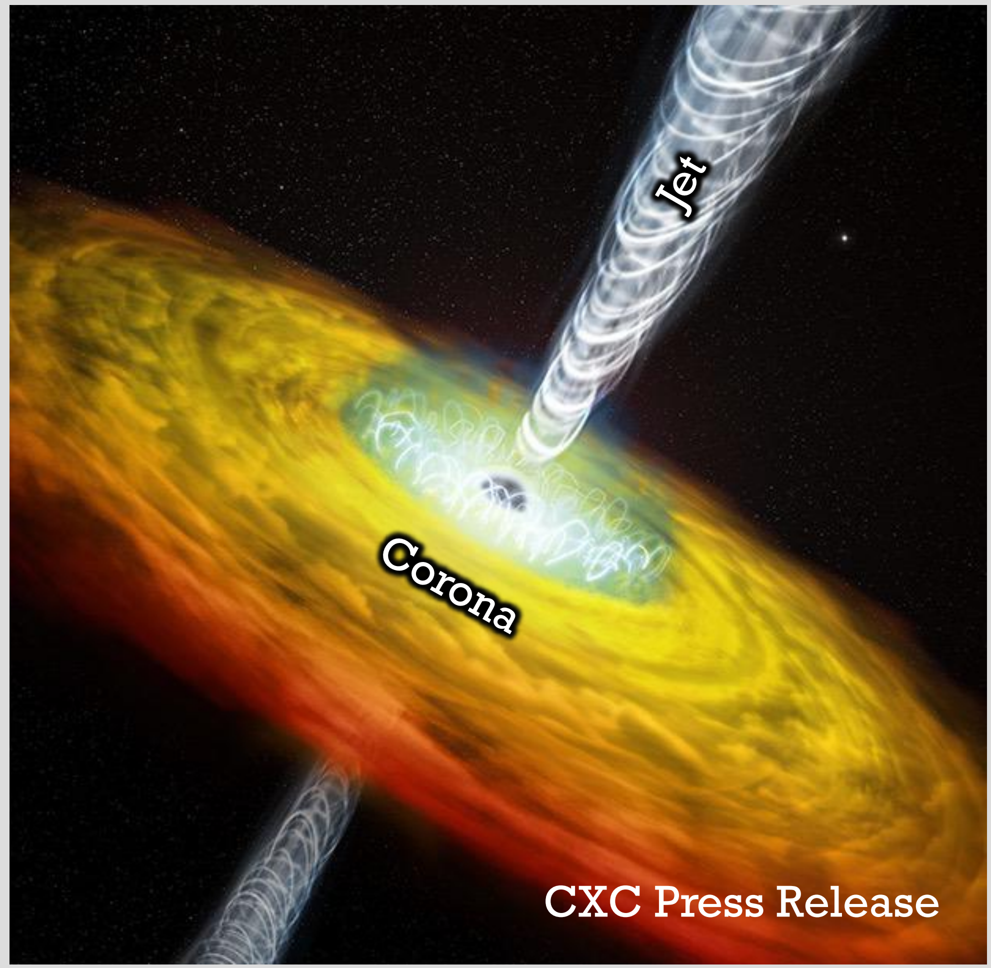
The Nature of the X-ray Emission from Typical Radio-Loud Quasars: Jets vs. Coronae

Shifu Zhu (Penn State), Niel Brandt (Penn State), John Timlin (Penn State), et al.

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 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.



Brief Sample Description

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

Select those 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)
- Multiwavelength SEDs from radio, WISE, VISTA, UKIDSS, SDSS, X-ray
- SDSS spectra with strong broad lines

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

L_X - L_{UV} - L_{Radio} Correlations

X-ray Spectra and Variability

α_{ox}-He II EW Relation

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

S. F. Zhu (朱世甫),[1,2★] W. N. Brandt,[1,2,3] B. Luo (罗斌),[4] Jianfeng Wu (武剑锋),[5] Y. Q. Xue (薛永泉)[6,7] and G. Yang (杨光)[8,9]

