	—	f	—	—	—
b26	H	−1.72	p	86	9.44	37.8	n26	P	−0.48	f	—	—	—
b27	P	0.14	f	—	—	—	n27	P	−0.88	s	> 486	< 0.27	< 36.9
b28	P	−0.55	s	> 68	< 0.18	< 35.7	n28	DP	−0.22	ds	> 6	< 0.42	< 34.8
b29	P	−0.24	f	—	—	—	n29	P	0.07	f	—	—	—
b30	H	−0.64	p	42	6.83	37.3	n30	P	−0.53	s	> 4123	< 0.22	< 37.8
b31	P	−0.22	f	—	—	—	n31	H	−0.79	p	439	1.26	37.2
b32	P	0.01	f	—	—	—	n32	P	1.03	f	—	—	—
b33	H	−0.59	dp	22	3.15	36.7	n33	H	−0.37	f	—	—	—
b34	H	−1.07	p	36	1.60	36.1	n34	H	—	f	—	—	—
b35	H	−1.09	p	25	5.18	36.8	n35	P	−0.06	f	—	—	—
b36	H	−1.47	p	50	0.53	35.8	n36	DP	−0.46	ds	> 37	< 0.55	< 36.1
b37	P	−0.56	s	> 59	< 0.45	< 35.9	n37	P	−0.14	f	—	—	—
b38	H	−0.35	f	—	—	—	n38	P	−0.06	f	—	—	—
b39	P	−0.37	f	—	—	—	n39	H	−0.17	f	—	—	—
b40	H	−0.23	f	—	—	—	n40	P	0.47	f	—	—	—
b41	H	−0.52	p	59	0.74	36.1	n41	H	−1.05	p	17	1.71	35.9
b42	DP	−0.44	ds	> 12	< 0.58	< 35.8	n42	P	−0.72	s	> 136	< 0.49	< 36.5
b43	P	−0.19	f	—	—	—	n43	P	−0.76	s	> 113	< 0.57	< 36.7
b44	H	−1.90	p	63	3.86	36.9	n44	DP	−0.68	ds	> 196	< 0.57	< 36.9
b45	H	−1.65	p	56	3.03	37.2	n45	H	−0.79	p	55	10.63	37.4
b46	H	−1.12	p	43	0.76	36.3	n46	H	−0.64	p	39	0.67	35.9
b47	H	−1.20	p	10	5.10	36.3	n47	P	0.28	f	—	—	—
b48	H	−1.02	p	26	1.01	35.7	n48	DP	—	ds	> 16	< 0.50	< 35.6

Note. Columns are as follows: (1) and (8) object ID; (2) and (9) function used for fitting to the radio spectrum, where P, DP, and H represent power law, double power law, and hyperbola, respectively; (3) and (10) estimated spectral index of the optically thin regime employed for classifying the spectral type; (4) and (11) result of the spectral classification; (5)–(7) and (12)–(14) estimated peak flux density S_p , peak frequency ν_p , and bolometric radio luminosity L_{bol} , of steep or peaked spectral sources.

features that are less susceptible to relativistic effects and have not been explored in preceding studies conducted in the GHz regime. These sources with two spectral components were categorized as sources with steep/peaked spectra (denoted as ‘ds’ or ‘dp’ in Figs 5 and 6, respectively), regardless of the value of the spectral index. Table 7 presents the results of the spectral classification and estimated physical values. Note that because the distinction between a steep and peaked spectrum is based on whether the peak frequency lies

within the observed frequency range, the dissimilarity between these two classifications is a matter of degree.

4.3 Comparison of the spectral class composition between the BAL and non-BAL quasar samples

Table 8 presents the number of sources with steep/peaked spectra and sources with flat/inverted spectra in the BAL and non-BAL quasar

Table 8. Results of spectral classification.

