The $L_x$–$L_{\text{uv}}$–$L_{\text{radio}}$ relation and corona–disc–jet connection in optically selected radio-loud quasars

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ABSTRACT

Radio-loud quasars (RLQs) are more X-ray luminous than predicted by the X-ray–optical/UV relation (i.e. $L_x \propto L_{\text{uv}}^\gamma$) for radio-quiet quasars (RQQs). The excess X-ray emission depends on the radio-loudness parameter ($R$) and radio spectral slope ($\alpha_r$). We construct a uniform sample of 729 optically selected RLQs with high fractions of X-ray detections and $\alpha_r$ measurements. We find that steep-spectrum radio quasars (SSRQs; $\alpha_r \leq -0.5$) follow a quantitatively similar $L_x \propto L_{\text{uv}}^\gamma$ relation as that for RQQs, suggesting a common coronal origin for the X-ray emission of both SSRQs and RQQs. However, the corresponding intercept of SSRQs is larger than that for RQQs and increases with $R$, suggesting a connection between the radio jets and the configuration of the accretion flow. Flat-spectrum radio quasars (FSRQs; $\alpha_r > -0.5$) are generally more X-ray luminous than SSRQs at given $L_{\text{uv}}$ and $R$, likely involving more physical processes. The emergent picture is different from that commonly assumed where the excess X-ray emission of RLQs is attributed to the jets. We thus perform model selection to compare critically these different interpretations, which prefers the coronal scenario with a corona–jet connection. A distinct jet component is likely important for only a small portion of FSRQs. The corona–jet, disc–corona, and disc–jet connections of RLQs are likely driven by independent physical processes. Furthermore, the corona–jet connection implies that small-scale processes in the vicinity of supermassive black holes, probably associated with the magnetic flux/topology instead of black hole spin, are controlling the radio-loudness of quasars.

Key words: black hole physics – galaxies: jets – galaxies: nuclei – quasars: general – X-rays: galaxies.

1 INTRODUCTION

Quasars are luminous active galactic nuclei (AGNs) whose central engines are supermassive black holes (SMBHs) that are actively feeding. A significant minority of quasars ($\approx 10$–$20$ per cent; e.g. Padovani et al. 2017) harbour a pair of powerful relativistic jets that launch from a region close to the SMBH. Because relativistic jets are strong radio emitters, the quasars with powerful jets (termed radio-loud quasars, RLQs) are observationally distinguished from other quasars (termed radio-quiet quasars, RQQs) by requiring a radio-loudness parameter $R \equiv L_{5\text{GHz}}/L_{4400\text{Å}} \geq 10$, where $L_{5\text{GHz}}$ and $L_{4400\text{Å}}$ are monochromatic luminosities at rest-frame $5\text{ GHz}$ and $4400\text{ Å}$, respectively (Kellermann et al. 1989). The jets may be powered by the rotational energy of the SMBH and/or the inner accretion flow that is extracted by large-scale magnetic fields threading them (e.g. Blandford & Znajek 1977; Blandford & Payne 1982; see the review paper of Blandford, Meier & Readhead 2019).
However, the mechanism that triggers the production of powerful relativistic jets in only a minority of quasars is not clear.

X-ray emission is nearly ubiquitous for quasars (Brandt & Alexander 2015, and references therein). The primary X-ray emission (≈1–100 keV) from RQQs is radiated from a ‘coronal’ structure containing hot plasma (e.g. Haardt & Maraschi 1993), which might be powered by magnetic reconnection (e.g. Beloborodov 2017). UV photons from the inner accretion disc are up-scattered by electrons in the plasma to produce X-rays. This thermal Compton-scattering process leaves an imprint on the X-ray spectrum as a high-energy cut-off at ≈100–200 keV, which has been observed in local AGNs (e.g. Fabian et al. 2015) and a few high-redshift quasars (e.g. Lanzuisi et al. 2019). Interestingly, a non-linear correlation between the luminosities of the coronal structure and accretion disc has been established, $L_{2keV} \propto L_{5GHz}^{\sim 0.5}$, which is referred to as the $L_{2keV} - L_{5GHz}$ relation (e.g. Avni & Tananbaum 1986; Just et al. 2007; Lusso & Risaliti 2016).\footnote{Throughout the paper, $\gamma$ with no subscript refers to the slope of the $L_{\gamma} - L_{\nu\gamma}$ relation for RQQs.} The $\alpha_{\text{out}} - L_{5GHz}$ relation describes the same non-linear correlation as a dependence of the shape of the optical/UV–X-ray spectral energy distribution (SED) on disc luminosity. Here, $\alpha_{\text{out}} \equiv \log(L_{2keV}/L_{2500\AA})/\log(v_{2500\AA}/v_{2keV})$ is the two-point spectral index between rest-frame 2 keV and 2500 Å (Tananbaum et al. 1979).

The X-ray properties of RLQs are different from those of RQQs. RLQs are generally more X-ray luminous than RQQs of matched optical/UV luminosity (e.g. Zamorani et al. 1981; Worrall et al. 1987; Miller et al. 2011; Ballo et al. 2012). Their X-ray spectra are systematically flatter than those of RQQs (e.g. Wilkes & Elvis 1987; Reeves et al. 1997; Page et al. 2005), particularly for the flat-spectrum radio quasars (FSRQs; e.g. Grandi, Malaguti & Focchi 2006).\footnote{The flat-spectrum and steep-spectrum objects have $\alpha_{\text{in}} \geq -0.5$ and $\alpha_{\text{in}} < -0.5$, respectively. Here, $\alpha_{\text{in}}$ is the power-law spectral index (i.e. $f_{\nu} \propto \nu^{\alpha_{\text{in}}}$) in the radio band.} Furthermore, Compton-reflection features are weaker in RLQs (e.g. Reeves et al. 1997; Reeves & Turner 2000). Among low-redshift AGNs, radio galaxies are more X-ray luminous than their radio-quiet counterparts (e.g. Gupta et al. 2018); broad-line radio galaxies (BLRGs) are found to have weaker reflection features than type-1 Seyfert galaxies (e.g. Wozniak et al. 1998; Eracleous, Sambruna & Mushotzky 2000). However, no strong evidence supports the X-ray spectra of BLRGs being flatter than those of radio-quiet Seyfert galaxies (e.g. Sambruna, Eracleous & Mushotzky 1999; Grandi et al. 2006; Gupta et al. 2018). The different X-ray properties of radio-loud and radio-quiet AGNs could be explained if the radio ‘core’ of the jets contributes significantly in the X-rays a broad-band component with a flat spectrum, in addition to the typical disc/corona emission being present (e.g. Lawson & Turner 1997; Grandi & Palumbo 2004).\footnote{The radio ‘core’ here refers to the sub-arcsec component of the radio image that spatially coincides with the optical and X-ray (point-source) position of the quasar. It is presumably related to the base of the jet.} However, except for a few FSRQs (e.g. Grandi et al. 2006; Madsen et al. 2015), the X-ray spectra of BLRGs (e.g. Wozniak et al. 1998; Sambruna et al. 2009; Ronchini et al. 2019) and steep-spectrum radio quasars (SSRQs; e.g. Lohfink et al. 2017) generally do not reveal a jet-linked flat continuum, suggesting that the orientation of the jets with respect to our line of sight might play an important role.

The coupling between the coronal structure and the accretion disc that is revealed by the $L_{2keV} - L_{2500\AA}$ relation of RQQs probably exists for RLQs as well. Both the jet-launching region and corona are in the immediate vicinity of the SMBH, and connections (e.g. through a joint dependence on the magnetic field) between relativistic jets and the corona might be expected. The discs/corona of quasars dissipate most of their radiated energy in the optical/UV and X-ray bands. Powerful relativistic jets have characteristic synchrotron radio emission, and might have contributions in the X-rays. Therefore, X-ray, optical/UV, and radio are the key observational windows through which to peer at the nature of RLQs. An empirical $L_{2keV} - L_{2500\AA} - L_{5GHz}$ relation has long been sought for RLQs (e.g. Tananbaum et al. 1983), in analogy to the $L_{2keV} - L_{2500\AA}$ relation for RQQs.\footnote{Such empirical relations not only advance our understanding of AGN physics but also have broad practical applications in, e.g. SED fitting (e.g. Yang et al. 2020).} Indeed, the amount of the X-ray excess of RLQs over RQQs of comparable optical/UV luminosities increases with both radio-loudness parameter and radio luminosity (e.g. Miller et al. 2011), supporting the idea that the X-ray luminosity is determined by considering the power of both the disc and the jets, which are represented by $L_{2500\AA}$ and $L_{5GHz}$, respectively. Except for extreme objects at extreme redshifts (i.e. quasars with log $R \gtrsim 2.5$ at $z \gtrsim 4$; Wu et al. 2013; Zhu et al. 2019), the $L_{2keV} - L_{2500\AA} - L_{5GHz}$ relation does not have an apparent redshift dependence (e.g. Worrall et al. 1987; Miller et al. 2011).

However, studies of the $L_{2keV} - L_{2500\AA} - L_{5GHz}$ relation for RLQs have generally lagged behind those of the $L_{2keV} - L_{2500\AA}$ relation for RQQs (e.g. Worrall et al. 1987; Miller et al. 2011). On one hand, the sample size of RLQs is about an order of magnitude smaller than that of RQQs from optical quasar surveys. On the other hand, to constrain the relations to a comparable precision, studies of the $L_{2keV} - L_{2500\AA} - L_{5GHz}$ relation within at least a three-dimensional parameter space generally require the sample size to be larger than that of RQQs, for which a two-dimensional parameter space is sufficient. Furthermore, an extra dimension of RLQ properties (i.e. radio luminosity) compared to RQQs also indicates an extra dimension of the model space. There are more candidate models for the $L_{2keV} - L_{2500\AA} - L_{5GHz}$ relation from which to choose. Beaming effects of the jet emission might add another layer of complexity.

The ambiguity in the functional form of the $L_{2keV} - L_{2500\AA} - L_{5GHz}$ relation makes its physical interpretation and implications unclear. It is possible that RLQs have a similar X-ray emitting disc/corona structure as that of RQQs and a distinct jet-linked X-ray component. The $L_{2keV} - L_{2500\AA} - L_{5GHz}$ relation would then simply describe the general positive correlations of total X-ray luminosities with the optical/UV and radio luminosities.

Alternatively, the $L_{2keV} - L_{2500\AA} - L_{5GHz}$ relation might indicate a connection between the jets and disc/corona; e.g. the discs/corona of quasars that have stronger relativistic jets could be more X-ray luminous than those of quasars that have weaker or no relativistic jets. Such a connection might link AGNs to the phenomena of Galactic black hole X-ray binaries (BHXRBs; or microquasars sometimes called) that are also powered by the black hole accretion process and show couplings between jets and the accretion flow (e.g. Marscher et al. 2002; Merloni, Heinz & di Matteo 2003). Most BHXRBs are transients and show outbursts that last months to years (e.g. Remillard & McClintock 2006). During a typical outburst, BHXRBs may cycle through a (few) state transitions that are marked by changes in spectral and timing properties (e.g. Homan & Belloni 2005), as well as jet activity (e.g. Fender, Belloni & Gallo 2004). The physical scales of SMBHs at the centres of massive galaxies are $>10^{5}$ times those of the stellar-mass black holes of...
BHXBs, making it practically difficult for observations to spot state transitions of individual AGNs directly (e.g. Schawinski et al. 2015). Instead, snapshot (as compared to the time-scale of state transitions) observations across different wavelengths discover a great variety of AGNs (e.g. Padovani et al. 2017). While some of the varieties are caused by inclination-dependent geometry as we are able to observe only one aspect of each AGN (e.g. Netzer 2015), accretion states of the central engine might also play an important role (e.g. Best & Heckman 2012). Investigating the disc/corona–jet connection of RLQs and establishing a phenomenological correspondence between AGN types and BHXB states can shed light on the physics of black hole accretion and relativistic jets.

Previous works did not systematically compare these scenarios (e.g. Tananbaum et al. 1983; Zamorani 1983, 1984; Worrall et al. 1987; Miller et al. 2011). Specifically, they usually focus on one functional model and obtain several sets of parameters that reflect different X-ray properties of different samples. Those sample-dependent empirical relations can be used to predict the X-ray luminosity for given optical/UV and radio luminosities, within a restricted parameter space. However, the driving mechanisms are hidden due to the lack of generality. Here we instead apply various models to the same sample and seek the most probable explanation of the data (i.e. model selection). Perhaps no single model is suitable for all RLQs. For example, FSRQs and SSRQs might require separate mechanisms to explain their X-ray data. Then, we compare the results across all samples, investigating their differences as well as similarities.