[1] *Department of Astronomy & Astrophysics, The Pennsylvania State University, University Park, PA 16802, USA*
[2] *Institute for Gravitation and the Cosmos, The Pennsylvania State University, University Park, PA 16802, USA*
[3] *Department of Physics, 104 Davey Lab, The Pennsylvania State University, University Park, PA 16802, USA*
[4] *School of Astronomy and Space Science, Nanjing University, Nanjing, Jiangsu 210046, China*
[5] *Department of Astronomy, Xiamen University, Xiamen, Fujian 361005, China*
[6] *CAS Key Laboratory for Research in Galaxies and Cosmology, Department of Astronomy, University of Science and Technology of China, Hefei 230026, China*
[7] *School of Astronomy and Space Sciences, University of Science and Technology of China, Hefei 230026, China*
[8] *Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843-4242, USA*
[9] *George P. and Cynthia Woods Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University, College Station, TX 77843-4242, USA*

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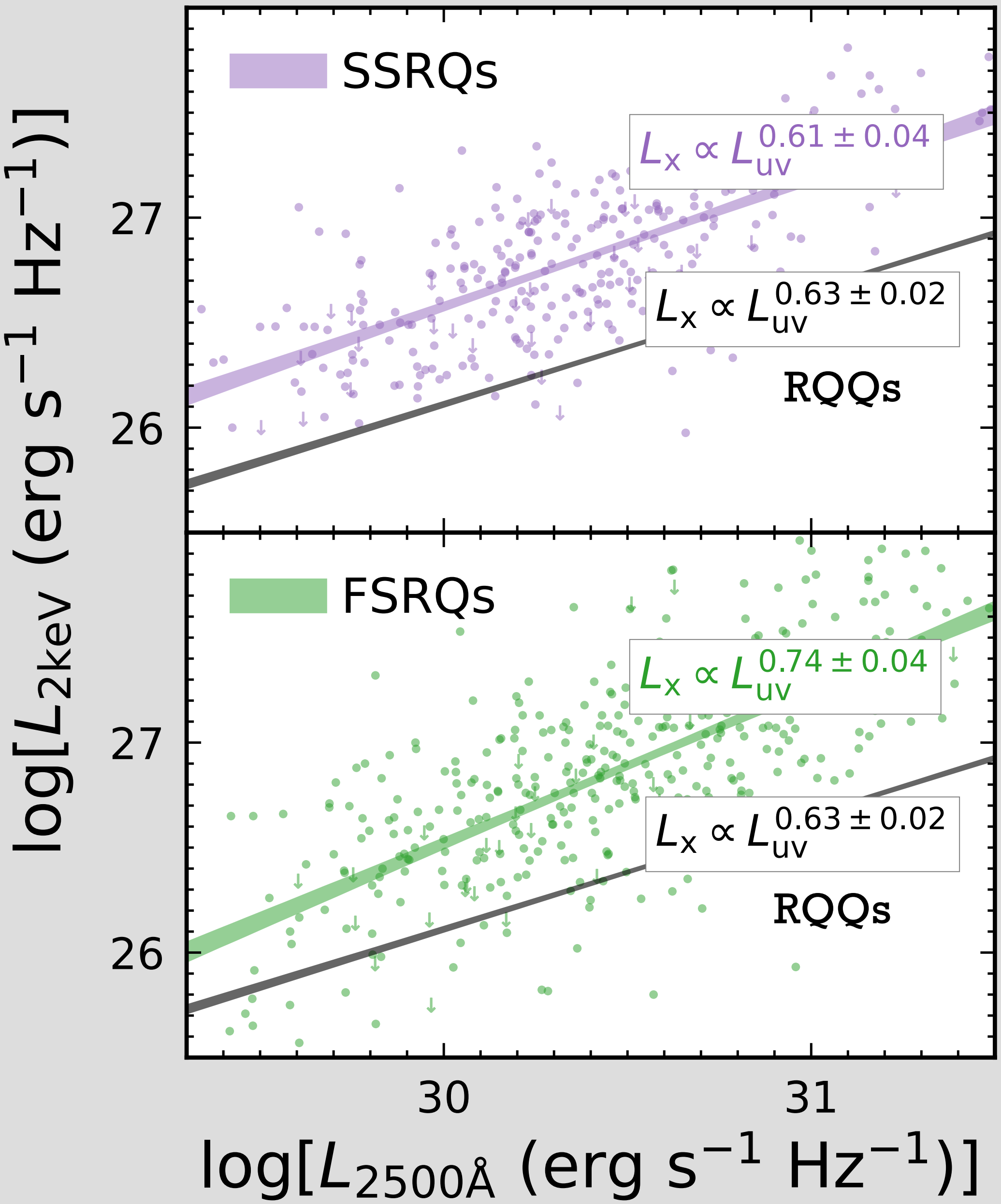
ABSTRACT

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; $\alpha_r \leq -0.5$) 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.