	Steep/peaked	Flat/inverted	Total
BAL quasar sample	35 (31)	13 (12)	48 (43)
Non-BAL quasar sample	21 (7)	27 (9)	48 (16)
Both samples	56 (38)	40 (21)	96 (59)

Note. The numbers within brackets denote the count of sources for which flux measurements at 8.4 GHz are available.

samples. The proportion of steep/peaked spectra is higher in the BAL quasar sample compared with the non-BAL quasar sample; the former contains 73 ± 13 per cent of sources with steep/peaked spectra, whereas the latter contains 44 ± 14 per cent, where errors are given by the 95 per cent confidence level. We conducted a chi-square test to examine the disparities in radio spectra between the BAL and non-BAL quasar samples, resulting in a p -value of 0.0038, which represents the likelihood of obtaining a result equal to or more extreme than the observed result, assuming the null hypothesis that the two samples are derived from the same parent population. The distinction between the two groups is considered significant at the 5 per cent significance level. Nevertheless, the obtained p -value still corresponds to $\sim 2.9\sigma$. This trend remains even after excluding objects with spatially resolved source structures (b01, b20, b25, n24, and n27), candidates showing flux variations (b04 and n24), and objects with no absorption lines in C IV but absorption lines in Al III (b02, n24), yielding the p -value of 0.0064. Therefore, we have obtained marginal evidence indicating that BAL quasars harbour more sources with steep/peaked spectra than non-BAL quasars.

Our samples include 43 BAL quasars and 16 non-BAL quasars with data above 8.4 GHz. During the spectral classification, the key criterion for identifying steep/peaked spectra is to detect high-frequency spectra with $\alpha < -0.5$. Objects with intrinsically optically thin spectra at high frequencies but no data available at those frequencies can be classified as sources with flat/inverted spectra. Hence, the fewer sources with high-frequency data in the non-BAL quasar sample could introduce a bias towards a reduced count of sources with steep/peaked spectra compared with the BAL quasar sample. In order to evaluate this effect, Table 8 also shows statistics confined to sources with flux density measurements at 8.4 GHz. As a result, 31 out of 43 BAL quasars with 8.4-GHz flux measurements were classified as sources with steep/peaked spectra (72 ± 13 per cent). Of 16 non-BAL quasars with flux measurements at 8.4 GHz, eight were classified as a sources with steep/peaked spectra (44 ± 24 per cent). The statistics for both sources with and without flux measurements at 8.4 GHz do not differ significantly. Therefore, the absence of high-frequency data does not affect our result.

4.4 Comparison of the spectral properties between the BAL and non-BAL quasar samples

In the previous subsection, we described the difference in the compositional ratios of spectral types within the BAL and non-BAL quasar samples. To investigate the origins of this difference, we analysed the spectral characteristics of both samples for each spectral type. This study focused on the peak frequencies, spectral indices, and radio luminosities at the rest frame. In order to address the challenge posed by sources with only upper or lower limits on these physical values and to compare them between the BAL and non-BAL quasar samples, we employed the Kaplan–Meier estimator, which is a non-parametric, maximum likelihood statistical estimator that estimates the cumulative distribution of the parent population