We construct a large (>700 objects) optically selected RLQ sample without regards to their radio/X-ray properties in Section 2. Those RLQs span a broad parameter (i.e. luminosity, radio slope, and radio-loudness) space and have a high X-ray detection fraction (∼90 per cent). Furthermore, almost all of them (∼96 per cent) have basic radio spectral information. We perform model-independent, model-fitting, and model-selection analyses in Section 3. We compare with literature results and discuss physical implications in Section 4. A summary of this paper and future prospects are in Section 5. In this paper, the quoted error bars represent 1σ uncertainties, and the upper limits are at a 95 per cent confidence level, unless otherwise stated. The spectral index (α) follows the convention that $f_\nu \propto \nu^{-\alpha}$. We use $L_{\text{X,obs}}$ and $L_{\text{radio}}$ interchangeably with $L_{2\text{keV}}$, $L_{2500\AA}$, and $L_{\text{GHz}}$. The median statistic is widely used throughout the paper. We calculate medians using the Kaplan–Meier estimator (e.g. Kaplan & Meier 1958) in cases where the data contain non-detections. We use the bootstrapping method if the uncertainties of medians are quoted. We adopt a flat-$\Lambda$CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_m = 0.3$.

## 2 Sample Selection

We select new RLQs utilizing the Sloan Digital Sky Survey (SDSS; York et al. 2000). The radio data are from the Faint Images of the Radio Sky at Twenty-Centimeters (FIRST; Becker, White & Helfand 1995) and the NRAO VLA Sky Survey (NVSS; Condon et al. 1998). Archival Chandra and XMM–Newton observations are used to constrain the X-ray luminosities. The newly selected RLQs are combined with those from Miller et al. (2011) to form a final sample of 729 optically selected RLQs, which is summarized in Table 1. Compared with Miller et al. (2011), both the sample size and X-ray detection fraction are increased. Furthermore, we double the numbers of spectroscopic redshifts and radio slopes, the latter of which affects the X-ray properties of RLQs (see Section 3). Importantly, the number of log $R > 3$ RLQs with reliable spectroscopic redshifts are significantly increased (by 70 per cent). We will show in Section 3.2.3 that such RLQs with the highest radio-loudness parameters have the largest statistical power in discriminating between models.

### 2.1 New RLQs from the SDSS DR14 quasar catalogue

#### 2.1.1 Initial selection

The SDSS DR14 quasar catalogue (DR14Q; Pâris et al. 2018) covers a sky area of 9376 deg$^2$ and contains spectroscopically identified quasars from the Legacy Survey of SDSS-III, the Baryon Oscillation Spectroscopic Survey (BOSS) of SDSS-III, and the extended Baryon Oscillation Spectroscopic Survey (eBOSS) of SDSS-IV. The size of DR14Q (5.3 $\times$ 10$^5$ quasars) is a factor of $\geq 7$ times that of DR5Q (7.7 $\times$ 10$^4$ quasars), which was utilized by Miller et al. (2011). The sky coverage of the FIRST survey has an extent of 10.575 deg$^2$ and largely coincides with that of the SDSS. The NVSS covers the entire sky north of Dec $= -40$ deg but with a beam about 10 times larger than that of FIRST. Since the FIRST images have a better resolution, we select new RLQs from the matching results of DR14Q with the final catalogue of the FIRST survey (Helfand, White & Becker 2015). Considering the fact that the quasars in DR14Q are generally fainter than those in DR5Q, we only consider RLQs with log $R > 2$, which ensures $m_i \leq 21$ quasars can be detected in the radio band given the (5σ) flux limit of about 1 mJy of the FIRST survey. The matching is performed as follows. We refer to each row in the FIRST catalogue as a radio component. We adopt the method of Banfield et al. (2015) to distinguish resolved and unresolved components (cf. their equation 1 and fig. 2). The radio flux of a resolved (unresolved) radio component refers to its integrated (peak) flux. We add the radio fluxes of all radio components within a radius of 90 arcsec around the optical position of a quasar and calculate a first corresponding radio-loudness parameter, which results in 24 772 candidate log $R \geq 2$ quasars in the redshift range of 0.5 $\leq z \leq 4$. Here, we have assumed $\alpha_i = -0.5$ to calculate $L_{\text{GHz,obs}}$ from the observed 1.4 GHz flux. The $i$-band apparent magnitude ($m_i$) is utilized to calculate $L_{\text{4400 \AA}}$, where the $K$-correction of Richards et al. (2006) and an optical spectral index of $\alpha_o = -0.5$ are assumed.

In the above, a very large matching radius (90 arcsec) is adopted to ensure that the extended radio emission (e.g. from jets and lobes) associated with each quasar is recovered. However, in many cases, the $R$ value calculated here is merely an upper limit, because background radio sources that are not associated with the quasar are also included. Visual inspection is required to eliminate such contamination from background radio sources (e.g. Lu et al. 2007). To minimize the work of visual inspection, we first match the list of candidate log $R \geq 2$ quasars with the observation catalogues of Chandra and XMM–Newton and apply unbiased empirical quality cuts. For the Chandra/ACIS observations, we require

$$T_{\text{exp}} > 1000 + 35 \times 10^{\theta/2},$$

where $T_{\text{exp}}$ is the exposure time in seconds and $\theta$ is the off-axis angle of the quasar on the X-ray image, in units of arcmin. This criterion requires the exposure time to be at least 1 ks, and it requires additional exposure time at large off-axis angles to compensate for the loss of sensitivity due to the larger point spread function. Similarly, the quality cuts for XMM–Newton/EPIC-pn and XMM–Newton/EPIC-MOS are

$$T_{\text{exp}} > 1000 + 20 \times 10^{\theta/2}$$

(2)
and $T_\text{exp} > 2000 + 20 \times 10^{(\varnothing/\Gamma)^2}$, (3) respectively. Note that $\varnothing$ is bounded by the field of view of the telescopes ($\varnothing < 15$ arcmin). In addition to the cut on the exposure time, we also require each quasar not to fall on to the edge of the detector or in CCD gaps. The requirements for sensitive X-ray coverage and quality cut here reduce the sample size to 1090.

For these quasars, if there is no radio component in the annulus of 2 arcsec $\leq r \leq 90$ arcsec, no visual inspection is performed (330 quasars) and the association is assigned automatically. We visually inspected the $4 \times 4$ arcmin$^2$ FIRST images of the remaining 760 quasars, where the radio components with apparent optical counterparts are labelled. Radio components that are associated with other background sources in the field of view are discarded. In cases where real association exists (see appendix A of Miller et al. 2011 for the utilized matching method), we associate the quasar with one or multiple radio components.

Furthermore, even though FIRST has a deeper nominal flux limit than that of NVSS, it is known to be less sensitive to extended radio components (e.g. White et al. 2007). Sometimes, the faint extended radio emission is ‘resolved out’ and completely missing in the FIRST catalogue (e.g. Blundell 2003).5 The LOFAR Two-metre Sky Survey (LoTSS; Shimwell et al. 2017) aims to image the 120–168 MHz northern sky with a sensitivity of 100 $\mu$Jy. The LoTSS data release 1 (DR1; Shimwell et al. 2019) covers a sky area of about 400 deg$^2$, which contains 63 of our RLQs. We compare the LoTSS and FIRST images of those RLQs and find three cases where FIRST resolves out extended radio components, among which the FIRST fluxes are significantly lower than those of NVSS by 30–50 per cent for two RLQs. Even though those are rare cases (2/63 $\approx$ 3 per cent), we preferentially use the radio fluxes from NVSS over those of FIRST to avoid underestimating total radio emission, provided that the former is not contaminated by very nearby background radio sources. Note that we regard the FIRST component $<2$ arcsec away from the quasar as the radio core. Using the ratio of the peak flux of the radio core to quasar total flux, we assess the dominance of the core (see Footnote 13).

Given the angular resolution of the FIRST survey ($\approx$5 arcsec), the core dominance here might overestimate the true core dominance that is revealed in very-long-baseline interferometric data. After the above procedures, the resulting sample has a size of 545. We label quasars as serendipitously observed if their X-ray observations have $\varnothing \geq 1$ arcmin, while the rest are labelled as targeted. We also label the quasars that are initially selected in SDSS colour space, regardless of their radio/X-ray properties; this allows us to construct an optically selected sample to match the methodology of Miller et al. (2011). We consider those quasars spectroscopically confirmed in the Legacy Survey that have LEGACY_TARGET1 flags of ‘QSO’, ‘HIZ’, and ‘serendipitous’ as optically selected, following Miller et al. (2011). For quasars targeted in BOSS, we consider the ‘CORE’ and ‘BONUS’ samples as indicated by the BOSS_TARGET1 flags. For quasars targeted in eBOSS, we include those belonging to the ‘CORE’ sample as indicated by the eBOSS_TARGET1 flags. We refer readers to Pâris et al. (2018) and references therein for the target selection flags of DR14Q.

### 2.1.2 X-ray data analysis

We first matched the quasar positions to the Chandra Source Catalog Release 2.0 (CSC 2.0; Evans et al. 2010) and the latest XMM–Newton Serendipitous Source Catalog (3XMM-DR8; Rosen et al. 2016) to obtain their X-ray fluxes (0.5–7 keV for Chandra observations and 0.5–4.5 keV for XMM–Newton observations). Galactic-absorption correction is performed subsequently (Dickey & Lockman 1990).

Then, for the observations that are not included in the source catalogs or where the quasar is not detected by the catalogue pipeline, we download the observations and analyse the data manually. Specifically, data reduction, cleaning, and image extraction are performed using CIAO (v4.11) and SAS (v17.0.0) for Chandra and XMM–Newton observations, respectively. Raw source counts are extracted from a circular region centred at the quasar position and enclosing $\approx$90 per cent of the total energy. Background counts are extracted from a source-free concentric annulus or nearby circular region. Using the source and background counts of each observation, we calculate the binomial no-source probability ($P_\mathrm{b}$; Weisskopf et al. 2007), which is the conditional probability of producing counts that are equal to or larger than the observed counts in the source extraction region given the intensity of the background. We take a source as detected if $P_\mathrm{b} < 0.01$ and calculate its net count rate. Instrumental response files (i.e. response matrix files and ancillary response files) at the position of the source are created using the standard routines of CIAO and SAS; these include the appropriate aperture correction. With these instrumental response files, the net count rate is converted to X-ray flux using SHERPA.

We have fixed the photon index to $\Gamma = 1.5$ for the power-law model, following Miller et al. (2011); the dependence of the X-ray flux on the choice of $\Gamma$ is mild for reasonable choices of $\Gamma$. Note that the X-ray flux is corrected for Galactic absorption by specifying the $N_\mathrm{H}$ value (Dickey & Lockman 1990) of the model in SHERPA. A source is treated as a non-detection if $P_\mathrm{b} > 0.01$. We calculate the upper limits on the net counts at a 95 per cent confidence level using the algorithm of Kraft, Burrows & Nousek (1991) for non-detected quasars, and the upper limits of the X-ray fluxes are calculated using the same method as detections.

The Galactic-absorption corrected X-ray flux (or upper limit), from either the source catalogs or manual analysis, is subsequently converted to the monochromatic luminosity at rest-frame 2 keV, $L_{2\text{keV}}$. |

### Table 1. Summary of optically selected RLQs utilized in the paper. |

| Sample       | No. of sources | X-ray detections | Serendipitous | Spectroscopic $z$ | Radio slope |
|--------------|----------------|------------------|--------------|-------------------|-------------|
| All RLQs     | 729            | 657 (90.1 %)     | 622 (85.3 %) | 587 (80.5 %)      | 704 (96.6 %) |
| FSRQs        | 394            | 363 (92.1 %)     | 340 (86.3 %) | 319 (81.0 %)      | 394 (100 %) |
| SSRQs        | 310            | 275 (88.7 %)     | 258 (83.2 %) | 253 (81.6 %)      | 310 (100 %) |

5By matching the DR14Q with FIRST, we might already miss RLQs with only faint and diffuse radio emission. However, those cases are rare ($\sim$2.3 per cent; e.g. Lu et al. 2007) such that quasars with an extended morphology are almost always luminous in the radio band.

6The target selection algorithms of the BOSS and eBOSS programmes might also utilize infrared photometry information where available.
2.1.3 Radio spectral indices

We matched the quasar list with sky surveys in the radio band to obtain radio slopes, using fluxes at 1.4 GHz and at another wavelength. Those radio surveys include the Green Bank 6-cm (GB6) Radio Source Catalog (4.85 GHz; Gregory et al. 1996), Westerbork Northern Sky Survey (325 MHz; Rengelink et al. 1997), TGSS Alternative Data Release (150 MHz; Intema et al. 2017), and LoTSS DR1 (144 MHz; Shimwell et al. 2019). For quasars that are not matched with those radio surveys, we gather their multi-wavelength radio fluxes in the NED\(^7\) and VizieR.\(^8\) For the 78 quasars that do not have multi-wavelength radio data in the NED or VizieR, 60 of them are covered by the ongoing VLASS (Lacy et al. 2020), which provides the 3 GHz flux. We downloaded VLASS quick-look images\(^9\) of these 60 quasars and measured their 3 GHz fluxes using aegean (Hancock et al. 2012; Hancock, Trot & Hurley-Walker 2018). Note that the peak and integrated fluxes from these quick-look images are corrected by factors of 1.15 and 1.10, respectively (Lacy, private communication). We inspect the FIRST/NVSS images while matching RLQs with the above radio surveys to ensure true association of radio components and to screen background contamination, which is important for the GB6 data since it has a large beam size (≈3 arcmin).\(^10\) In total, 263 quasars have high-frequency (>1.4 GHz) radio data, while 346 quasars have low-frequency (<1.4 GHz) radio data. Even though the radio slope measurements are not from homogeneous data sets, they are sufficient to distinguish flat-spectrum and steep-spectrum objects. Furthermore, for objects having fluxes at ≥3 different frequencies, the radio spectral shape is generally consistent with a single power-law, which argues against a strong effect of redshift. However, we label those ‘GHz peaked’ and related quasars (28 objects) that are inconsistent with a power-law spectrum but seem to be peaked at GHz to 100 MHz frequencies (e.g. O’Dea 1998). Note that these objects are eventually excluded from the final sample since their X-ray properties are often different from typical RLQs (e.g. Siemiginowska et al. 2008).