X-ray vs. Optical Luminosity Correlations

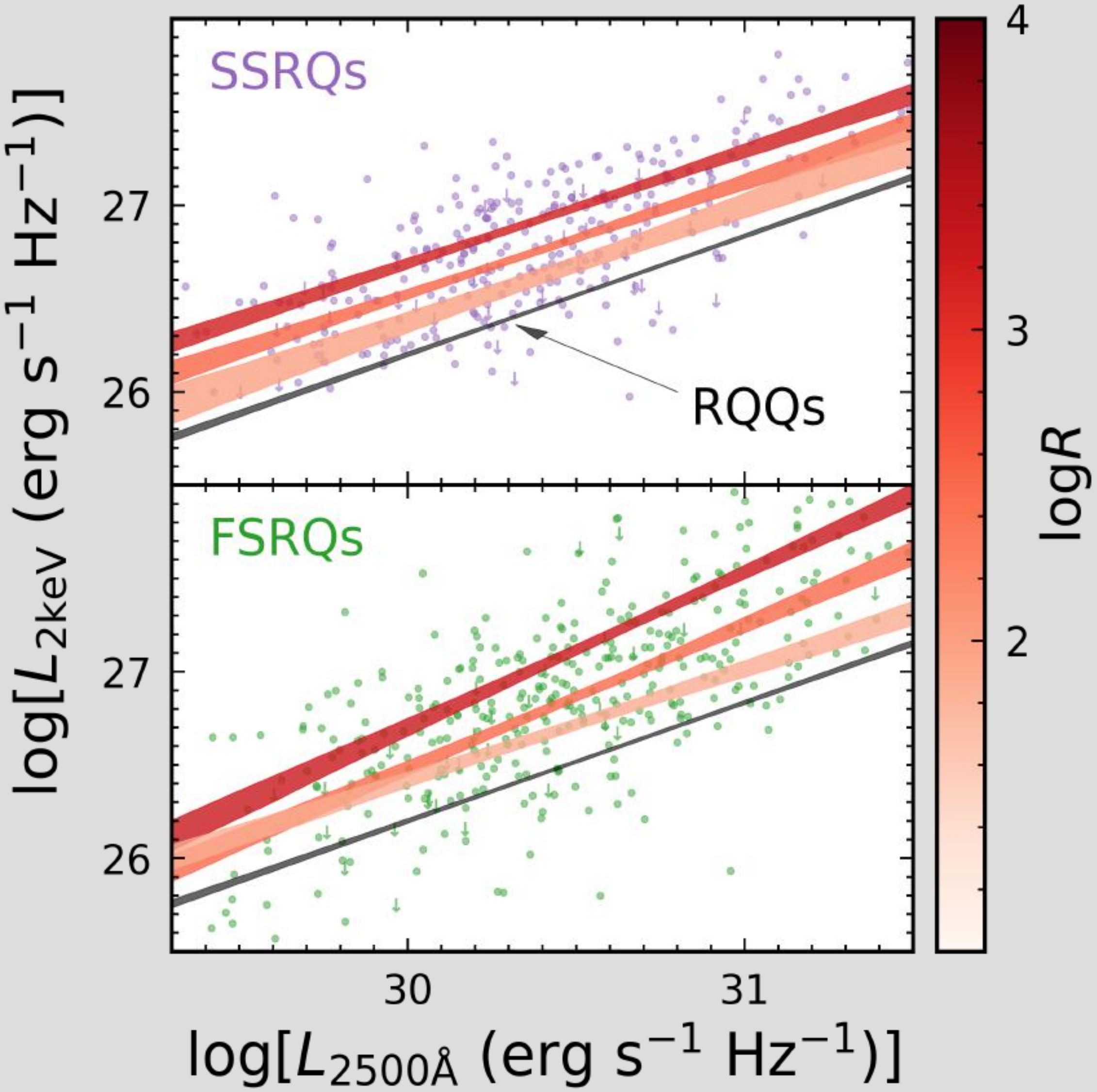


Radio-quiet quasars (RQQs) follow a long-established correlation between X-ray (corona) and optical (disk) luminosities.

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

Flat-spectrum RLQs 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

We performed statistical model selection, aiming to compare critically the different possible interpretations.