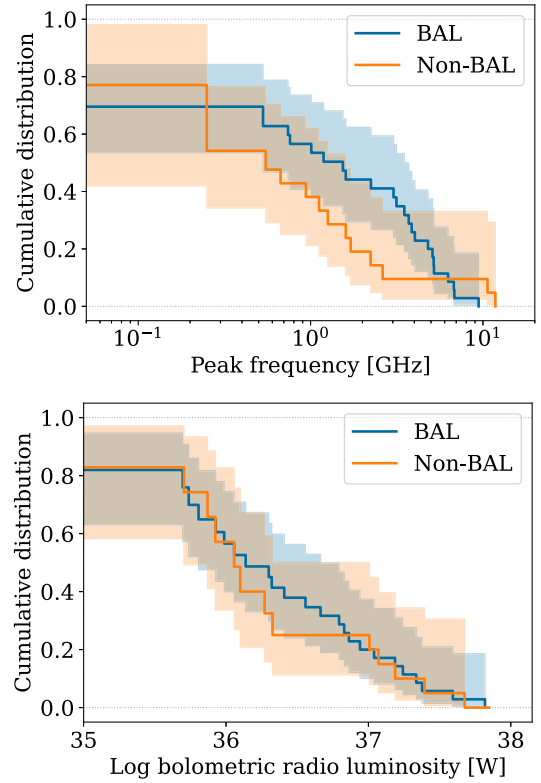


Figure 7. Cumulative distributions of peak frequency and bolometric luminosity of sources with steep/peaked spectra for the BAL (blue) and non-BAL (orange) quasar samples using the Kaplan–Meier estimator with a 95 per cent confidence interval. Top panel, peak frequency, ν_p ; bottom panel, bolometric luminosity, L_{bol} . A log-rank test yields a p -value of 0.28 and 0.87 for ν_p and L_{bol} , respectively. These p -values indicate the probability of obtaining a result equal to or more extreme than the observed result, assuming the null hypothesis that the two samples are drawn from the same parent population.

(Kaplan & Meier 1958). We applied the KaplanMeierFitter module from the Python package, *lifelines*.

4.4.1 Sources with steep/peaked spectra

We examined whether there were any distinctions in the spectral features between the BAL and non-BAL quasar samples for sources with steep/peaked spectra. Fig. 7 represents comparisons of the peak frequencies, ν_p , and bolometric radio luminosities, L_{bol} , derived from the model fitting to the spectra. We approximated $L_{\text{bol}} \simeq 4\pi D_L^2 f_p \nu_p$ for the bolometric radio luminosity (e.g. Feng et al. 2006), where D_L is luminosity distance. For all steep spectral sources where only an upper limit of ν_p was constrained, the spectrum around the lowest observed frequency was observed as flatter than the spectral index of -1 (see Tables 5 and 6). Assuming this trend continues even at lower frequencies, we can impose an upper limit on L_{bol} . In Fig. 7, we find that the BAL quasar sample indicates a higher median peak frequency than the non-BAL quasar sample, but a log-rank test on the distributions of the BAL and non-BAL quasar samples for ν_p and L_{bol} generates p -values of 0.28 and 0.87, respectively. These p -values indicate the probability of achieving a result equal to or more extreme than observed, assuming a null hypothesis that the two distributions originate from the same parent populations. The statistical tests show no evidence of a distinction between the two groups at the 5 per cent significance level. Even after excluding

objects with spatially resolved source structures (b01, b20, b25, and n27) and candidates showing flux variations (b04), these trends do not change, yielding p -values of 0.17 and 0.38 for the distributions of ν_p and L_{bol} , respectively.

We also compared spectral indices and luminosities derived from observed flux densities between the two samples. Fig. 8 displays the cumulative distributions for spectral indices at low, mid, and high frequencies (labelled α_{low} , α_{mid} , and α_{high} , respectively) that were obtained over the frequency ranges of 144–322 MHz, 322 MHz to 1.4 GHz, and 1.4–3.0 GHz, respectively. These values are independent of the model applied to the flux measurement data. Our analysis indicates that the BAL quasar sample exhibits a higher proportion of objects with optically thick spectral indices at low frequencies than the non-BAL quasar sample, which aligns with the observation of a higher median peak frequency, ν_p , in the BAL quasar sample (Fig. 7). Nevertheless, as in ν_p , a log-rank test on the distributions of the BAL and non-BAL quasar samples for α_{low} , α_{mid} , and α_{high} results in p -values of 0.066, 0.23, and 0.33, respectively, providing limited evidence for the distinction between the two groups at the 5 per cent significance level. Even after excluding objects suffering from significant RFI in the 322-MHz data, spatially resolved sources, and candidates showing flux variations (b01, b04, b18, b20, b25, n10, and n27; Table 4), these trends remain, yielding p -values of 0.052, 0.23, and 0.32 for the distributions of α_{low} , α_{mid} , and α_{high} , respectively.