2.1.4 Cleaning the sample using multi-wavelength colors and optical/UV spectra

We matched the 545 quasars resulting from initial selection (Section 2.1.1) with infrared sky surveys, including the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010), the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007), the UKIRT Hemisphere Survey (UHS; Dye et al. 2018), and the VISTA Hemisphere Survey (VHS; McMahon et al. 2013). We also matched our sample with the Pan-STARRS Stack Object Catalog (Chambers et al. 2016) to include \(\gamma\)-band photometry. Including the SDSS, we have high-quality photometric coverage from the UV to mid-infrared. For the mid-infrared data, we have utilized the forced photometry from the unWISE coadd images (Lang, Hogg & Schlegel 2016), which improves the number of detections in the W1–W4 bands. Since not all the forced-photometry data are high-quality measurements, we replace those fluxes with signal-to-noise ratio (SNR) smaller than 2 with their 95 per cent confidence upper limits, and flag them as non-detections.\(^11\) For those quasars that do not have forced photometry, we still use the measurements from the AllWISE catalogue. The forced photometry increases the number of detections by ≈30–50 for each mid-infrared band. These photometric data are corrected for Galactic extinction using the dust map of Schlafly & Finkbeiner (2011) before the following analysis.

We found that some of the RLQs have abnormal multi-wavelength colours and SDSS spectra that are not consistent with those of typical quasars featuring big blue bump-dominated SEDs and strong optical/UV emission lines. We here further screen the sample based on their SDSS spectra and multi-wavelength colors. We matched the 545 RLQs with the SDSS-DR7 Quasar Catalog (DR7Q; Schneider et al. 2010; Shen et al. 2011) and SDSS-DR12 Quasar Catalog (DR12Q; Pâris et al. 2017). For the 501 quasars that are in DR7Q or DR12Q, 31 are classified as broad absorption line quasars (BALs). For the remaining 44 quasars, one is a BAL because its Balnicity index is larger than 0 (Pâris et al. 2018). We have removed these BAL quasars from further consideration because their X-ray properties are likely affected by complex absorption (e.g. Miller et al. 2009). We also flagged 10 quasars whose SDSS spectra are Type II-like. They are relatively local (\(z < 0.76\)) with strong \([\text{O} \text{ III}]\), weak \(\text{H}\beta\), and often red continua. Four of them are in the Type II quasar catalogue of Reyes et al. (2008) or Yuan, Strauss & Zakamska (2016). These quasars also likely have complex X-ray absorption, so are screened. We screened out quasars that have red SDSS and/or infrared colours that satisfy the following criteria:

\[
\begin{align*}
\alpha - W_4 &> 12.0 \quad \text{or} \quad W_3 - W_4 > 9.4 \quad \text{or} \quad \alpha - i > 0.95, \quad z < 1.5 \\
\alpha - W_4 &> 11.9 \quad \text{or} \quad W_3 - W_4 > 9.7 \quad \text{or} \quad g - i > 1.0, \quad 1.5 < z \leq 2.5 \\
\alpha - W_3 &> 8.4 \quad \text{or} \quad z > 0.6, \quad 2.5 < z \leq 4.
\end{align*}
\]

Note that these colour cuts effectively remove red quasars (79 objects) that either suffer from severe dust extinction or have prominent jet emission in the infrared through UV bands. Furthermore, we exclude quasars that do not have strong emission lines, since their rest-frame optical/UV emission might be contaminated by strongly boosted jet emission, rendering the observed \(L_{2500} \lambda\) an overestimate of their disc power. Specifically, we measure the rest-frame equivalent width (REW) of \(\text{Mg}\) ii (when it is covered by SDSS spectra) and exclude those quasars (three objects) with \(\text{REW} < 10 \AA\). After these procedures, the resulting sample has a size of 421, among which 327 quasars are selected using SDSS colors (see the last paragraph of Section 2.1.1). Note that serendipitous X-ray coverage makes up about 79 per cent of this sample, so the majority of these quasars have X-ray observations unbiased by source properties. Those quasar jets with the most extremely boosted emission are underrepresented in our sample, due to the colour cuts and the constraint on emission-line strength. However, their fraction is estimated to be only \(\lesssim 6\) per cent, considering a conservative Lorentz factor of \(\Gamma = 8\) for the jets and a half-opening angle of 30 deg for the dusty torus, and thus the results of this paper will not be strongly biased.

\(^7\)https://ned.ipac.caltech.edu/  
\(^8\)http://vizier.u-strasbg.fr/vizier/sed/  
\(^9\)https://archive-new.nrao.edu/vlass/quicklook/  
\(^10\)We measure FIRST/NVSS-VLASS radio slopes for those quasars having FIRST/NVSS-GB6 measurements to ensure that the inhomogeneous beam sizes do not strongly bias the results.  
\(^11\)http://wise2.ipac.caltech.edu/docs/release/allwise/expsup/sec3_1a.html
2.2 Improving the Miller et al. (2011) RLQ sample

Miller et al. (2011) construct a sample of 791 quasars with log $R^∗ ≥ 1$. The overall X-ray detection fraction of this sample is high (85 per cent). Their full sample consists of 654 optically selected primary RLQs, and the rest are supplementary RLQs that are generally not optically selected. The X-ray data for the primary sample are from archival Chandra, XMM–Newton, and ROSAT observations, most (86 per cent) of which are serendipitous and thus unbiased with respect to RLQ properties.

However, about half of their primary RLQs lack radio spectral information. Furthermore, the primary sample of Miller et al. (2011) includes 312 spectroscopically confirmed quasars culled from the SDSS DR5 Quasar catalogue (DR5Q; Schneider et al. 2007), while the remaining 342 quasars are photometrically selected but not spectroscopically confirmed (Richards et al. 2009). The improvement upon RLQs from Miller et al. (2011) thus mainly comes from higher fractions of radio-slope measurements and spectroscopic redshifts.

We measure the radio slopes using the same method as for newly selected RLQs by matching with radio sky surveys, NED and VizieR, and the quick-look images of VLASS. The spectral indexes are measured for 719 quasars, making up 91.1 per cent of all quasars from Miller et al. (2011). As to the optically selected RLQs, their radio-slope measurements are 91.4 per cent complete. Note that to obtain a final data set with uniform measurements in the radio bands, we also update the total radio fluxes for RLQs from Miller et al. (2011) using NVSS as in Section 2.1.1.

For the 342 photometrically selected quasars in the primary sample of Miller et al. (2011), SDSS/BOSS/eBOSS spectra from the SDSS/BOSS spectrograph can now be found for 183 of them. We exclude nine quasars whose rest-frame optical/UV spectra are BL Lac-like with a featureless continuum. Another nine quasars are excluded because they are likely to be BAL quasars. For the rest (165) of the quasars with new spectroscopic measurements, we replace their photometric redshifts with spectroscopic redshifts and update their luminosities accordingly. Note that catastrophic failures in the photometric redshifts where $|z_{\text{photo}} - z_{\text{spec}}|/(1 + z_{\text{spec}}) > 0.15$ make up ≈5 per cent of these quasars, suggesting that the photometric redshifts of the remaining (159) quasars that still lack spectroscopic measurements are largely reliable.

As for the new RLQs, we also gather multi-wavelength data (mid-infrared to UV) for the sample of Miller et al. (2011) and apply colour cuts described in Section 2.1.4, which eliminate 93 objects. Another nine objects are excluded since their X-ray observations do not satisfy the criteria in Section 2.1.1.

2.3 The final optically selected RLQ sample

We merge the newly selected sample with the refined sample of Miller et al. (2011), resulting in 940 unique RLQs. Note that some quasars might be present in both samples, mainly because many photometric quasars of Miller et al. (2011) now have optical/UV spectra. For the physical quantities describing these quasars, we use their newly measured values in this paper. Since some quasars in the SDSS QSO catalogue are selected by their radio or X-ray properties, we utilize only the optically selected subset (789 objects) that does not suffer from apparent radio/X-ray selection biases in the following sections. Note that 49 quasars are not considered since they either have peaked radio spectra or are compact objects with steep spectra. Another 11 quasars are excluded as rare cases that are known to be X-ray weak (2 quasars; e.g. Risaliti 2005), are in the vicinity of luminous clusters (1 quasar; e.g. Rykoff 2009), or have exceedingly flat X-ray spectra signifying strong absorption (8 quasars; e.g. Miyaji et al. 2006). The properties of the resulting 729 RLQs are listed in Table 2.

We show in Fig. 1 the infrared-to-UV composite SED of the final optically selected RLQs, which has the blue colour of typical Type I quasars that are dominated by the emission from the accretion disc. Note that the composite SED (orange) in Fig. 1 utilizes $≈10^4$ photometric data points of $>700$ quasars. In comparison, we show the composite SED of RLQs from Shang et al. (2011) in the same plot. Fig. 2 shows the composite median spectra for various subsets of optically selected RLQs. They are divided into redshift, radio slope, and $R$ bins in the three panels of Fig. 2. Prominent emission lines are present in all composite median spectra, indicating that the optical/UV continuum of the RLQs is generally not contaminated by boosted jet emission. Indeed, from the catalogs of Shen et al. (2011) and Pâris et al. (2017), 573/729 quasars of the final sample have REW measurements for at least one emission line among $\text{C} \IV$, $\text{Mg} \II$, $\text{H} \beta$, and the median REWs are $(42^{+6}_{−3}, 37^{+8}_{−5}, 77^{+9}_{−4})$ Å and $(48^{+9}_{−5}, 40^{+11}_{−7}, 83^{+11}_{−6})$ Å for FSRQs and SSRQs, respectively. This indicates that even the FSRQs in our sample do not have a substantial optical/UV continuum contribution from a jet.

We show the final sample in the $L_{\text{GHz}}–L_{2500\text{Å}}$ plane in Fig. 3. The colour of each RLQ indicates its redshift, according to the colour bar on the right-hand side. Furthermore, we show four lines on the plane that are defined by constant radio-loudness parameters.

2.4 Comparison optically selected RQQ samples

To compare the X-ray properties of RLQs with those of RQQs, we also utilize a large sample of RQQs from Lusso & Risaliti (2016). These RQQs were selected from the SDSS quasar catalogue, and the X-ray data are exclusively from XMM–Newton observations. Following Lusso & Risaliti (2016), we select RQQs from their tables 1 and 2 that satisfy $E(B − V) ≤ 0.1$, $S/N > 5$, and $1.9 ≤ z ≤ 2.8$ from the main sample (cf. table 3 of Lusso & Risaliti 2016). We further exclude a small number of RQQs that are not optically selected. The resulting sample has a size of 1074, among which 699 have detected X-ray emission. We use this sample to constrain the $L_X–L_{\text{FWHM}}$ relation, which is established for RQQs that span 4 decades in luminosity (e.g. Just et al. 2007; Lusso & Risaliti 2016) and show no redshift dependence up to $z > 6$ (e.g. Vito et al. 2019).

Furthermore, we utilize $z < 0.5$ PG quasars from Boroson & Green (1992), which are optically selected and have relatively deep radio constraints (e.g. Kellermann et al. 1989, 1994). We only consider a subsample of 59 RQQs that do not have strong CIV absorption from Laor & Behar (2008), 50 of which have detected radio emission while the remaining 9 have upper limits. All 59 quasars are detected by ROSAT in X-rays (Brandt, Laor & Will's...
Table 2. Properties of optically selected RLQs utilized in the paper, in ascending order of RA. Only the top five objects are listed.

| SDSS name                  | z    | $m_i$  | log $L_{2500\AA}$ | log $L_{24\mu m}$ | log $R_{2k\,eV}$ | XFlag $^a$ | sd $^b$ | spec $^c$ | $\alpha_r$ | $cD^d$ |
|----------------------------|------|--------|-------------------|-------------------|------------------|------------|--------|----------|----------|--------|
| 000442.18+000023.3         | 1.008| 18.98  | 30.22             | 32.09             | 26.91            | 1          | 1      | 1        | 1        | –      | 0.59     |
| 000622.60–000424.4         | 1.038| 19.58  | 30.05             | 34.94             | 27.32            | 1          | 1      | 1        | 1        | –      | 0.80     |
| 001646.54–005151.7         | 2.243| 21.00  | 30.20             | 32.66             | 26.36            | 2          | 1      | 1        | 1        | –      | 1.00     |
| 001910.95+034844.6         | 2.022| 20.30  | 30.35             | 32.91             | 26.54            | 2          | 1      | 1        | 1        | –      | 0.56     |
| 003054.63+045908.4         | 2.201| 20.95  | 30.19             | 33.81             | 26.59            | 3          | 1      | 1        | 1        | –      | 0.76     |

Note. $^a$If the quasar is detected in X-rays, XFlag = 1, while XFlag = 0 if otherwise. $^b$sd = 1 if the X-ray observation is labelled serendipitous and sd = 0 if the quasar was targeted. $^c$If the quasar is spectroscopically confirmed, spec = 1. If the redshift is based on photometric data, spec = 0. $^d$The ratio of the flux of the radio core over the total radio flux (see Section 2.1.1).