Use Akaike and Bayesian Information Criteria.

The data generally prefer the coronal scenario with a corona-jet connection for SSRQs and RLQs in general.

A distinct jet X-ray component is likely important for a small portion of FSRQs.

See Zhu et al. (2020) for the many details.

$L_{\rm X}$ - $L_{\rm UV}$ - $L_{\rm Radio}$ Correlations

X-ray Spectra and Variability

$\alpha_{\rm ox}$-He II EW Relation

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

S. F. Zhu,[1,2]★ John D. Timlin III,[1,2] and W. N. Brandt[1,2,3]
[1]*Department of Astronomy & Astrophysics, The Pennsylvania State University, University Park, PA 16802, USA*
[2]*Institute for Gravitation and the Cosmos, The Pennsylvania State University, University Park, PA 16802, USA*
[3]*Department of Physics, 104 Davey Lab, The Pennsylvania State University, University Park, PA 16802, USA*

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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 $L_{2500\text{Å}}$ and z. The median power-law photon index (Γ) of RLQs is $1.84^{+0.01}_{-0.01}$, which is close to that of matched RQQs ($1.90^{+0.02}_{-0.01}$). No significant correlations between Γ and radio-loudness, $L_{\rm x}/L_{\rm x,rqq}$ (the X-ray luminosity over that expected from the $L_{\rm x}$-$L_{\rm uv}$ 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 $\approx 40\%$ for RLQs on timescales of months-to-years in the rest frame, which is somewhat smaller than for the matched RQQs ($\approx 60\%$) on similar timescales, 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 disk/corona, as is also indicated by a recent luminosity correlation study.

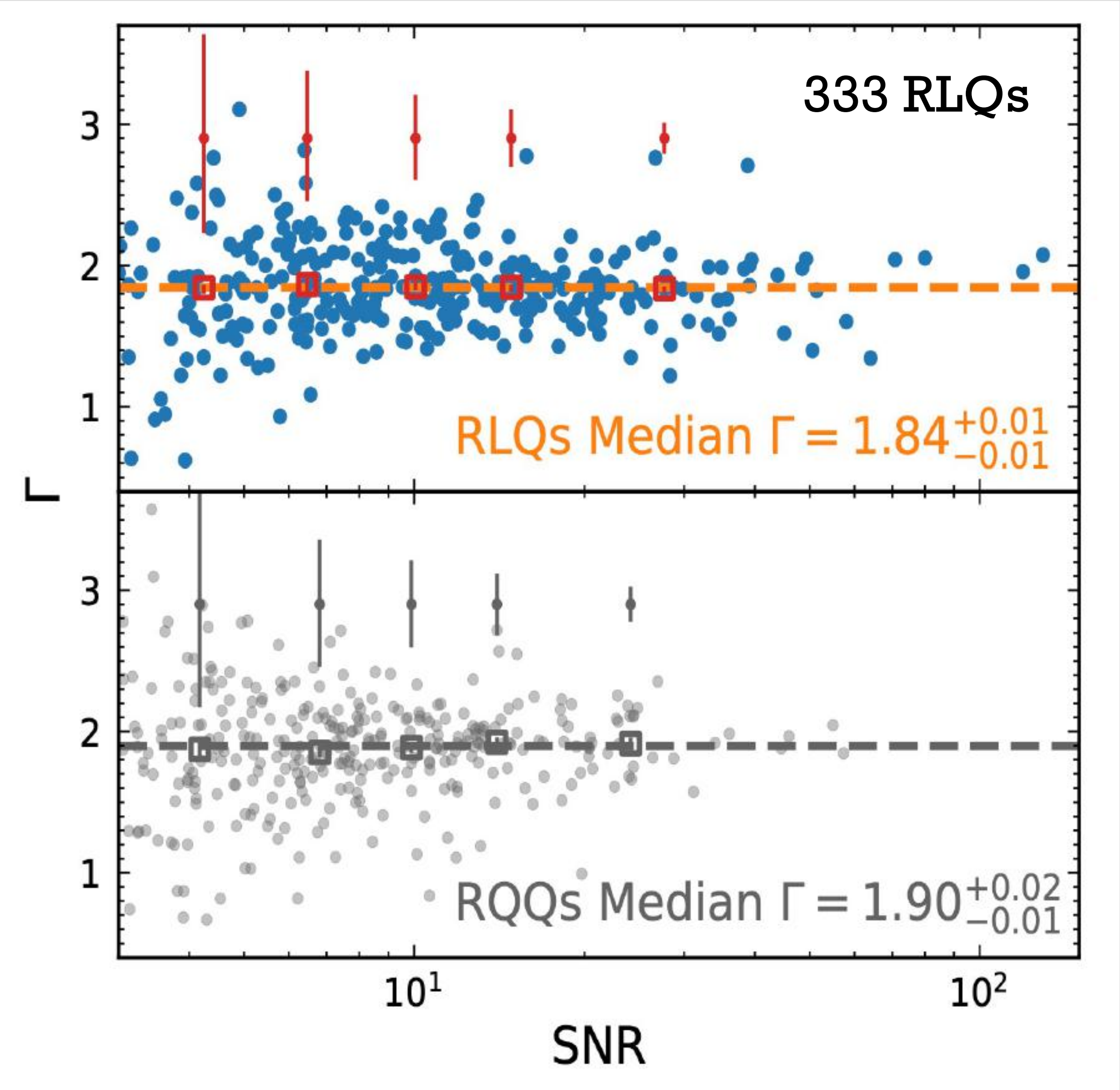
Key words: quasars: general – X-rays: galaxies – galaxies: nuclei – galaxies: jets – black hole physics