We can now compute the specific luminosity at low frequency without making assumptions based on the acquired spectral index with the newly obtained 322-MHz data. We selected our targets based on the redshift criterion of $1.68 \leq z \leq 4.73$, and the observed redshift range in this study spans $1.69 \leq z \leq 3.38$, resulting in observed rest frequencies of 387–631 MHz, 866–1410 MHz, 3.7–6.2 GHz, and 8.0–13.2 GHz for observations at 144 MHz, 322 MHz, 1.4 GHz, and 3.0 GHz, respectively. Therefore, by using the spectral indices obtained from the data, we calculated the rest-frame specific radio luminosities at 700 MHz, 3.0 GHz, and 7.0 GHz through interpolation (labelled $L_{0.7}$, L_3 , and L_7 , respectively). Tables 5 and 6 present the computed values of $L_{0.7}$, L_3 , and L_7 , while their cumulative distributions obtained for both the BAL and non-BAL quasar samples are depicted in Fig. 8. Our analysis has not revealed any apparent differences between the plots of the two groups. In order to further evaluate this, we conducted a log-rank test on the distributions of the two samples for $L_{0.7}$, L_3 , and L_7 , which produces p -values of 0.19, 0.65, and 0.22, respectively, indicating a lack of evidence for a difference between the two samples. These results persist even when considering only the compact, non-variable objects without RFI in the 322-MHz data, yielding p -values of 0.27, 0.89, and 0.51 for $L_{0.7}$, L_3 , and L_7 , respectively.

4.4.2 Sources with flat/inverted spectra

We also investigated the difference in spectral properties between the BAL and non-BAL quasar samples for sources with flat/inverted spectra. Fig. 9 displays the estimated cumulative distribution of the parent population for spectral indices and specific radio luminosities, respectively, employing the Kaplan–Meier estimator.

We conducted a log-rank test on the distributions of the BAL and non-BAL samples for α_{low} , α_{mid} , and α_{high} , resulting in p -values of 0.62, 0.22, and 0.73, respectively. We do not recognize a significant difference in spectral indices at the 5 per cent significance level. Even after excluding objects with no absorption lines in C IV but absorption lines in Al III (b02 and n24), these trends remain,

yielding p -values of 0.59, 0.23, and 0.55 for the distributions of α_{low} , α_{mid} , and α_{high} , respectively. Additionally, a log-rank test on the distributions for $L_{0.7}$, L_3 , and L_7 results in p -values of 0.27, 0.46, and 0.29, respectively, indicating a lack of evidence for a difference between the two samples. These results remain unchanged even when excluding the objects with no absorption lines in C IV but absorption lines in Al III, yielding p -values of 0.22, 0.40, and 0.15 for $L_{0.7}$, L_3 , and L_7 , respectively. Consequently, our analyses show no significant differences in the spectral indices and luminosities of sources with flat/inverted spectra between the two groups.

5 DISCUSSION

Our investigation, involving data down to the 150-MHz band, corresponding to 387–631 MHz in the rest frame, has revealed a higher prevalence of a steep/peaked spectrum in BAL quasars than their non-BAL counterparts within flux-limited samples. Because all objects in our samples, except those shown in Figs 1 and 4, are point sources at the resolution of the FIRST survey (~ 5 arcsec), most of the sources with steep/peaked spectra identified in this study can be categorized into GPS/CSS sources (O’Dea 1998), which are candidates for lobe-dominated young radio sources observed from a large viewing angle with respect to the jet axis. However, point sources displaying a flat/inverted spectrum are interpreted as core-dominated radio sources observed from a pole-on perspective (Browne et al. 1982; Orr & Browne 1982). Because no significant differences between the two groups have been observed in the spectral index or luminosity of radio sources with each spectral class, even at low frequencies, we do not expect any difference in their intrinsic jet activity between the two samples. These outcomes favour the orientation scheme for BAL quasars (e.g. Rankine et al. 2020), which is suggested by a steeper spectral index between 4.9 and 8.4 GHz for BAL quasars than for non-BAL quasars (DiPompeo et al. 2011, 2012).

Note that our BAL and non-BAL quasar samples are constructed to have similar luminosity distributions based on flux density at 1.4 GHz (Fig. 2). In contrast, whole non-BAL quasars are known to be brighter than our current samples (e.g. Shankar et al. 2008). These bright quasars in the radio may experience more intense relativistic beaming effects in their jets (see Orr & Browne 1982). It would be crucial to investigate the fraction of flat/inverted spectra in those bright non-BAL quasars to test the orientation scheme further.

