The Nature of the X-ray Emission and Innermost Accretion Regions of Typical Radio-Loud Quasars

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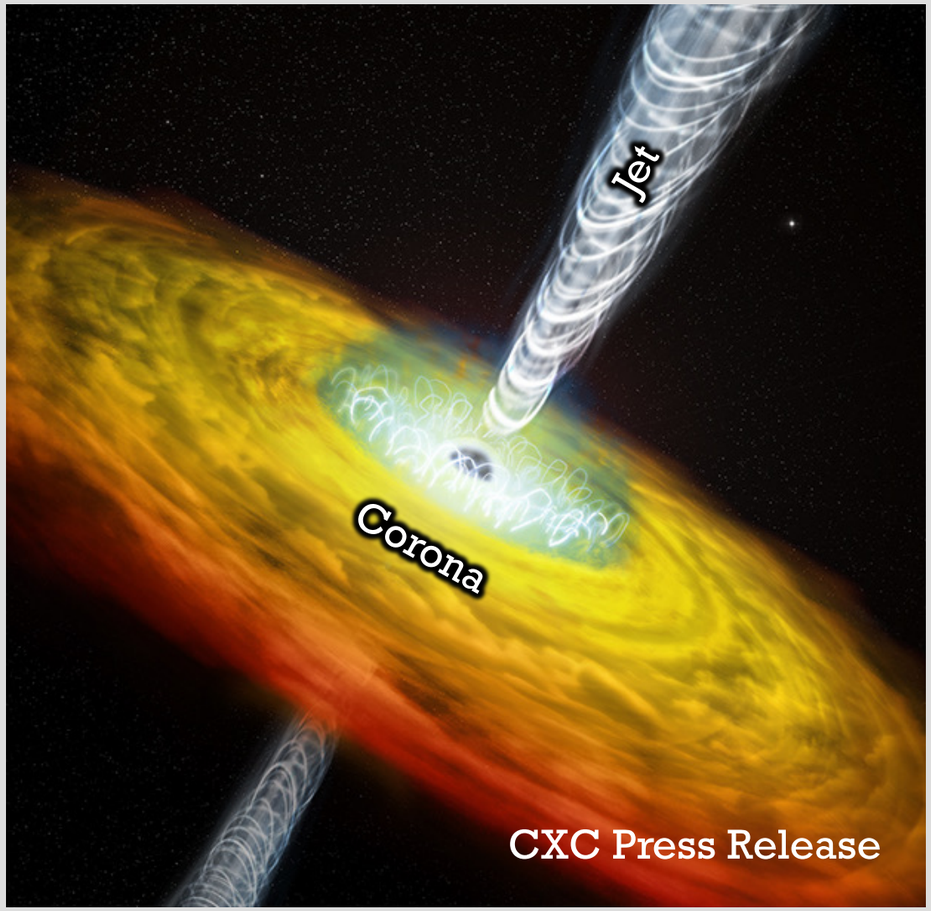
Since the 1980's, standard picture has been that the nuclear X-ray emission from *most* RLQs largely arises from their **jets**.

Based on extensive analyses of new SDSS high-quality samples, we believe that the nuclear X-ray emission largely arises from the **corona** for *most* RLQs.

There are exceptions – rare, highly radio-luminous flat-spectrum RLQs.



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The L_X–L_{uv}–L_{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. $L_X \propto L_{uv}^{\gamma}$) for radio-quiet quasars (RQQs). The excess X-ray emission depends on the radio-loudness parameter (R) and radio spectral slope (α_r). We construct a uniform sample of 729 optically selected RLQs with high fractions of X-ray detections and α_r measurements. We find that steep-spectrum radio quasars (SSRQs; $\alpha_r \lesssim -0.5$) follow a quantitatively similar $L_X \propto L_{uv}^{\gamma}$ 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_{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 (≈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 $R \equiv L_{5\,GHz}/L_{4400\,\text{Å}} \geq 10$, where $L_{5\,GHz}$ and $L_{4400\,\text{Å}}$ are monochromatic luminosities at rest-frame 5 GHz and 4400 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).