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, $R \equiv L_{\rm 5GHz}/L_{4400\text{Å}}$, where $L_{\rm 5GHz}$ and $L_{4400\text{Å}}$ are monochromatic luminosities at rest-frame 5 GHz and 4400 Å, respectively (Kellermann et al. 1989). Only 10–20% 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 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

RLQ Power-Law Continuum Slopes



Median Γ of RLQs close to that of matched RQQs.

Steeper than for past RLQ samples with X-ray spectra.

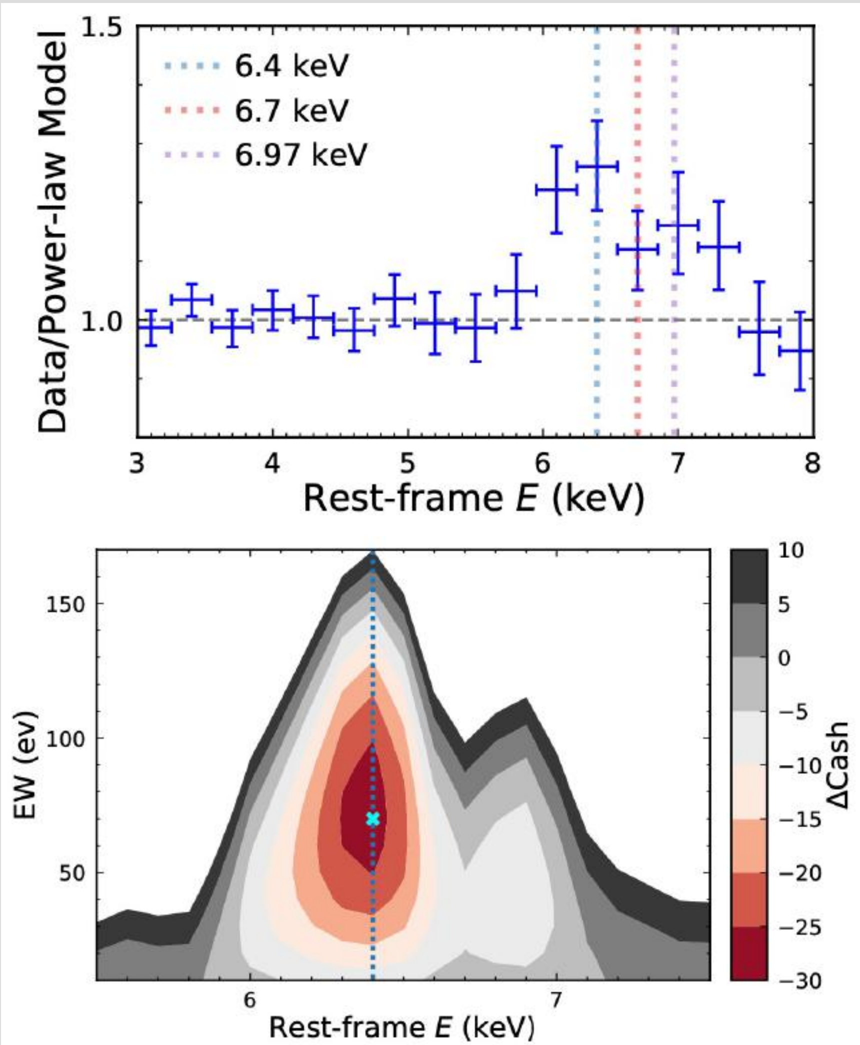
Past samples were small and heterogeneous, with over-representation of radio-selected FSRQs (beamed objects).