Figure 1. The composite median SED (orange) of optically selected RLQs, from the mid-infrared to UV. The top and bottom ticks are in units of rest-frame frequency and wavelength, respectively. The small dots are data points for individual quasars, where grey symbols are non-detections in the WISE bands, distinguished from detections (black). Any data points with rest-frame frequency $>\nu_{1250\AA}$ are not used in constructing the composite SED due to intergalactic absorption. Also plotted is the composite SED of the local RLQs from Shang et al. (2011, blue) for comparison.

Figure 2. The composite median SDSS spectra (in $I_f \lambda$ representation) of optically selected RLQs. From top to bottom, RLQs are divided into bins of redshift, radio slope, and radio-loudness. The dash-dotted vertical lines show the frequencies of six emission lines as labelled. Note that the composite spectra are arbitrarily shifted vertically to avoid overlapping. In all cases, prominent emission lines are apparent, indicating that the optical/UV emission of the RLQs is not contaminated by strong boosted jet emission.

3 THE RELATION BETWEEN X-RAY, OPTICAL/UV, AND RADIO LUMINOSITIES

3.1 Insights from scatter plots

In the top panel of Fig. 5, the $L_{radio}–L_{uv}$ plane is divided into $3 \times 3$ sub-regions, the boundaries between which are the 33rd and 66th
Figure 3. The optically selected RLQ sample in the $L_{\text{radio}}$–$L_{\text{uv}}$ plane, where the data points are colour-coded by their redshifts. Different symbols have been used to indicate the radio spectral information. Five lines defined by constant radio-loudness parameters are also shown. We also show 59 RQQs from Laor & Behar (2008), where squares and downward arrows are detections (50 quasars) and non-detections (9 quasars) in the radio band, respectively.

Figure 4. The RQQ samples in the $L_{\text{x}}$–$L_{\text{uv}}$ plane. The black symbols are (SDSS) RQQs from Lusso & Risaliti (2016), while the (PG) RQQs from Laor & Behar (2008) are further divided into two bins (orange squares and red diamonds) by their median radio-loudness parameter ($R = 0.25$). Fitting a line to the black data points results in the equation at the lower-right corner (cf. the bottom row of Table 4). The uncertainties of this relation are indicated by the black-shaded region. The PG quasars are consistent with the fitted $L_{\text{x}}$–$L_{\text{uv}}$ relation. No apparent radio dependence for PG RQQs is found.

Figure 5. Top: The dependence of X-ray luminosity on $L_{\text{5GHz}}$ (y-axis) and $L_{2500\text{Å}}$ (x-axis). The scattered points are all optically selected RLQs, which are further grouped into nine bins. Those bins are separated by the 33rd and 66th percentiles along each axis. We calculate the median X-ray luminosity of each bin as indicated by the colour bar on the right-hand side. Clearly, $L_x$ increases with both increasing $L_{\text{5GHz}}$ and $L_{2500\text{Å}}$. Bottom: Same as the top panel for the $R$–$L_{2500\text{Å}}$ plane.
indicate that there are strong radio and optical/UV dependences for the X-ray luminosities of RLQs.

We investigate the radio dependence for FSRQs and SSRQ separately in Fig. 6, where their X-ray luminosities divided by those of RQQs at given $L_{2500\AA}$ are plotted against $\log R$. SSRQs by 10–20% per cent. Furthermore, the medians of FSRQs are larger than those of RQQs, probably due to their seemingly larger scatter than that of SSRQs. The X-ray luminosities of FSRQs and SSRQs probably have different radio and optical/UV dependences (at about 2.5σ significance) as indicated by Figs 6 and 7.

In short, the X-ray luminosity of RLQs depends on $L_{2500\AA}$, $L_{\text{radio}}$ (or $R$), and radio slope, which has also been concluded by many previous works (e.g. Worrall et al. 1987; Brinkmann, Yuan & Siebert 1997; Grandi et al. 2006; Miller et al. 2011). In addition to the disc–corona interplay that is revealed by the $L_x$–$L_{2500\AA}$ relation for RQQs, we probably need at least two more mechanisms, or one mechanism that is affected by two key parameters, for those dependences in RLQs. We focus on the $L_x$–$L_{2500\AA}$ relation and consider $R$ and radio slope as controlled additional factors. Specifically, we fit the $L_x$–$L_{2500\AA}$ relations for the three $R$ bins of FSRQs and SSRQs (as in Fig. 6), separately, and show the results in Fig. 8. The corresponding 1σ confidence regions are in Fig. 9.

A notable pattern for SSRQs emerges that the slope of the $L_x$–$L_{2500\AA}$ relation is always consistent with that for RQQs, while the intercept increases monotonically with $R$. If the excess X-ray luminosity of SSRQs relative to RQQs is caused by emission from the core region of the jets, the contribution of this component increases with $R$, as expected. However, two properties are required further by Fig. 8 (bottom) that (a) the jet component depends strongly on $L_{2500\AA}$ and (b) the slope of this dependence is consistent with $\gamma$. For example, the SSRQs in the most radio-loud bin are on average a factor of about 3 more X-ray luminous than RQQs in all panels. The slope of SSRQs is consistent with that of RQQs ($\gamma \approx 0.63$, white), while the slope of FSRQs is steeper at an $\approx 2.5\sigma$ significance level.

**Figure 6.** The X-ray luminosities of FSRQs (green dots) and SSRQs (purple squares) over those of RQQs at given $L_{2500\AA}$ are plotted against $\log R$. We group each sample into three $R$ bins and calculate their medians and uncertainties.

**Figure 7.** The $L_x$–$L_{2500\AA}$ relations for all RLQs, FSRQs, and SSRQs, from top to bottom. The resulting slope with uncertainty estimation is at the lower right corner of each panel. The $L_x$–$L_{2500\AA}$ relation for RQQs (black) is also plotted for comparison. At given optical/UV luminosity, RLQs are more X-ray luminous than RQQs in all panels. The slope of SSRQs is consistent with that of RQQs ($\gamma = 0.63\pm0.04$), while the slope of FSRQs is steeper at an $\approx 2.5\sigma$ significance level. A notable pattern for SSRQs emerges that the slope of the $L_x$–$L_{2500\AA}$ relation is always consistent with that for RQQs, while the intercept increases monotonically with $R$. If the excess X-ray luminosity of SSRQs relative to RQQs is caused by emission from the core region of the jets, the contribution of this component increases with $R$, as expected. However, two properties are required further by Fig. 8 (bottom) that (a) the jet component depends strongly on $L_{2500\AA}$ and (b) the slope of this dependence is consistent with $\gamma$. For example, the SSRQs in the most radio-loud bin are on average a factor of about 3 more X-ray luminous than RQQs (see Fig. 6), which means that the jet component (if it exists) dominates their X-ray luminosities; the dependence of their $L_x$ on $L_{2500\AA}$ is still strong with a slope $= 0.60\pm0.05$ (see Fig. 9), which is only different from $\gamma$ by $\approx 5$ per cent. Indeed, perhaps we do not need two distinct X-ray components (i.e. from the corona and jet core) that are indistinguishable with regard to...
Figure 8. The $L_x$–$L_{uv}$ relation for FSRQs (top) and SSRQs (bottom) divided into three $R$ bins as indicated by the colour-bar on the right-hand side. The slopes and intercepts for the relations are given in Fig. 9. The $L_x$–$L_{uv}$ relation for RQQs (black) is plotted for comparison. For SSRQs, the slope is always consistent with that of RQQs while the intercept increases with $R$. FSRQs follow another pattern where both the intercept and slope increase with $R$.

Figure 9. The 1σ confidence regions for slope and intercept of the $L_x$–$L_{uv}$ relations in Fig. 8.

their correlations with $L_{uv}$ and their spatial properties. A more natural and compact explanation is that the X-ray emission of SSRQs reveals only one component and is produced in the same way as for RQQs; this component is attributed to the hot corona that is coupled with the disc (i.e. the $L_x$–$L_{uv}$ relation). Furthermore, there is a connection between the activity of the corona (i.e. the intercept of the $L_x$–$L_{uv}$ relation) in the immediate vicinity of the SMBH and that of the large-scale jets (i.e. $R$), such that those RLQs harboring more powerful relativistic jets also have more powerful coronae.

The results for FSRQs are not as clear in Figs 8 and 9. For the lowest $R$ bin, the slope is consistent with $\gamma$, supporting the idea that the observed X-rays are also dominated by the corona, and the intercept is consistent with that of SSRQs within error bars. However, the slope increases with $R$ to 0.7–0.9 for FSRQs in the other two bins, and the intercepts are also larger than

---

15The current X-ray telescope with superb sub-arcsec resolution (i.e. Chandra) cannot resolve the nuclear X-ray emission of RLQs into different spatial components.

16In principle, another possible explanation for Fig. 8 (bottom) could be that even RQQs have a jet-linked X-ray continuum (as many RQQs do have small jets, and some envision the X-ray corona in radio-quiet objects to be the base of a jet). Following this explanation, we should expect a corona-jet connection for RQQs as well, which is, however, not supported (see Section 3.3 and Fig. 14). More generally, luminosity correlations and X-ray spectral properties support a thermal Compton-scattering origin for the X-ray continuum of RQQs (see Section 1).
for the corresponding SSRQs (although only suggestively for the second $R$ bin). Therefore, the $L_x-L_{\gamma}$ relation for the moderate-to-most radio-loud FSRQs probably requires additional mechanisms. However, we stress that the medians of FSRQs and SSRQs of similar radio-loudness in Fig. 6 are only different at a 10–20 per cent level. Therefore, the additional mechanisms affecting FSRQs are likely secondary such that their X-ray luminosities are generally controlled by the enhancement of the putative coronal emission as for SSRQs.\footnote{In consequence, this statement is probably true for almost all RLQs.} We test in the next section whether a distinct component from the jet core might play an important role or not.

3.2 Parametrized modelling

Qualitatively similar plots to those in Section 3.1 can also be found in previous works (e.g. Worrall et al. 1987; Miller et al. 2011), although our quantitative constraints here are considerably tighter owing to our improved data quality. For example, the results in Fig. 9 are in line with those in fig. 1 of Worrall et al. (1987). However, despite such consistent plots, this paper and the literature reach different conclusions. Specifically, we suggest that the disc/corona of RLQs are systematically more X-ray luminous than those of RQQs, while both Worrall et al. (1987) and Miller et al. (2011) attribute the excess X-ray emission of RLQs to the jet core. These two interpretations need to be further compared. In this section we use formal model selection to show that our interpretation in Section 3.1 is indeed preferred by the data. Furthermore, the varying contributions of the two additive X-ray components (jets and corona) are probably more easily revealed by direct model fitting than by finding the proportionality of total X-ray luminosity with luminosities at other wavelengths (e.g. Section 3.1).

3.2.1 Models for the X-ray-optical/UV-radio relation of RLQs

We first set up a decomposition for the X-ray emission from RLQs, and then discuss three functional models within this framework. We write the X-ray luminosity of RLQs as

$$L_x = AL_{\gamma}^{\text{opt}} + BL_{\gamma}^{\text{radio}},$$  \hspace{1cm} (7)

where $AL_{\gamma}^{\text{opt}}$ and $BL_{\gamma}^{\text{radio}}$ represent the parts of the emission from the corona and jets, respectively. Here, the X-ray luminosity from the disc/corona depends on the disc luminosity ($L_{\gamma}$) to the power of $\Gamma_{\gamma}$, and is subject to a normalization factor $A$. This $L_x-L_{\gamma}$ relation for the disc/corona emission of RLQs has thus been assumed to be of similar functional form to that of RQQs. Whether the specific parameters of this relation are universal to both all RLQs and RQQs is not assumed. Given that the X-ray and radio luminosities of the sample span 4–6 decades, we adopt a power-law dependence for the case of the jet component as well (i.e. $L_x^{\text{jet}} = BL_{\gamma}^{\text{radio}}$). This functional form is reasonably flexible and can accommodate many potential underlying physical emission mechanisms. In practice, the data might not require both components to be present, in cases where one of the normalization factors is consistent with zero (most likely $B$).

In Table 3, we list three functional models that describe different $L_{3\gamma e V}-L_{2500\AA}-L_{\text{GHz}}$ relations, all of which are interpreted in the context of equation (7). For example, when we assess the dependence of the X-ray luminosity on the optical/UV luminosity of the disc/corona, i.e. $L_{\gamma}$, we will use $\gamma_{\text{opt}} + \gamma_{\text{radio}}$ of Model I and Model III, while we will use $\gamma_{\text{radio}}$ of Model II.