While we have found a difference in the composition of the spectral classes between the two samples, the BAL and non-BAL quasar samples also include a considerable number of sources with flat/inverted spectra and sources with steep/peaked spectra, respectively. Therefore, a simple orientation scheme may not comprehensively account for the distinction between BAL and non-BAL quasars (see Matthews, Knigge & Long 2017; Yong et al. 2018). Similar issues have been raised regarding radio morphology (Cegłowski et al. 2015; Kunert-Bajraszewska et al. 2015; Nair & Vivek 2022) and radio flux variations (Zhou et al. 2006; Ghosh & Punsly 2007; DiPompeo et al. 2011; Cegłowski et al. 2017), pointing towards the possibility of polar BAL quasars (Punsly & Lipari 2005; Brotherton, De Breuck & Schaefer 2006; Wang et al. 2008; Berrington et al. 2013; Reynolds, Punsly & O’Dea 2013).

As a complement to the orientation scheme, an intermittent BAL phase associated with periods of restarting jet activity was proposed to explain multiple spectral components at low frequencies (Bruni et al. 2015). However, we have found that the number of sources with multiple spectral components is comparable between the two samples; three and four sources are identified as having a spectral

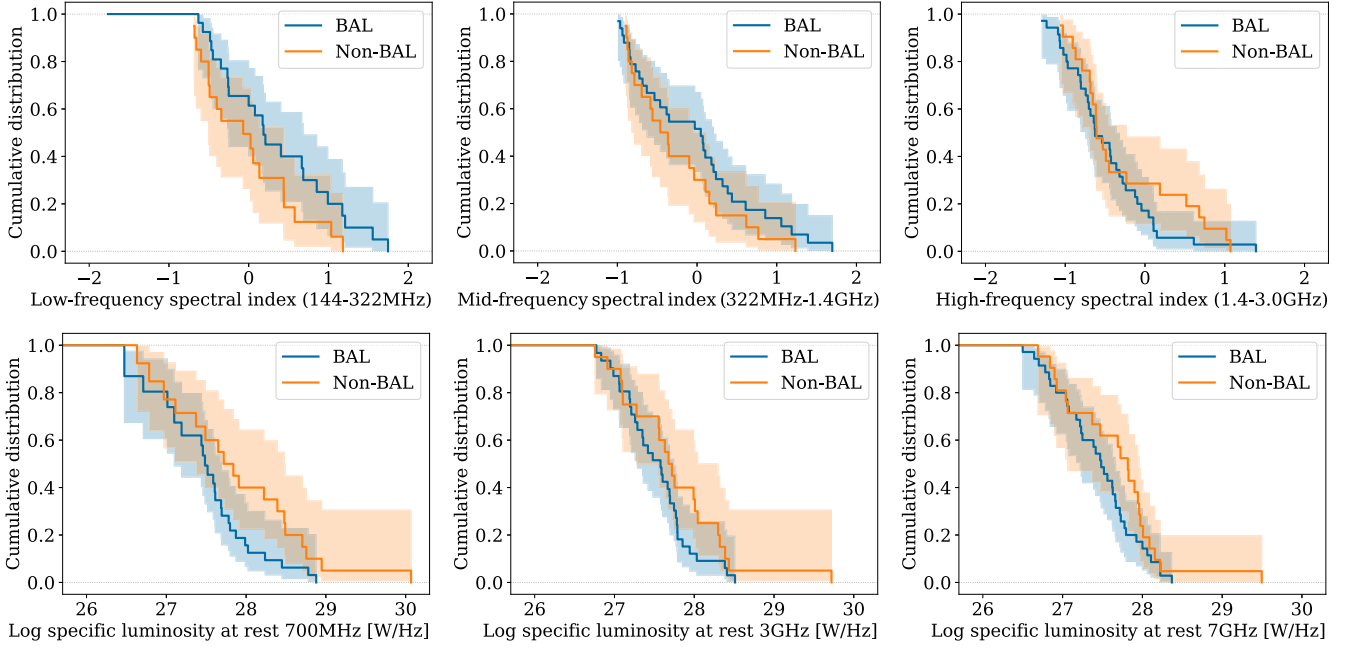


Figure 8. Cumulative distributions of spectral indices and specific luminosities for sources with steep/peaked spectra in the BAL (blue) and non-BAL (orange) quasar samples using the Kaplan–Meier estimator with a 95 per cent confidence interval. The top panel shows the distributions of low-frequency spectral index, α_{low} , between 144 and 322 MHz, mid-frequency spectral index, α_{mid} , between 322 MHz and 1.4 GHz, and high-frequency spectral index, α_{high} , between 1.4 and 3.0 GHz (displayed from left to right). A log-rank test produces a p -value of 0.066, 0.23, and 0.33 for α_{low} , α_{mid} , and α_{high} , respectively. The bottom panel shows the distributions of rest-frame luminosity at 700 MHz, $L_{0.7}$, interpolated by α_{low} , rest-frame specific luminosity at 3.0 GHz, L_3 , interpolated by α_{mid} , and rest-frame specific luminosity at 7.0 GHz, L_7 , interpolated by α_{high} (displayed from left to right). A log-rank test produces a p -value of 0.19, 0.65, and 0.22 for $L_{0.7}$, L_3 , and L_7 , respectively.

classification of ‘dp’ or ‘ds’ in our BAL and non-BAL samples, respectively. Therefore, it is challenging to infer factors beyond the orientation scheme from the results of low-frequency observations in this study.