No strong correlations of Γ with

- Radio loudness
- L_X / $L_{X,RQQ}$

RLQ X-ray Reflection Features

Stacking of 216 RLQs



If X-ray emission largely from jets, reflection should be weak.

Stacked RLQ spectra show Fe Kα emission with total EW ≈ 190 eV.

EWs for RLQs and matched RQQs statistically consistent.

Also, suggestive evidence for the Compton-reflection hump.

All as expected for coronal origin of X-rays.

Long-term X-ray variability for 105 RLQs consistent with coronal X-rays.

L_X - L_{UV} - L_{Radio} Correlations

X-ray Spectra and Variability

α_{ox}-He II EW Relation

The α_{ox}–He II EW connection in radio-loud quasars

John Timlin,[1] Shifu Zhu,[1] W. N. Brandt,[1] and Ari Laor[2]

[1] *Department of Astronomy & Astrophysics, 525 Davey Lab, The Pennsylvania State University, University Park, PA 16802, USA*
[2] *Physics Department, Technion, Haifa 32000, Israel*

Keywords: Radio loud quasars (1349), X-ray quasars (1821), Quasars (1319)

ABSTRACT

Radio-loud quasars (RLQs) are known to produce excess X-ray emission, compared to radio-quiet quasars (RQQs) of the same luminosity, commonly attributed to jet-related emission. Recently, we found that the He II EW and α_{ox} in RQQs are strongly correlated, which suggests that their extreme-ultraviolet (EUV) and X-ray emission mechanisms are tightly related. Using 48 RLQs, we show that steep-spectrum radio quasars (SSRQs) and low radio-luminosity (L_R) flat-spectrum radio quasars (FSRQs) follow the α_{ox}–He II EW relation of RQQs. This suggests that the X-ray and EUV emission mechanisms in these types of RLQs is the same as in RQQs, and is not jet related. High-L_R FSRQs show excess X-ray emission given their He II EW by a factor of ≈ 3.5, which suggests that only in this type of RLQ is the X-ray production likely jet related.