Model I was utilized by previous works because it describes a joint dependence of the X-ray luminosity on both the optical/UV and radio luminosities (see Fig. 5) with the smallest number of parameters (e.g. Tananbaum et al. 1983; Worrall et al. 1987; Miller et al. 2011). To preserve consistency with past work, we still use the form $L_{3\gamma e V} \propto L_{2500\AA}^{\gamma_{\text{opt}}}L_{\text{GHz}}^{\gamma_{\text{radio}}}$. We note from Fig. 8 that, for fixed $R$, the $L_x-L_{\gamma}$ relation of RLQs has a slope such that $\Gamma_{\gamma} = \gamma_{\text{opt}} + \gamma_{\text{radio}} \approx \gamma$ for the majority of bins. Previous model fitting results using Model I (e.g. table 7 of Miller et al. 2011) are roughly consistent with this suggestion. Here, a corona–jet connection is parametrized so that the normalization factor (intercept) correlates with the radio-loudness parameter to the power of $\gamma_{\text{radio}}$ (i.e. $\mathcal{A} \propto R^{\gamma_{\text{radio}}}$. An X-ray emitting region that is associated with the relativistic jets is not explicitly included (i.e. $B$ is set to zero).

Similar to equation (7), Model II explicitly divides the X-ray emission of RLQs into corona ($A L_{\gamma}^{\text{opt}}$) and jet core ($B L_{\gamma}^{\text{radio}}$) components. However, it stands for a special but commonly assumed scenario where $\Gamma_{\gamma}^{\text{radio}}$ might be consistent with the X-ray luminosity of RQQs; therefore, RLQs are treated as a basic combination of an RQQ engine with additional powerful jets from the perspective of the X-rays (e.g. Worrall et al. 1987). For the jet component, the X-rays might correlate linearly (i.e. $\gamma_{\text{radio}} = 1$) with the radio emission from the same region as suggested by previous works (e.g. Zamorani 1984; Browne & Murphy 1987; Worrall et al. 1987). No apparent connection between the jets and the corona is present in this model; each contribution is mathematically independent. Model II has been applied to FSRQs (e.g. Zamorani 1984; Worrall et al. 1987) and SSRQs (e.g. Zamorani 1984) in previous works. With small-size samples, their results actually hinted at a difference between the coronae of RLQs and those of RQQs, though no solid conclusion was reached.\footnote{Another advantage of this preference in model fitting is that there is non-zero covariance between the measurement errors of $R$ and $L_{2500\AA}$, while $L_{\text{GHz}}$ and $L_{2500\AA}$ are independent measurements.}

It is also possible that both Model I and Model II are describing part of reality. In Section 3.1, we require a corona-jet connection for the differences between RQQs and SSRQs and cannot rule out a jet component in FSRQs. We thus propose Model III (see Table 3) that combines those features. Model I and Model II are special cases of Model III, where either $B$ or $\gamma_{\text{radio}}$ is set to zero, respectively. From this point of view, we utilize only Model III and discuss whether its certain parameters are zero or not.

3.2.2 Methods

Following Miller et al. (2011), we first normalize the quasar luminosities to $L_{2500\AA} = 30.5$, $L_{5\text{GHz}} = 33.3$, and $L_{2\text{keV}} = 27.0$, which are near to the median luminosities of our sample. The maximum-likelihood estimates are then obtained for the models in Table 3. The model fitting is performed using LMFIT (Newville et al. 2014), and the likelihood function takes into account the upper limits on the X-ray luminosities (e.g. Isobe, Feigelson & Nelson 1986). The maximum-likelihood and uncertainty estimations of...
model parameters are calculated using a Markov chain Monte Carlo (MCMC) algorithm (EMCEE; Foreman-Mackey et al. 2013). This method is thus equivalent to a Bayesian approach with flat priors. We initially leave all parameters free to vary to reveal the most general results. However, we fix the parameter values for cases where the parameters are either unconstrained or unphysical (see details in Appendix A), which also prevents the model performance from being imprecisely characterized by the model-selection methods we use below (e.g. Nelson et al. 2020).

Second, as to model selection, the likelihood-ratio test (e.g. F-test) is not applicable here since Model I and Model II are not nested. We thus use standard information criteria (ICs) to compare the performance of models. We adopt the widely used Akaike Information Criterion (AIC; Akaike 1974) and Bayesian Information Criterion (BIC; Schwarz 1978), which are defined as

\[
\text{AIC} = -2 \ln \mathcal{L}_{\text{max}} + 2k,
\]

\[
\text{BIC} = -2 \ln \mathcal{L}_{\text{max}} + k \ln N.
\]

Here, \( \mathcal{L}_{\text{max}} \) is the maximum likelihood, \( k \) the number of free parameters of the model, and \( N \) the number of data points. Under such definitions, the model with the smallest information criterion is selected. ICs thus favour high model likelihood (\( \mathcal{L}_{\text{max}} \)) and penalize high model complexity (\( k \)). BIC penalizes model complexity more severely than AIC when \( N > 7 \). The significance of the selection result (i.e. the evidence for the selected model) is indicated by \( \Delta \text{AIC} \) (e.g. section 2.6 of Burnham & Anderson 2002) and \( \Delta \text{BIC} \) (e.g. section 3.2 of Kass & Raftery 1995) between models. In this paper, AIC and BIC always agree on the best model, and in most cases, the best models are strongly favoured with \( |\Delta \text{AIC}| \gtrsim 5 \) and \( |\Delta \text{BIC}| \gtrsim 5 \). It is probably not safe to rely solely on statistical methods and to draw conclusions without considering physical plausibility. The results of the following two subsections are secured by the fact that the ICs-selected model fits also depict the most reasonable physical pictures.

### 3.2.3 Results of all RLQs without distinguishing radio slope

The fitting results for all RLQs, FSRQs, and SSRQs are listed in Table 4, where the bottom row is the \( L_\gamma-L_{5 \text{GHz}} \) relation for the comparison RQQ sample from Lusso & Risaliti (2016). We first check whether the fitting results for all RLQs are consistent with the hypotheses of the models. Model I results in \( \Gamma_{uv} = \gamma_{uv} + \gamma_{\text{radio}} = 0.69^{+0.03}_{-0.02} \) which is 1.6\% away from \( \gamma = 0.63^{+0.02}_{-0.01} \). Due to the fact that the resulting error bar is relatively large for Model II, comparing \( \Gamma_{uv} = \gamma_{uv} = 0.72^{+0.08}_{-0.05} \) and \( \gamma \) results in a similar statistical significance (i.e. 1.5\% \( p = 0.06 \)). The normalization factor \( A = 0.44^{+0.05}_{-0.04} \) is 2.2\% away from the 0.33\% value applicable for RQQs. However, these two parameters together indicate that the corona component of RLQs is inconsistent with that of RQQs at a 3.1\% \( p = 9 \times 10^{-3} \) significance level. Consequently, RLQs cannot be treated as radio-quiet central engines plus jet cores in X-rays. The value of \( \Gamma_{uv} = \gamma_{uv} + \gamma_{\text{radio}} = 0.66^{+0.02}_{-0.03} \) resulting from Model III is consistent with \( \gamma \). Therefore, the physical picture of Model II is not supported, while the results of Model III are favoured. We note that the only difference between the fitting results of Model I and Model III is that in Model III there is a minute amount of jet-linked X-ray emission (\( B = 0.03^{+0.01}_{-0.00} \)). This component only deviates from zero at a 1.9\% \( p = 0.03 \) significance level and makes up \( B/(A+B) \lesssim 3 \) per cent of the total X-ray luminosity. Note that we can use \( B/(A+B) \) to assess the typical jet contribution because the luminosities are normalized to values that are near to their medians before model fitting. We thus omit the difference between Model I and Model III and focus on comparing them with Model II.

Secondly, the corresponding information criteria are listed in Table 5. For the results for all RLQs, Model III has smaller ICs (e.g. Model I and Model III and focus on comparing them with Model II. Model II, comparing \( \Delta \text{AIC} = -3.1 \) and \( \Delta \text{BIC} = -13.19 \). Therefore, it is highly unlikely that the corona component of RLQs is identical to that of RQQs. Model II is as strongly disfavoured if we compare it with Model I as well.

We plot in Fig. 10 the best-fitting Model I (blue), Model II (orange), and observational data for RLQs in the \( L_{2\text{keV}}-L_{2500\text{Å}}-L_{5\text{GHz}} \) space, in order to provide an overall geometrical impression...
Table 4. Model fitting results for RLQs and RRQs, both of which are optically selected.

| Model parameters | Sample | II: $\log L_{2500\AA} = \log \left( A L_{2500\AA} + B L_{5GHz} \right)$ | III: $\log L_{2500\AA} = \log \left( A L_{2500\AA} + B L_{5GHz} \right)$ |
|------------------|--------|-------------------------------------------------|-------------------------------------------------|
|                  | $\alpha$ | $\beta$ | $\gamma_{\text{radio}}$ | $\gamma_{\text{uv}}$ | $\gamma_{\text{radio}}$ | $\gamma_{\text{uv}}$ |
| All RLQs         | $-0.08_{-0.01}^{+0.02}$ | $0.34_{-0.02}^{+0.03}$ | $0.49_{-0.02}^{+0.03}$ | $0.49_{-0.02}^{+0.03}$ | $0.49_{-0.02}^{+0.03}$ | $0.49_{-0.02}^{+0.03}$ |
| SSRQs           | $-0.06_{-0.03}^{+0.02}$ | $0.31_{-0.02}^{+0.03}$ | $0.45_{-0.02}^{+0.03}$ | $0.45_{-0.02}^{+0.03}$ | $0.45_{-0.02}^{+0.03}$ | $0.45_{-0.02}^{+0.03}$ |
| RQQs            | $-0.14_{-0.02}^{+0.02}$ | $0.39_{-0.02}^{+0.03}$ | $0.26_{-0.02}^{+0.03}$ | $0.26_{-0.02}^{+0.03}$ | $0.26_{-0.02}^{+0.03}$ | $0.26_{-0.02}^{+0.03}$ |

Note: The luminosities of the quasars are normalized to $L_{2500\AA} = 2500$ Å units. We have fixed $\beta = 0.63$ of Model II for SSRQs and fixed $\beta$ is consistent with zero, we only show the upper bound of the 90 per cent probability interval. The fitting results for SSRQs using Model I are consistent with the corresponding results listed in table 7 of Miller et al. (2011).

The dispersion (0.29 dex at a 1σ level) of individual RLQs in Fig. 11 (right) has multiple sources. We assume typical uncertainties of 20 per cent/30 per cent/40 per cent for the radio/UV/X-ray luminosities (e.g. Miller et al. 2011), including observational uncertainties and quasar variability, the latter of which probably dominates (e.g. Gibson, Brandt & Schneider 2008; Gibson & Brandt 2012). Subtracting those effects, about 0.23 dex of residual dispersion might be attributed to unaccounted for physical processes, which is similar to the magnitude estimated for RQQs (e.g. Salvestrini et al. 2019).

### 3.2.4 The results for FSRQs and SSRQs and the amount of X-ray emission from jets

FSRQs and SSRQs are RLQs that are generally observed at relatively small and large inclination angles, respectively (e.g. Urry & Padovani 1995). If part of the X-ray luminosity is from the beamed core region of jets, the contribution of this component is expected to be larger in FSRQs than SSRQs. Indeed, their properties seem to be different as suggested in Section 3.1; FSRQs are generally more X-ray luminous than SSRQs at fixed $L_{\text{uv}}$ and $R$ (see Fig. 6).

23The same conclusion is revealed if the y-axis is instead normalized to the best-fitting Model II.
For the fitting results for FSRQs in Table 4, the parameters of Model I do not support $\Gamma_{uv} = \gamma$, while those of Model II do not support a component that is consistent with the coronae of RRQs. Model III might point to the most plausible scenario with $\Gamma_{uv} = \gamma_{uv} + \gamma_{radio} = 0.67^{+0.04}_{-0.03}$ consistent with $\gamma$. The fitting results of Model II do not support a corona component that is identical to those of RRQs ($A = 0.42^{+0.06}_{-0.05}$ versus $10^0 = 0.33^{+0.01}_{-0.01}$) and $\gamma_{radio} = 0.48^{+0.06}_{-0.04}$ departs strongly from unity. Furthermore, Model II is not favoured in comparison with Model I with $\Delta AIC = -1.21$ and $\Delta BIC = -1.21$ (see Table 5). Note that the model selection results here are not as significant as for the cases of all RLQs and FSRQs, due to a smaller sample size and lower X-ray detection fraction for SSRQs.

Benefiting from its flexibility, Model III either is selected as the best model or can be consistent with the best model for all samples. Using the results of Model III in Table 4, we now assess the importance of the jets in accounting for the X-ray luminosities of RLQs. We input $L_{2500\AA}$ and $L_{5GHz}$ as well as estimates of parameters into Model III. We quantify the fraction of jet emission for each RLQ using $f_{jet} = BL_{5GHz}^{radio}/(A_{5GHz} L_{2500\AA}^{radio} + BL_{5GHz}^{radio})$. The mean and three percentiles (10th, 50th, and 90th) of $f_{jet}$ for samples that might have a jet component are listed in Table 6, while the full distributions are plotted in Fig. 12. For SSRQs, we only list their 90th percentile, which indicates that for 90 per cent of SSRQs the jet component contributes less than 0.5 per cent of the observed nuclear X-ray emission. Note that $B/(A + B)$ is generally between the mean and median of $f_{jet}$.