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The X-ray spectral and variability properties of typical radio-loud quasars

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ABSTRACT

We present X-ray spectral and long-term variability analyses of an unbiased sample of 361 optically selected radio-loud quasars (RLQs) utilizing sensitive serendipitous X-ray data from the *Chandra* and *XMM-Newton* archives. The spectral and temporal properties of RLQs are compared with those of radio-quiet quasars (RQQs) matched in $L_{2\,keV,0}$ and z. The median power-law photon index (Γ) of RLQs is $1.84^{+0.05}_{-0.03}$, which is close to that of matched RQQs ($1.90^{+0.02}_{-0.02}$). No significant correlations between Γ and radio-loudness, $L_R/L_{6\,\mu m}$ (the X-ray luminosity over that expected from the L_X–$L_{6\mu}$ relation for RQQs), redshift, or Eddington ratio are found for our RLQs. The stacked X-ray spectra of our RLQs show strong iron-line emission and a possible Compton-reflection hump. The intrinsic X-ray variability amplitude is ≈40 per cent for RLQs on time-scales of months-to-years in the rest frame, which is somewhat smaller than for the matched RQQs (≈60 per cent) on similar time-scales, perhaps due to the larger black hole masses and lower Eddington ratios in our RLQ sample. The X-ray spectral and variability results for our RLQs generally support the idea that the X-ray emission of typical RLQs is dominated by the disc/corona, as is also indicated by a recent luminosity correlation study.

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

1 INTRODUCTION

Radio-loud quasars (RLQs) have powerful relativistic jets that are absent in radio-quiet quasars (RQQs; e.g. Padovani et al. 2017). These two types of quasars are observationally distinguished by the radio-loudness parameter, $R \equiv L_{5\,GHz}/L_{4400\,\text{Å}}$, where $L_{5\,GHz}$ and $L_{4400\,\text{Å}}$ are monochromatic luminosities at rest-frame 5 GHz and 4400 Å, respectively (Kellermann et al. 1989). Only 10–20 per cent of quasars are RLQs with $R \geq 10$, while the rest are RQQs (e.g. Ivezić et al. 2002). Typical RLQs have similar near-infrared-to-UV spectral energy distributions (SEDs) to those of RQQs, showing the so-called big blue bump with strong emission lines superimposed (e.g. Elvis et al. 1994; Shang et al. 2011). However, RLQs are generally brighter X-ray emitters than RQQs and thus have a flatter optical/ultraviolet (UV)-to-X-ray spectral slope, α_{ox} (e.g. Worrall et al. 1987; Miller et al. 2011), where $\alpha_{ox} \equiv \log(L_{2\,keV}/L_{2500\,\text{Å}})/\log(\nu_{2\,keV}/\nu_{2500\,\text{Å}})$ assuming a power-law spectral shape between rest-frame 2 keV and 2500 Å (Tananbaum et al. 1979). Furthermore, the excess X-ray emission of RLQs above that of RQQs correlates with both R and $L_{6\,\mu m}$, which has been taken as an evidence that the nuclear X-ray emission of RLQs contains both a standard accretion-disc corona component as well as a distinct X-ray component associated with the base of the powerful radio jets (e.g. Worrall et al. 1987; Miller et al. 2011). This explanation seems consistent with some previous studies that have found that RLQs have systematically flatter X-ray (<10 keV) spectra than those of RQQs (e.g. Wilkes & Elvis 1987; Reeves et al. 1997; Page et al. 2005), which could arise due to the mixture of the coronal X-ray emission and a generally harder X-ray spectrum from the jet-linked emission (e.g. Grandi & Palumbo 2004).

This original two-component model of the nuclear X-ray emission from typical RLQs has recently been challenged by Zhu et al. (2020), who studied the correlations of the continuum emission from the corona, disc, and jets of RLQs. Zhu et al. (2020) investigated the correlations between X-ray, optical/UV, and radio luminosities[1] using a large and well-characterized sample consisting of more than 700 optically selected RLQs. The steep-spectrum radio quasars (SSRQs), which have a radio spectral slope $\alpha_r \lesssim -0.5$, showed a L_X–L_{uv} relation that is quantitatively similar to that of RQQs (i.e. $L_X \propto L_{uv}^{\gamma}$, $\gamma \approx 0.6$; e.g. Just et al. 2007; Risaliti & Lusso 2019), despite the fact that these SSRQs are typically a factor of ≈2–3 times more X-ray luminous than RQQs at a given L_{uv}. The quantitatively similar L_X–L_{uv} correlation for SSRQs supports the idea that the nuclear X-ray emission of these SSRQs is still dominated by the corona that is coupled with the accretion disc (e.g. Arcodia et al. 2019), and no jet component is required. Zhu et al. (2020) also showed that the jet-linked component is only important for a small fraction (< 10 per cent) of flat-spectrum radio quasars (FSRQs; $\alpha_r > -0.5$); thus, the corona-linked component also dominates the X-ray emission of most typical FSRQs. The relation between α_{ox} and the equivalent width (EW) of He II in RLQs is consistent with the result of Zhu et al. (2020) that RLQ X-ray emission is mainly related to the disc/corona instead of the jets (Timlin et al. 2021).