Previous VLBI observations have revealed that a subset of GPS/CSS sources associated with radio-loud BAL quasars demonstrates characteristics of lobe-dominated young radio sources in terms of little flux variability, a two-sided structure on a VLBI scale, and unpolarized radio emission in the core region (e.g. Bruni et al. 2013; Doi et al. 2013; Hayashi et al. 2013). Nevertheless, flat spectral radio quasars can exhibit a peaked spectrum during a flare (Tornikoski et al. 2001; Tornaiainen et al. 2005, 2007), and GPS sources may involve core-jet objects resembling blazars (Stanghellini et al. 1997, 2001). Therefore, VLBI observations are crucial to ascertain whether the identified sources with steep/peaked spectra genuinely represent lobe-dominated compact radio sources. We are currently conducting a VLBI programme on the samples in this study, the results of which will be presented in a forthcoming paper.

6 CONCLUSIONS

We have performed new GMRT observations on 48 radio-loud BAL quasars, chosen from Gibson et al. (2009), and a corresponding number of radio-loud non-BAL quasars. Using these observational data in conjunction with previous flux measurements, we have studied low-frequency spectra of the two samples. Our key findings are as follows.

(i) In our BAL quasar sample, 73 ± 13 per cent of objects exhibit a steep/peaked spectrum, in contrast to 44 ± 14 per cent for the non-

BAL quasar sample, with errors reported at the 95 per cent confidence level. While the statistical evidence is limited to a $\sim 2.9\sigma$ level, the BAL quasar sample reveals a higher incidence of steep/peaked spectra than the comparison sample.

(ii) No significant difference between the two quasar groups is found in peak frequencies (ν_p) and bolometric radio luminosities (ν_{bol}) of the sources with steep/peaked spectra. Additionally, no significant distinctions between the two samples are observed in spectral indices (α_{low} , α_{mid} , and α_{high}) and specific radio luminosities ($L_{0.7}$, L_3 , and L_7) of sources with steep/peaked spectra and sources with flat/inverted spectra.

The orientation scenario of BAL quasars can account for these spectral features, attributing the higher prevalence of steep/peaked spectra in the BAL quasar sample to a relatively edge-on perspective. Nevertheless, more than the orientation scheme is also needed to explain all the observational results, including the presence of flat/inverted spectra in the BAL quasar sample. Additionally, our analyses do not rule out the possibility that peaked spectral sources in both samples are contaminated by blazars in a flaring state. In this regard, acquiring more densely packed data along the time direction and implementing high-resolution observations with VLBI would provide substantial advantages.