The distributions of $f_{jet}$ are highly asymmetric in Fig. 12. As a consequence, the median is always smaller than the mean in Table 6. The median is probably a better statistic to assess the typical value of $f_{jet}$, which is <5 per cent for all samples. FSRQs are the group of RLQs that have the largest jet contribution. Notably, the 10th and 90th percentiles span several decades in Table 6, which indicates a large variance of $f_{jet}$ from object to object. The mean is strongly affected by a small number of RLQs that have relatively large $f_{jet}$. Less than 10 per cent of FSRQs have $f_{jet}$ ≥ 30 per cent, which manifest themselves as a long tail in the right-hand panel of Fig. 12. Thus, only in a minority of FSRQs does the jet component become important.

At fixed $L_{2500\AA}$, RLQs are generally a factor of 1.5–4 times more X-ray luminous than RRQs, depending on the radio-loudness parameter (see Fig. 6). Given our limits on $f_{jet}$, this difference is mainly caused by the difference between the coronae of RLQs and those of RRQs, not the emission from jets. Furthermore, typical FSRQs are more X-ray luminous than SSRQs at fixed $L_{2500\AA}$ and $R$ by 10–20 per cent (Fig. 6), which is only partially attributed to the jet component according to our estimation here, given that the median $f_{jet}$ is only 4.2 per cent for FSRQs. Therefore, other processes are probably involved as well (e.g. a small level of jet contribution to the...
The distributions of the optically selected RLQs on the $L_{500\text{GHz}}$–$L_{2500\text{Å}}$ plane with overlaid constant-log $R$ lines (dash–dotted) is also shown. The dashed line (orange) is orthogonal to the constant-log $R$ lines and passes through the median values of $L_{2500\text{Å}}$ and $L_{500\text{GHz}}$ of the sample. The profile (side view) of Model II at the position of the dashed line is shown in the right-hand panel. Right: A ‘side view’ of Fig. 10, where the plane is filled by colours that represent the difference between best-fit Model I and Model II. The position of the dashed line is shown in the right-hand panel. Right: A ‘side view’ of Fig. 10, where the plane is filled by colours that represent the difference between best-fit Model I and Model II. The position of the dashed line is shown in the right-hand panel.

**Table 6.** Mean and percentiles of $f_{\text{jet}}$ (in units of per cent) for different RLQ samples. $f_{\text{jet}}$ represents the fraction of the X-ray emission from jets.

| Sample     | Mean (per cent) | Percentile (per cent) | 10th | 50th (median) | 90th |
|------------|----------------|-----------------------|------|---------------|------|
| All RLQs   | 5.2            | 0.3                   | 2.3  |               | 14.4 |
| FSRQs      | 9.5            | 0.6                   | 4.2  |               | 27.5 |
| SSRQs$^a$  | –              | –                     | –    |               | 5.9  |

*Note. $^a$We only list the 90th percentile for SSRQs, the X-ray luminosities of which contain a negligible jet component.*

**Figure 12.** The distributions of $f_{\text{jet}}$ for all RLQs and FSRQs. The height of the highest bin is fixed to be identical in the two panels. In both cases, $f_{\text{jet}}$ is clustered around very small values, while FSRQs have a long tail that extends to $f_{\text{jet}} \approx 80$ per cent.
independent relations such that \( L_x \propto R_	ext{radio}^{\gamma} \) and \( L_x \propto L_{\text{UV}}^{\gamma+\gamma^{\prime}} \).

Therefore, \( L_x \) depends primarily on \( L_{\text{UV}} \) and \( R \), while its relation with \( L_{\text{radio}} \) is a by-product. Miller et al. (2011) notice that \( L_x/L_{\text{radio}} \) RQQ has a stronger dependence on \( R \) than \( L_{\text{radio}} \) (especially for SSRQs), which is consistent with the idea that \( R \) is the more meaningful parameter for describing the corona–jet connection of RLQs. Consequently, the index of the X-ray-optical/UV relation for the corona is universal among RLQs and RQQs (i.e. \( \Gamma_{\text{UV}} = \gamma_{\text{radio}} + \gamma_{\text{opt}} = \gamma \)), which is now a direct result of separated correlation analysis of two quasar populations.

More importantly, due to the above exposed statistical independence, another process is probably in control of the corona–jet connection in RLQs aside from the disc–corona interaction that is at work for both RLQs and RQQs. Following Section 3.2.1, the discussion is continued in the context of equation (7) where \( A \) is a function of \( R \). We plot \( A \) of SSRQs divided by that of RQQs against \( R \) in Fig. 14. The scattered individual data points together with binned data points (separated by the 33rd and 66th \( \log R \) percentiles of SSRQs) are shown. We calculate the generalized Spearman’s rank correlation coefficient of the individual points in Fig. 14, using the Astronomy Survival Analysis package (Lavalley, Spearman’s rank correlation coefficient of the individual points in R together with binned data points (separated by the 33rd and 66th \( \log R \)).

The correlation is strongly supported with a \( p \)-value of \( \approx 1 \times 10^{-43} \). The solid blue line (with shaded region showing estimated uncertainties) in Fig. 14 is a projection of Model I in Table 4 for SSRQs, and not a new fitting of the individual data points. The normalization factor of RQQs (i.e. \( A_{\text{RQQ}} \)) is at unity (dashed black line), where the shaded region represents its small uncertainty. We are unaware of any established radio dependence of the \( L_x-L_{\text{UV}} \) relation for RQQs (e.g. Steffen et al. 2006; Just et al. 2007; Lusso et al. 2010). More importantly, the radio luminosity of RQQs might not be dominated by the synchrotron emission from quasar jets (e.g. Kellermann et al. 2016; Panessa et al. 2019). After subtracting the effects of measurement errors and quasar variability, the physical intrinsic scatter of the \( L_x-L_{\text{UV}} \) relation is about 0.2 dex (e.g. Lusso & Risaliti 2016; Chiaraluce et al. 2018; Salvestrini et al. 2019). There is thus limited error budget for additional physical processes involving radio luminosity (or radio-loudness parameter) to play an important role in RQQs as in RLQs. We show the 59 RQQs from Laor & Behar (2008) as black symbols, where they are also grouped into two \( R \) bins. These PG quasars are consistent with the horizontal line and do not show an \( R \) dependence.

The dashed and solid lines are satisfyingly consistent with each other at \( R \approx 10 \); this agreement has not been enforced but arises entirely from the independent model fits. Consequently, if we express the X-ray luminosity of RQQs as

\[
L_x = A_{\text{RQQ}} L_{\text{UV}}^{\gamma'},
\]

the X-ray luminosity of the corona of RLQs can be written as

\[
L_x = A_{\text{RLQ}} (R/10)^{\gamma} L_{\text{UV}}^{\gamma'}.
\]

The good match between \( A_{\text{RQQ}} \) and \( A_{\text{RLQ}} \) around \( R \approx 10 \) (instead of some much smaller radio-loudness parameter) in Fig. 14 prevents extension of the corona-jet connection of RLQs into the radio-quiet regime.

It is also tempting to attempt to connect RQQs and RLQs with a single function that contains a ‘jet component,’ which grows smoothly from being negligible at \( R \lesssim 10 \) to being significant at \( R \approx 10 \). However, this hypothetical component unavoidably has a strong dependence on optical/UV emission (e.g. Fig. 8) and a relatively weak dependence on radio emission (e.g. Fig. 13), in contrast with expectations for a ‘jet component.’ We thus suggest that a break at \( R \approx 10 \) is probably required, which points to an intrinsic difference between the innermost accretion flows of RLQs and RQQs. Therefore, the radio-loudness parameter of quasars is more fundamental than simply empirical. Future works focusing on the X-ray properties of quasars with \( 0 \leq \log R \leq 2 \) might reveal the exact transition clearly.

4 DISCUSSION

4.1 Comparison with literature results

Given that we find the corona is still responsible for most of the X-ray emission of RLQs (as for RQQs), it is of value to compare with literature results on the spectral, imaging, and timing properties of radio-loud AGNs in X-rays to assess overall consistency.
4.1.1 X-ray spectral properties

X-ray spectral analyses of radio-loud AGNs, except for some FSRQs, using high-quality X-ray data rarely reveal a distinct jet component. For example, the X-ray spectra of BLRGs like 3C 382 (e.g. Gliozzi et al. 2007; Ballantyne et al. 2014; Ursini et al. 2018), PKS 2251 + 11 (e.g. Ronchini et al. 2019), 3C 120 (e.g. Rani & Stalin 2018), and 3C 390.3 (e.g. Sambruna et al. 2009; Lohfink et al. 2015) are consistent with being disc/corona-related. Specifically, their observed primary power law, reflected Fe Kα line (and Compton hump), and soft excess are all established features common to radio-quiet AGNs as well. Also, importantly, those studies utilizing NuSTAR data in the hard X-rays generally find a high-energy cut-off at ~100 keV (e.g. Ballantyne et al. 2014; Lohfink et al. 2015; Rani & Stalin 2018), signifying a thermal Comptonization process of X-ray continuum production as for radio-quiet Seyfert galaxies. Lohfink et al. (2017) analysed the Swift/NuSTAR X-ray spectra of an SSRQ (4C 74.26); no sign of jet emission but a high-energy cut-off of 183 +31 −31 keV was revealed.

Note that a jet-dominated spectrum usually shows an ‘upturn’ (in SED representation) in hard X-rays, extending to MeV energies (and sometimes beyond), instead of a ‘rollover’. Indeed, the upturn is present in those FSRQs where the jet emission dominates (e.g. Paliya et al. 2016; Ghisellini et al. 2019) or has a significant contribution (e.g. Grandi & Palumbo 2004; Madsen et al. 2015) in X-rays. However, those objects with strongly beamed jet X-ray emission are only a small portion of their parent population (see Section 2.1.4). Some sample-based archival X-ray spectral studies finding flat X-ray power-law continua for RLQs relative to those of RQQs (e.g. Wilkes & Elvis 1987; Lawson & Turner 1997; Reeves et al. 1997; Page et al. 2005) utilize heterogeneous RLQ samples, dominated (at the 60–100 per cent level) by flat-spectrum RLQs, and potentially extreme objects. Thus, these samples cannot be reliably used to constrain the X-ray spectral properties of general RLQs, the focus of this work. Generally, once FSRQs are excluded, the X-ray spectra of the remaining BLRGs, narrow-line radio galaxies, and SSRQs are similar to those of radio-quiet AGNs (e.g. Lawson et al. 1992; Galbiati et al. 2005; Grandi et al. 2006).  

Gupta et al. (2018) investigated luminous radio galaxies and their radio-quiet counterparts with comparable Eddington ratios and black hole masses. The radio galaxies were found to be, on average, a factor of ~2 more luminous in hard X-rays than the radio-quiet AGNs, while their power-law spectral slopes and high-energy breaks were similar. The authors concluded that the X-ray emission in both samples is produced by a common mechanism. However, the X-ray production efficiency is apparently higher for the radio-loud group, which is consistent with our suggestion of a corona–jet connection (e.g. Section 3.3). Gupta, Sikora & Rusinek (2020) extended the comparison and showed that Type 1 AGNs are not X-ray louder than Type 2 AGNs, within both radio-loud and radio-quiet groups. Therefore, the dependence of observed X-ray

\[ \rho = 0.467 \]
\[ p = 1 \times 10^{-43} \]

Figure 14: The dependence of \( A \) on \( \log R \) for RQQs and RLQs. \( A \) is the normalization factor of the coronal component (equation 7). A vertical line (dotted black) has been used to separate RLQs and RQQs. The small dots and downward arrows in blue are X-ray detected and non-detected SSRQs, respectively. The generalized Spearman rank correlation coefficient (\( \rho \)) and corresponding \( p \)-value are given in the lower-right corner. These SSRQs are further grouped into three \( R \) bins of comparable sizes, where medians with uncertainty estimates are calculated (large blue dots with error bars). The RQQs from Laor & Behar (2008) are small squares and leftward arrows in black, while binned data for those RQQs are large squares. A vertical line (dotted black) line at unity, as no strong dependence on \( \log R \) is reported in the literature or supported by the RQQ sample of Laor & Behar (2008). Note that the solid blue line is derived from the fitting results for SSRQs using Model I (see Table 4). The shaded regions represent 1\( \sigma \) uncertainties, which are small for the case of RQQs. Note that the good match between dashed and solid lines at \( \log R = 1 \) is not an enforced prerequisite but a direct result of the model fitting.

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25 The reflection features of BLRGs in statistical samples are known to be weaker than those of radio-quiet Seyfert galaxies, which can be attributed to mechanisms other than the dilution by continuum X-ray emission from jets (e.g. Eracleous et al. 2000).

26 Note that even if the X-ray spectra of general RLQs are somewhat flatter than those of RQQs, this would not necessarily demonstrate that the X-ray emission is jet linked (e.g. Laor et al. 1997).

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luminosity on viewing angle seems weak, inconsistent with beamined jet X-ray emission.