Brief Sample Description

Work with SDSS DR14 RLQs optically selected from 9376 deg^2 – radio data from FIRST and NVSS.

Select objects with sensitive Chandra or XMM-Newton coverage.

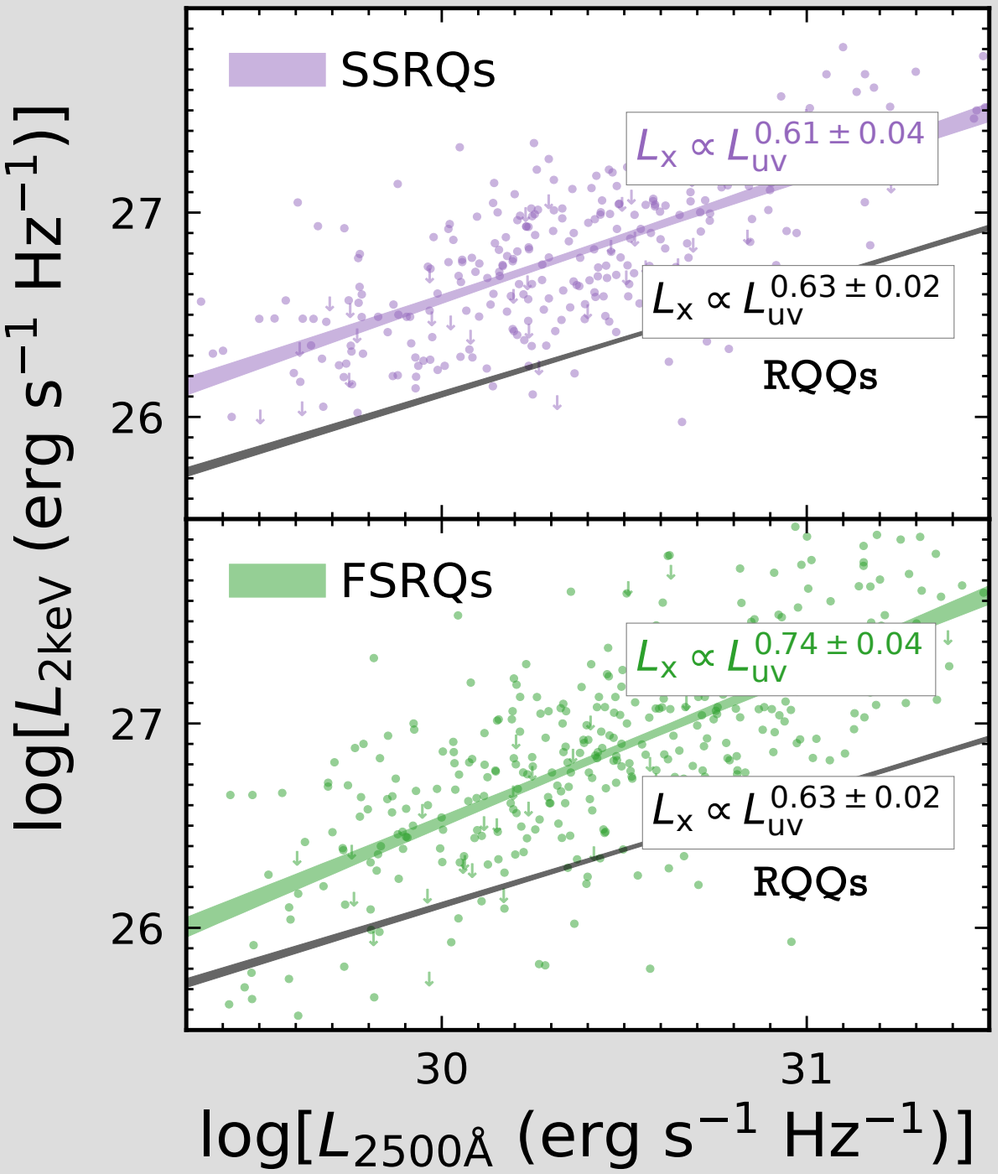
Results in 729 well-characterized RLQs:

- Mostly serendipitous X-ray coverage (minimizes biases)
- 90.1% are X-ray detected
- 96.6% have radio-slope measurements (e.g., VLASS)
- SDSS spectra with strong broad lines
- Multiwavelength SEDs from radio, WISE, VISTA, UKIDSS, SDSS, X-ray

We use appropriate subsets of these 729 RLQs for the various studies.