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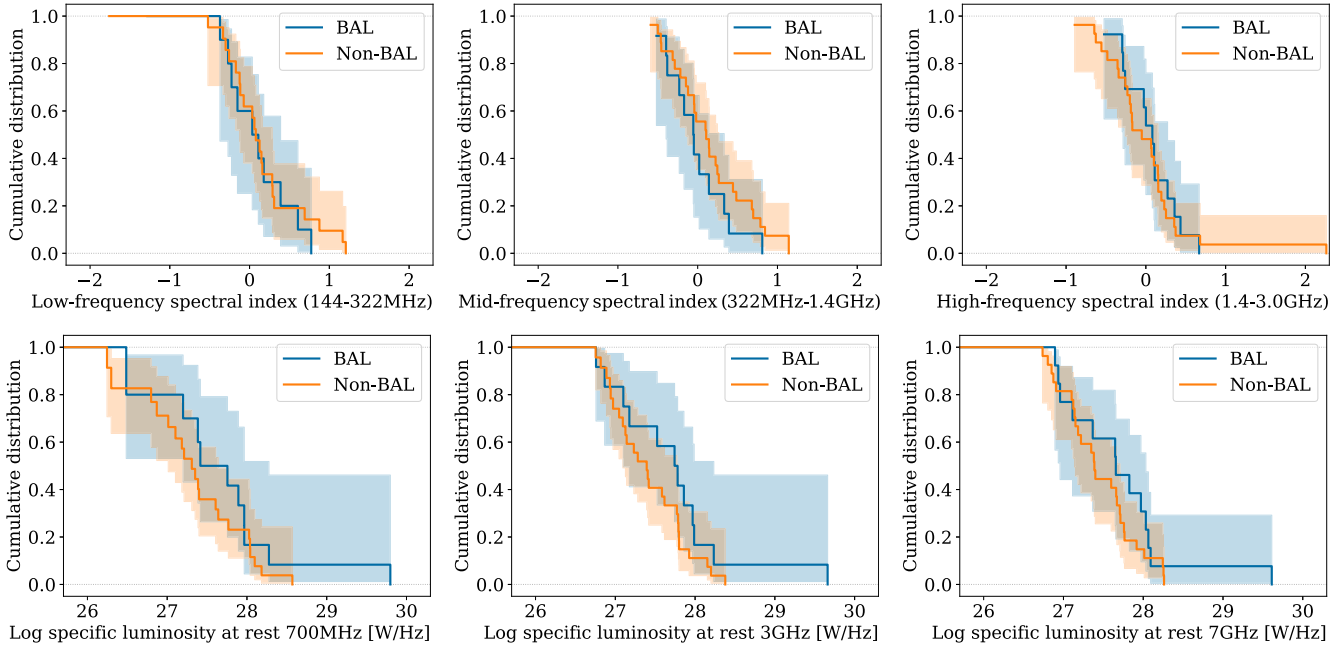


Figure 9. Cumulative distributions of spectral indices and specific luminosities for sources with flat/inverted spectra in the BAL (blue) and non-BAL (orange) samples using the Kaplan-Meier estimator with a 95 per cent confidence interval. The top panel shows the distributions of low-frequency spectral index, α_{low} , between 144 and 322 MHz, mid-frequency spectral index, α_{mid} , between 322 MHz and 1.4 GHz, and high-frequency spectral index, α_{high} , between 1.4 and 3.0 GHz (displayed from left to right). A log-rank test produces a p -value of 0.62, 0.22, and 0.73 for α_{low} , α_{mid} , and α_{high} , respectively. The bottom panel shows the distributions of rest-frame luminosity at 700 MHz, $L_{0.7}$, interpolated by α_{low} , rest-frame specific luminosity at 3.0 GHz, L_3 , interpolated by α_{mid} , and rest-frame specific luminosity at 7.0 GHz, L_7 , interpolated by α_{high} (displayed from left to right). A log-rank test produces a p -value of 0.27, 0.46, and 0.29 for $L_{0.7}$, L_3 , and L_7 , respectively.

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DATA AVAILABILITY

The raw data underlying this article are available via the GMRT online archive facility: <https://naps.ncra.tifr.res.in/goa/data/search>. All data analysis packages used in this work are publicly available.

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