4.1.2 X-ray imaging properties

The *Chandra* observatory with sub-arcsec angular resolution has detected kpc-scale X-ray jets from many RLQs (e.g. Harris & Krawczynski 2006), which might contribute to the X-ray fluxes we use (see Section 2.1.2). The observed X-ray luminosities of these extended jets are generally only a few percent those of the cores (e.g. Marshall et al. 2005, 2018), consistent with the amount of jet contribution we estimated in Section 3.2.4.

Imaging the nuclear region of quasars in X-rays is currently limited to indirect methods (e.g. gravitational lensing). The sizes of the nuclear X-ray emission regions derived from gravitational-lensing studies seem to be systematically larger in RLQs than in RQQs, for a given SMBH mass, although the source statistics are presently very limited (e.g. Burak Dogruel et al. 2019). Therefore, we might not expect the coronae of RLQs and RQQs to have the same physical properties, the former of which could be larger in units of black hole radius.

4.1.3 X-ray timing properties

Long-term timing studies are generally more observationally extensive than single-epoch spectral studies of AGNs in X-rays, and thus are sparse for general radio-loud AGNs. Leighly et al. (1997) investigated the 9-month X-ray variability of the BLRG 3C 390.3 and found its fractional amplitude of variability is about 33 per cent. This amount of variability is not apparently different from those of radio-quiet Seyfert galaxies given the luminosity of 3C 390.3 and the time-scales this study covers. Furthermore, the hour-to-year power spectra of several BLRGs (e.g. 3C 120, Marshall et al. 2009; 3C 390.3, Gliozzi et al. 2009; 3C 111, Chatterjee et al. 2011) are also similar to those of radio-quiet Seyfert galaxies.

The X-ray variability properties of RLQs are poorly constrained for systematically derived samples as well, let alone for subsamples with established radio slopes. Sambruna (1997) investigated the soft X-ray variability of a few FSRQs on month-to-year time-scales (≥6 epochs) and found a typical variability amplitude of 10–30 per cent, roughly consistent with that of RQQs (e.g. Gibson & Brandt 2012). Gibson & Brandt (2012) studied the X-ray variability of about 20 non-BAL RLQs and found suggestive evidence that they are less variable than RQQs. However, the observations of these RLQs generally have only 2–3 epochs. Future X-ray variability studies utilizing RLQ samples with measured radio spectral slopes and observations with more epochs might improve our understanding of the X-ray variability properties of RLQs and shed further light on the origin of their X-ray emission.

4.2 A jet line for AGNs

In this section, we investigate further the connection between the disc/corona and jets from the perspective of the $\alpha_{\text{ox}} - L_{\text{ox}}$ relation. Fig. 15 shows the transposed $\alpha_{\text{ox}} - L_{\text{ox}}$ plot for RQQs and SSRQs, which is no more than an alternate representation of Fig. 8 (bottom). However, we gain new insights from it by analogy with BHXRBs.

We interpret Fig. 15 as a quasar-version of the hardness–intensity diagram (HID). The HID is frequently used in BHXRB studies. The $y$-axis serves as a proxy for the accretion rate of the black hole, while the $x$-axis represents the relative contributions of the thermal (at 2500 Å) and power-law (at 2 keV) components that are radiated from the accretion disc and corona, respectively. As discussed in detail earlier, a significant jet contribution in X-rays for SSRQs is highly unlikely, legitimizing our approach. Note that the data points in an HID for BHXRBs often represent the evolutionary stages of a single black hole, which in Fig. 15 are represented by an ensemble of black holes that span ranges in accretion rate, ‘hardness ratio’, and jet power.

In Fig. 15, the dashed line (black) represents the $\alpha_{\text{ox}} - L_{\text{ox}}$ relation for RQQs, which was transformed from the $L_{\text{ox}} - L_{\text{uv}}$ relation in Table 4 (bottom row) and Fig. 4. For SSRQs, we utilize the fitting results of Model I in Table 4 to derive their $\alpha_{\text{ox}} - L_{\text{ox}}$ relation (light blue) at fixed $\log R = 2.69$, which is the median radio-loudness parameter for SSRQs in our sample. The dashed and solid lines are parallel to each other, as a consequence of $\Gamma_{\text{uv}} \approx \gamma$. Open squares and filled circles are RQQs from Laor & Behar (2008) and SSRQs, respectively. SSRQs are further colour-coded by their radio-loudness parameters. Among RQQs, more luminous objects have steeper $\alpha_{\text{ox}}$, and hence a smaller power-law fraction. SSRQs to first approximation follow this trend as well. However, the radio-loudness parameter also plays an important role such that those more radio-loud objects have flatter $\alpha_{\text{ox}}$ at given $L_{\text{ox}}$, which is a consequence of $A_{\text{RLQ}} \approx A_{\text{SSRQ}} (R/10)^{\gamma'}$ (as per equations 10 and 11). To summarize, as shown in Fig. 15:

(i) The most radio-loud SSRQs (say, with $\log R = 4$) lie on a line near the right edge of the data points that is parallel to the $\alpha_{\text{ox}} - L_{\text{ox}}$ relation for RQQs.
(ii) Horizontally shifting such a line leftward, it passes through SSRQs with generally decreasing $R$.
(iii) Finally, the line arrives at the region populated by RQQs.

Radio observations of BHXRBs suggest the existence of a critical line in the HID such that jets are active on the right-hand side of this line, but seem to be quenched once a BHXRB moves leftward and passes the line (e.g. Fender et al. 2004). Fig. 15 might reveal a similar jet line for AGNs, which is approximately the $\alpha_{\text{ox}} - L_{\text{ox}}$ relation for RQQs. The jet line for BHXRBs seems to be tilted in a way such that the quenching happens at a larger hardness ratio when the luminosity is lower (e.g. Fender, Homan & Belloni 2009), similar to the alignment of the black-dashed line in Fig. 15.

The jet line adds to the mounting evidence for the idea that black hole accretion/jet physics is largely scale-invariant (e.g. Merloni et al. 2003; McHardy et al. 2006; Arcodia et al. 2020). RLQs and RQQs are likely scaled-up versions of BHXRBs in different accretion states (e.g. Nipoti, Blitzell & Binney 2005; Körding, Jester & Fender 2006; Sobolewska, Gierliński & Siemiginowska 2009).

4.3 Origin of radio-loudness

4.3.1 The overall corona–disc–jet relation

We show in Fig. 16 the SSRQs in the $L_{\text{radio}} - L_{\text{ox}}$ plane, reorienting the discussion from, hitherto, the nature of X-ray emission to the origin of powerful radio jets. The symbol colours represent the X-ray luminosities divided by those of RQQs at given matched $L_{\text{ox}}$,
Corona–disc–jet connection in RLQs

Figure 15. The distributions of RQQs (open squares) and SSRQs (solid circles) in the $L_{2500\text{\AA}}$–$\alpha_{\text{ox}}$ plane. The RQQs are from Laor & Behar (2008). SSRQs are colour-coded according to their radio-loudness parameters (following the colour-bar on the right-hand side). The dashed (black) line is the $\alpha_{\text{ox}}$–$L_{\text{uv}}$ relation for RQQs, derived from the $L_x$–$L_{\text{uv}}$ relation in Fig. 4. The solid (light blue) line is derived from the fitting results for SSRQs using Model I (see Table 4), fixed at the median radio-loudness ($\log R = 2.69$). We interpret this plot as an HID for quasars, in analogy to that for BHXRBs. We propose that the $\alpha_{\text{ox}}$–$L_{\text{uv}}$ relation for RQQs corresponds to an approximate ‘jet line’ for quasars; the quasars lying well to the right of the jet line have powerful relativistic jets, which are quenched for quasars that are ‘on’ or to the left of the jet line.

Figure 16. The SSRQs of this paper and RQQs of Laor & Behar (2008) in the $L_{\text{radio}}$–$L_{\text{uv}}$ plane. The symbol colours represent observed X-ray luminosities divided by those expected for RQQs at given matched optical/UV luminosity, $L_x/L_{x,RQQ}$, as indicated by the colour-bar on the right-hand side. X-ray non-detected SSRQs (11.3 per cent) are not shown, the distribution of which is consistent with the detections (see Fig. 14). Radio non-detected RQQs are shown as downward arrows. Four lines indicate $\log R = 1$–$4$, from light to dark. There is an apparent correlation between $L_x/L_{x,RQQ}$ and $R$ for SSRQs (cf. Fig. 6).
i.e. $L_{\text{r}}/L_{\alpha,\text{RQQ}}$, utilizing the $L_{\text{r}}-L_{\alpha}$ relation in Fig. 4. The X-ray non-detections (11.3 per cent) are omitted in Fig. 16, the distribution of which is similar to that of the detections for SSRQs (cf. Fig. 14); omitting non-detections will not bias the result. The 59 RQQs of Laor & Behar (2008) are also shown for comparison, where radio non-detected objects are represented by downward arrows. Apparently, RQQs follow a different track in Fig. 16 than SSRQs such that typical RQQs are about 3 orders of magnitude less radio-luminous than RLQs at a given accretion rate (e.g. Rawlings 1994). Whether the dichotomy between RLQs and RQQs is real or not has long been debated (e.g. Kellermann et al. 1989, 2016; Ivezic et al. 2002; Cirasuolo et al. 2003; Baloković et al. 2012; Condon et al. 2013). The results of this paper (e.g. Fig. 14) support the idea that RLQs and RQQs are intrinsically different objects, regardless of the bimodality of the distribution of $R$ (e.g. Padovani 2016). The accretion flow for RQQs is probably in a state that is not compatible with launching powerful relativistic jets.

The most prominent relation for SSRQs in Fig. 16 is that between $L_{\text{radio}}$ and $L_{\alpha}$, which is not one of the main topics of this paper but reveals probably no less important physics (e.g. Serjeant et al. 1998; van Velzen & Falcke 2013). The $L_{\text{radio}}-L_{\alpha}$ relation is expected from the near-linear correlation between the radiative powers of the outflowing jets and the infalling accretion disc for RLQs (e.g. Ghisellini et al. 2014), supporting a dependence of the jet power on accretion rate (e.g. Rawlings & Saunders 1991). Therefore, in addition to the corona-jet connection investigated in this work and disc–corona interplay, RLQs also feature a disc–jet connection. For the first time, not only has the overall corona–disc–jet relationship of RLQs been revealed, but also the number of responsible physical processes has been determined. In short, the corona–disc–jet relationship is three-fold such that any two of these structures are physically linked. Furthermore, the underlying drivers for these three relations are independent, and none of these three relations is simply a side effect of the other two. For example, we found that $R$ is a more useful property to consider than $L_{\text{radio}}$ when the corona–jet connection is examined in Section 3.3, which now has a physical reason. Specifically, the radio luminosity is affected by both the disc–jet and corona–jet connections; using $R$ minimizes the intrusion of the former into studies of the latter. Fig. 16 demonstrates more clearly the independence between the disc–jet and corona–jet connections. There is an apparent correspondence between $R$ and $L_{\text{r}}/L_{\alpha,\text{RQQ}}$ (cf. Fig. 6) such that the symbol-colour gradient appears largely perpendicular to the constant-$\log R$ lines. From Fig. 16, it is strongly suggested that the spread of $R$ within the RLQ group is directly caused by small-scale processes in the vicinity of SMBHs (relating black hole spin, Eddington ratio, and magnetic field) that, at the same time, affect the corona.

4.3.2 The role of black hole spin

Models for the launching of quasar jets need to explain our corona-jet connection in RLQs as well. The role of rapidly spinning black holes can thereby be constrained, which are often taken to be an important ingredient for jet launching (e.g. Blandford et al. 2019). At first sight, it seems plausible that since higher prograde black hole spins increase both the jet-production efficiency and radiative efficiency of the inner accretion flow, a correlation between $R$ and $L_{\text{r}}/L_{\alpha,\text{RQQ}}$ may be naturally produced (cf. Figs 6 and 16). However, the majority of spin parameters resulting from X-ray Fe Kα modeling of SMBHs are $\gtrsim0.9$ (e.g. Reynolds 2019, cf. Laor 2019), even for radio-quiet Seyfert galaxies. Unless some mechanism can largely decouple black hole spin and the corona (for only) radio-quiet AGNs, those RQQs with the highest black hole spins are then expected to be as X-ray luminous as their most radio-loud counterparts. In Fig. 17, we show the cumulative distribution functions of $L_{\text{r}}/L_{\alpha,\text{RQQ}}$ for our SSRQs and the RQQ sample of Lusso & Risaliti (2016). Apparently, there are almost no corresponding RQQs to the top 15 per cent of SSRQs (i.e. the most radio-loud group) in $L_{\text{r}}/L_{\alpha,\text{RQQ}}$. If we instead use a subset of SSRQs with $R > 1000$ (red curve in Fig. 17), the value can be relaxed to the top 30 per cent.

Considering a worst-case scenario where the X-ray Fe Kα method significantly overestimates the spin parameter of radio-quiet AGNs and all RQQs have slowly rotating black holes, a group of X-ray under luminous RLQs is expected since black holes with high retrograde spin parameters can likely launch relativistic jets as well (e.g. Tchekhovskoy & McKinney 2012), the radiative efficiency of which will be lower than those of RQQs. However, no SSRQ extends beyond the 15 per cent of RQQs at the lower end in $L_{\text{r}}/L_{\alpha,\text{RQQ}}$ (see Fig. 17).