We plan to expand with the SDSS DR16+ samples in the future.

X-ray vs. UV Luminosity Correlations

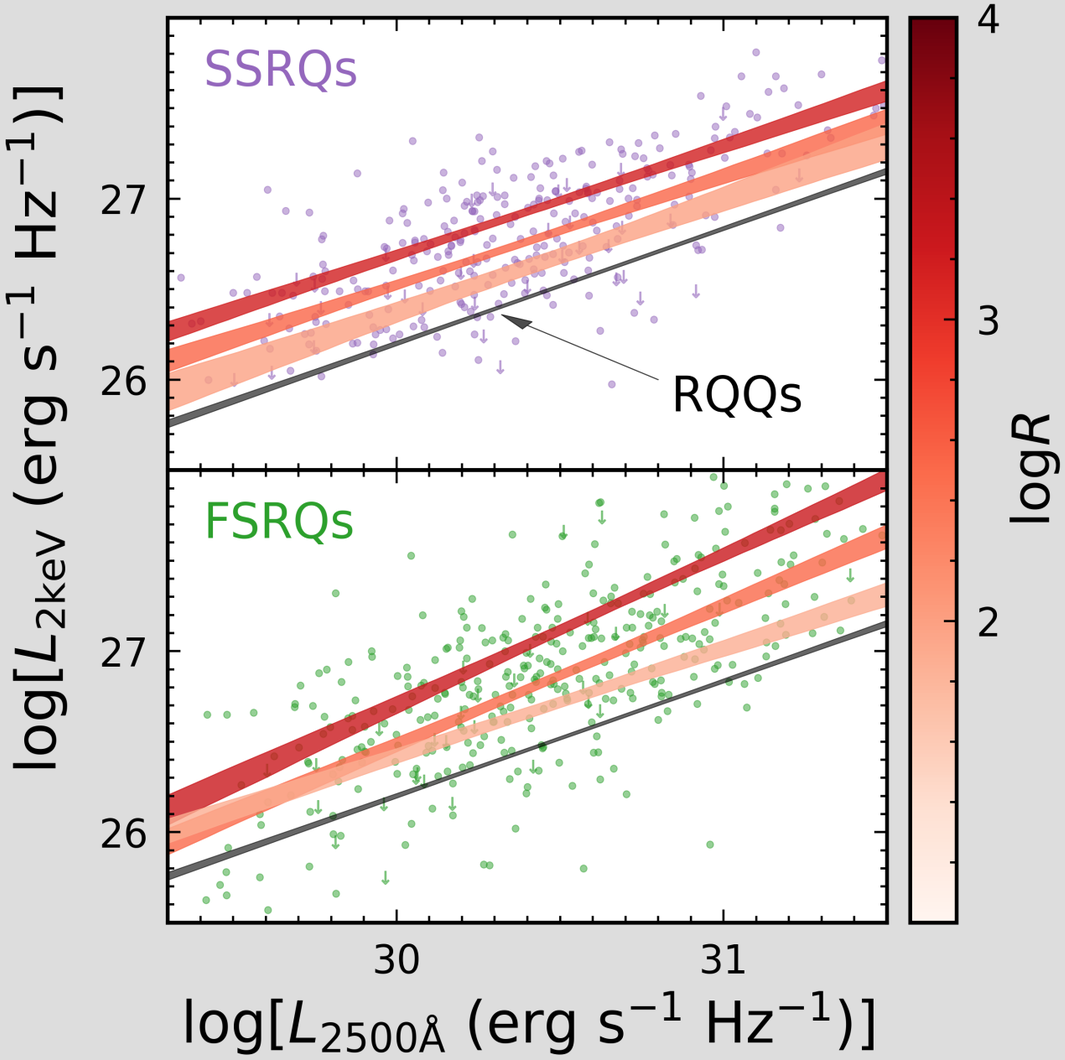


Radio-quiet quasars (RQQs) follow a long-established correlation between X-ray (corona) and UV (disk) luminosities.