A decisive role of black hole spin is also inconsistent with the jet line for AGNs in Section 4.2. Indeed, a BHXRB can be in both jet-active and jet-inactive states without a significant change of the black hole spin, a conclusion which by analogy probably applies to SMBHs as well.

Therefore, the corona-jet connection supports the idea that rapid BH spin is a necessary but not sufficient condition for the development of jets, which likely requires a second, independent factor (e.g. Blandford et al. 2019).

Figure 17. The cumulative distribution functions of $L_{\text{r}}/L_{\alpha,\text{RQQ}}$ for RQQs (from Lusso & Risaliti 2016; black), SSRQs (blue), and a subset of SSRQs with $R > 1000$ (red). Almost no RQQs are as X-ray luminous as the top 15 per cent of all SSRQs or the top 30 per cent of SSRQs with $R > 1000$. Similarly, almost no SSRQs are less X-ray luminous than the bottom 15 per cent of RQQs.

28RQQs share only a common disc–corona interplay with RLQs.

29We have already shown the independence between the corona–jet connection and disc–corona interplay in Section 3.3.

30Using the Sołtan (1982) argument, constraints on the accretion efficiency may also imply that most RQQs have rapidly spinning SMBHs (e.g. Elvis, Risaliti & Zamorani 2002; Yu & Tremaine 2002; Shankar et al. 2020). However, these Sołtan-argument constraints still have a sizeable variance owing to the uncertainties of several utilized parameters (e.g. Brandt & Alexander 2015; Comastri et al. 2015).
4.3.3 The role of magnetic flux/topology

We suggest that the magnetic flux threading the SMBH is likely the key physical factor controlling the radio-loudness of AGNs (e.g. Sikora & Begelman 2013). Merloni & Fabian (2001, 2002) discussed the possibility of a connection between the corona and relativistic jets in the most direct form such that the former contains the magnetic fields required for the launching of the latter. Therefore, only when these magnetically dominated coronae are sufficiently strong can jets be launched from them, and a possible corona-jet connection is expected. Indeed, our results support the idea that the activity of the corona is at least a tracer for the magnetic flux responsible for the launching of relativistic jets of RLQs. Note that the topology of the magnetic field might play a role in determining accretion states and jet launching as well (e.g. Livio, Pringle & King 2003; Dexter et al. 2014).

Furthermore, the inner accretion flows of RLQs may be a magnetically arrested disc (MAD; e.g. Igumenshchev, Narayan & Abramowicz 2003; Narayan, Igumenshchev & Abramowicz 2003), in contrast with the standard and normal evolution (SANE; e.g. Narayan et al. 2012) scenario for RQQs. In the MAD state, the magnetic flux threading the black hole is regulated by the accretion rate (e.g. Tchekhovskoy, McKinney & Narayan 2012; Zamaninasab et al. 2014), perhaps thereby naturally producing a $L_{\text{radio}}$–$L_{\text{soft}}$ relation for RLQs (see Fig. 16). As a consequence, to explain the corona–jet connection established in this work, we need another factor that can independently affect the magnetic flux, in addition to the accretion rate. We speculate that the thickness of the MAD is a good candidate since a thicker disc is able to support a stronger magnetic field (e.g. Tchekhovskoy & McKinney 2012). The MAD disc contains optically thick accretion streams that are rapidly spiralling toward the black hole and magnetically dominated low-density voids that can contribute to hard X-ray emission via the inverse-Compton scattering process (i.e. behaving like coronae; e.g. Igumenshchev 2008). The magnetospheric radius (i.e. size of the MAD disc) also positively depends on the disc thickness (e.g. Xie & Zdziarski 2019). Therefore, a thicker disc can launch more powerful jets (e.g. Tchekhovskoy & McKinney 2012) as well as produce an enlarged X-ray emitting corona, producing the corona–jet connection. Note that the disc thickness might be affected by other more fundamental parameters (e.g. the Eddington ratio).

5 SUMMARY AND FUTURE PROSPECTS

5.1 The main results of this paper

In this paper, we construct a large uniform RLQ sample with high-quality multi-wavelength coverage (see Section 2). We investigate the X-ray–optical/UV–radio relation and the nature of the X-ray emission of RLQs. The main results are summarized as follows:

(i) The X-ray luminosities of RLQs are systematically larger than those of appropriately matched RQQs and depend on $L_{\text{opt}}$, $L_{\text{radio}}$ (or $R$), and radio spectral index. The slope of the $L_{\text{x}}$–$L_{\text{opt}}$ relation for SSRQs is consistent with that for RQQs to within ≈ 3 per cent $(0.61^{+0.04}_{-0.04}$ versus $0.63^{+0.02}_{-0.02}$), supporting the idea that SSRQ X-ray emission is mainly from the corona instead of the jets. The corresponding intercept for SSRQs is always larger than that for RQQs (by factors up to ≈3) and increases with $R$, suggesting a coordination between the activities of the jets and corona.

(ii) We propose that the $L_{\text{x}}$–$L_{\text{opt}}$ relation for RLQs approximates a jet line for AGNs, drawing an analogy with BHXBs. See Section 4.2.

(iii) We perform model fitting and formal model selection in Section 3.2. The models and methods are described in Sections 3.2.1 and 3.2.2, respectively. In the model selection for all RLQs, a model with a strong jet X-ray contribution is ruled out. The preferred models either attribute all X-ray emission to the corona or contain only a small amount of jet X-ray emission. See Section 3.2.3.

(iv) For SSRQs and FSRQs considered as groups, a model with a strong jet contribution to the X-ray emission is not favoured either. The typical jet contribution for SSRQs is consistent with zero, again indicating that the corona is the dominant X-ray emitting structure. The observed X-rays from FSRQs might have a contribution from the jets, which is, however, only significant for ≲ 10 per cent of FSRQs. See Section 3.2.4.

(v) We propose that the $L_{\text{x}}$–$L_{\text{opt}}$ relation for RQQs approximates a jet line for AGNs, drawing an analogy with BHXBs. See Section 4.2.

(vi) RLQs feature corona-jet, disc-corona, and disc-jet connections, each of which seems to be driven by a distinct physical process. The magnetic flux threading the SMBH instead of the black hole spin is most likely controlling the jet-launching process of RLQs. See Section 4.3.

Perhaps the most important result of this paper is that the jets generally contribute much less to the X-ray emission than was previously thought. The corona-jet connection and other results are then unavoidable corollaries. Our modeling results do allow to mimic the most modest X-ray emission to arise from the jets in general, as is expected on basic physical grounds and also sometimes observed via X-ray imaging studies (see Section 4.1.2). However, aside from a minority of FSRQs, this jet-linked X-ray emission generally appears secondary relative to that from the corona.

5.2 Future work

Many lines of study that extend our results can follow as future work. First, as mentioned at the end of Section 3.3, the apparent break at $R \approx 10$ needs further investigation, possibly with a large sample of $0 \leq \log R \leq 2$ quasars. Secondly, X-ray spectral analyses for a sample of SSRQs along a sequence of increasing $L_{\text{x}}/L_{\text{BHO}}$ (or $R$) might reveal how the corona changes, following the increasing production efficiency of jets. Thirdly, in addition to the viewing-angle based unified model, an evolutionary aspect of the AGN phenomenon is likely essential as well (e.g. Kinknitz et al. 2019). The identification of a jet line makes Fig. 15 a useful diagnostic for accretion states of various AGN populations. For example, at least some weak-line quasars and BAL quasars are intrinsically X-ray weak (e.g. Leighty et al. 2007; Luo et al. 2014), thus perhaps representing different states than normal quasars. Fourthly, one still-missing piece of the
jigsaw for the X-ray properties of RLQs is systematic sample-based studies of their X-ray variability. It would be valuable to compare RQQs and RLQs (with established $\alpha_r$ values) as well as AGNs and BHXRBs in this regard. Finally, the total radio luminosity we use traces the time-averaged jet power over perhaps up to $\sim 10^7$ yr, while the X-ray luminosity is a more instantaneous tracer of the current activity of the corona. Therefore, the corona–jet connection we find is probably subject to a delay and variability induced ‘smearing’ already. We might anticipate a closer correlation through long-term radio/X-ray variability monitoring of individual RLQs, in particular the high-frequency radio emission that is from regions closer to (or even co-spatial with) the X-ray emitting corona and has shorter delays.

These future projects will benefit from ongoing and scheduled multi-wavelength sky surveys, especially in the radio bands that are witnessing a resurgence (e.g. Norris 2017). The eROSITA telescope (Merloni et al. 2012) and Large Synoptic Survey Telescope (Ivezić et al. 2019) will provide copious time-domain X-ray and IR/optical/UV data that can advance our understanding of the variability properties of AGNs.

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SUPPORTING INFORMATION

Supplementary data are available at MNRAS online.

Table 2. Properties of optically selected RLQs utilized in the paper, in ascending order of RA.

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APPENDIX A: THE FIXED PARAMETERS IN MODEL FITTING

We fix $\gamma_{\text{radio}} = 1$ for Model III in Table 4 to have a better constraint on the X-ray contribution from the jets, which is one of our scientific goals. This treatment is similar to that of Browne & Murphy (1987). The $BL_{5000 \text{GHz}}^{\text{radio}}$ term of Model III represents the X-ray luminosity from the core region of the quasar jets. When it makes up a small portion of the total emission, the parameters $B$ and $\gamma_{\text{radio}}$ can only be loosely constrained. The fitting results in the case where no parameter of Model III is fixed are listed in Table A1. The maximum-likelihood estimates of $\gamma_{\text{radio}}$ are $0.92^{+0.32}_{-0.32}$ and $1.22^{+0.34}_{-0.34}$ for all RLQs and FSRQs, which are close to unity. The quoted error bars indicate $1\sigma$ uncertainties. The fitting results of Zamorani (1984) and Worrall et al. (1987) also suggest that there is a linear correlation between the radio and X-ray luminosities for the jet component. Miller et al. (2011) prefer a scenario where the excess X-ray emission of RLQs relative to RQQs is jet-linked, and this jet-linked X-ray emission is beamed with a smaller bulk Lorentz factor than that of the radio emission, which suggests $\gamma_{\text{radio}} < 1$. However, FSRQs are more X-ray luminous than SSRQs at given $L_{\text{radio}}$ and $R$ (see Fig. 6), which is inconsistent with the idea that the jet-linked X-ray emission has less anisotropy than the radio emission. Note that fixing $\gamma_{\text{radio}} = 1$ does not affect the result that the jet component is a very minor term but allows for an estimate of $B$ with smaller uncertainty.

**Table A1.** The fitting results using Model III with all parameters allowed to vary.

| Sample | III: $log L_{2 keV} = \log \left( A L_{5000 \text{GHz}}^{\text{radio}} B L_{5000 \text{GHz}}^{\text{radio}} \right) / L_{2500 \text{Å}}^{\text{radio} \text{B}}$ | $\gamma_{\text{uv}}$ | $\gamma_{\text{radio}}$ |
|---|---|---|---|
| All RLQs | $0.75^{+0.01}_{-0.20}$ | $0.03^{+0.19}_{-0.01}$ | $0.92^{+0.15}_{-0.32}$ |
| FSRQs | $0.77^{+0.03}_{-0.14}$ | $0.03^{+0.12}_{-0.01}$ | $1.26^{+0.34}_{-0.34}$ |
| SSRQs | $0.32^{+0.13}_{-0.07}$ | $0.35^{+0.06}_{-0.11}$ | $0.89^{+0.18}_{-0.24}$ |

The fitting results of Model III with all parameters set free to vary.

| Sample | II: $log L_{2 keV} = \log \left( A L_{5000 \text{GHz}}^{\text{radio}} + B L_{5000 \text{GHz}}^{\text{radio}} \right) / L_{2500 \text{Å}}^{\text{radio} \text{B}}$ | $\gamma_{\text{uv}}$ | $\gamma_{\text{radio}}$ |
|---|---|---|---|
| SSRQs | $0.23^{+0.07}_{-0.04}$ | $0.39^{+0.03}_{-0.06}$ | $1.03^{+0.09}_{-0.15}$ |

The fitting for SSRQs in Table A1 is unphysical. First, $A \leq B$ would suggest that the jets are equal to or more important than the corona in explaining the X-ray luminosities of SSRQs, which is in contrast with other samples. In fact, we expect much less contribution from the jets in SSRQs than in FSRQs. Secondly, the value of $\Gamma_{\text{uv}} = \gamma_{\text{uv}} + \gamma_{\text{radio}} = 1.01^{+0.15}_{-0.25}$ is not even close to $\gamma$. Model II has similar issues when it is applied to SSRQs. The fitting results using Model II with all four free parameters are listed in Table A2. They are non-physical for the same reasons as the case of Model III. These issues with Model II and Model III (without fixing parameters) already suggest that they are not appropriate models for SSRQs. To make a meaningful comparison between a model that invokes a distinct jet component and the model attributing X-ray luminosity to the corona, $\gamma_{\text{uv}}$ of Model II is fixed to 0.63 in Table 4.

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