Steep-spectrum RLQs (SSRQs) follow *almost the same correlation* quantitatively, just offset to higher normalization; indicates they may have coronal X-rays.

Flat-spectrum RLQs (FSRQs) show a somewhat steeper correlation, indicating likely jet contributions to X-ray emission, at least sometimes.

Splitting into Radio-Loudness Bins



The normalization for SSRQs increases smoothly with *R*, retaining the RQQ-relation slope.

Appears to be RQQ-like coronal emission with a jet-linked X-ray "volume control".

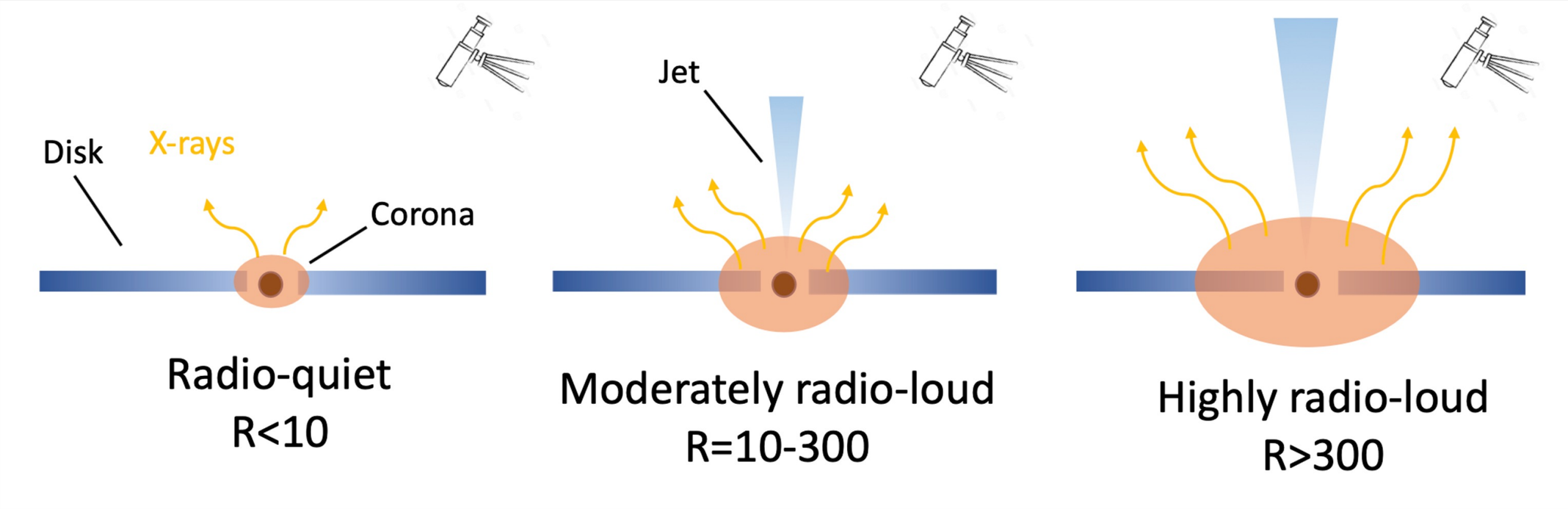
That is, a *corona-jet connection*.

FSRQs progressively depart from the RQQ-relation slope as *R* increases.

Statistical model selection shows the data generally prefer the coronal scenario with a corona-jet connection for SSRQs and RLQs in general – see Zhu et al. (2020) for details.

X-ray power-law slopes, Fe Kα line emission, and long-term variability also indicate coronal X-ray emission – see Zhu et al. (2021) for details.

Magnetized Coronae of RLQs Become X-ray Brighter with Increasing Jet Power



It appears the magnetic fields in corona are needed for jet launching
and
our observed corona-jet connection is reflecting changes in magnetic flux and/or topology.

Broader Conclusions and Connections

Improve unification of quasars and BH X-ray binaries; the latter also generally have corona-dominated X-ray emission when launching jets.

Allow identification of the $\alpha_{ox} - L_{UV}$ relation for RQQs as quasar "jet line" in hardness-intensity diagram.

BH spin alone probably does not control quasar radio loudness – magnetic flux and/or topology also likely critical.

See Zhu et al. (2020, 2021) for full details.

Also see https://www.youtube.com/watch?v=cfG-sGSEJ7E