THE HE II AND α_{ox} PROPERTIES OF RLQS

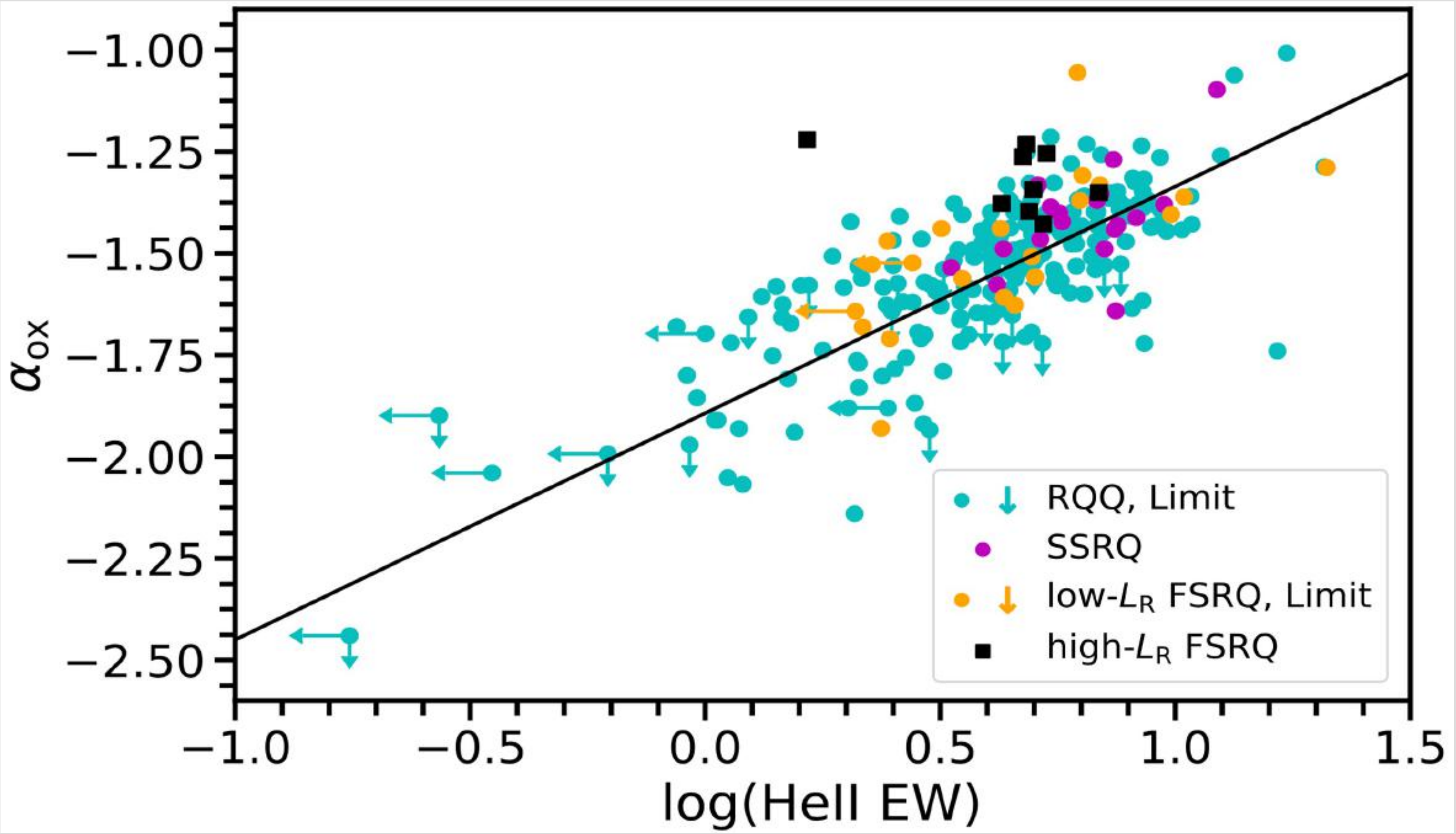
RLQs comprise $\approx$ 10–20% of the total quasar population, are generally more X-ray luminous than their RQQ counterparts, and typically exhibit a flatter X-ray-to-optical spectral slope (α_{ox}).[1] Zhu et al. (2020) (hereafter, Z20) studied the joint radio, optical, and X-ray luminosities of a large, optically selected sample of typical RLQs and found evidence that their X-ray emission largely originates in the corona, challenging the idea that a distinct jet component contributes substantially to the X-ray emission of typical RLQs (e.g., Miller et al. 2011). They suggested a small fraction (<10%) of FSRQs (which have radio spectral slope $\alpha_r > -0.5$) may have a significant (>30%) jet X-ray contribution. In a follow-up investigation of the X-ray spectral and variability properties of typical RLQs, they found that all but the most radio-luminous ($L_R > 10^{34.3}$ erg s^{-1} Hz^{-1}; where L_R is the monochromatic 5 GHz luminosity) FSRQs had X-ray emission as would be expected from the corona (Zhu et al. 2021, submitted; hereafter Z21). Here, we provide additional evidence supporting their result.

For this investigation, we follow Timlin et al. (2021, submitted; hereafter T21) who studied the α_{ox}–He II EW relationship for RQQs. The He II emission line is a weak, high-ionization line that provides a "clean" measure of the number of EUV photons between 50–200 eV present (see Section 1 of T21). T21 found a tight correlation between α_{ox} and He II EW in RQQs, even after removing these parameters' L_{2500} dependences, indicating that the EUV continuum is related to the X-ray emission, and possibly originates in a "warm Comptonization" coronal region. Given this tight correlation for RQQs, and that RLQ beamed jet emission is not expected to produce additional He II, investigating the α_{ox}–He II EW relation for RLQs might provide insight into the origin of RLQ X-ray emission.

Our RLQ sample was constructed using RLQs from the three quasar samples outlined in Section 2 of T21 (Just

α_{ox}-He II EW Relation for RLQs vs. RQQs

X-ray-to-Optical Flux Ratio



Tracer of EUV Continuum at 4+ Ry

For most RLQs, when the X-rays are brighter the unbeamed EUV making He II is *correspondingly* brighter – not expected for beamed jet X-rays.

Exception is for highly radio-luminous FSRQs, owing to expected jet X-rays.

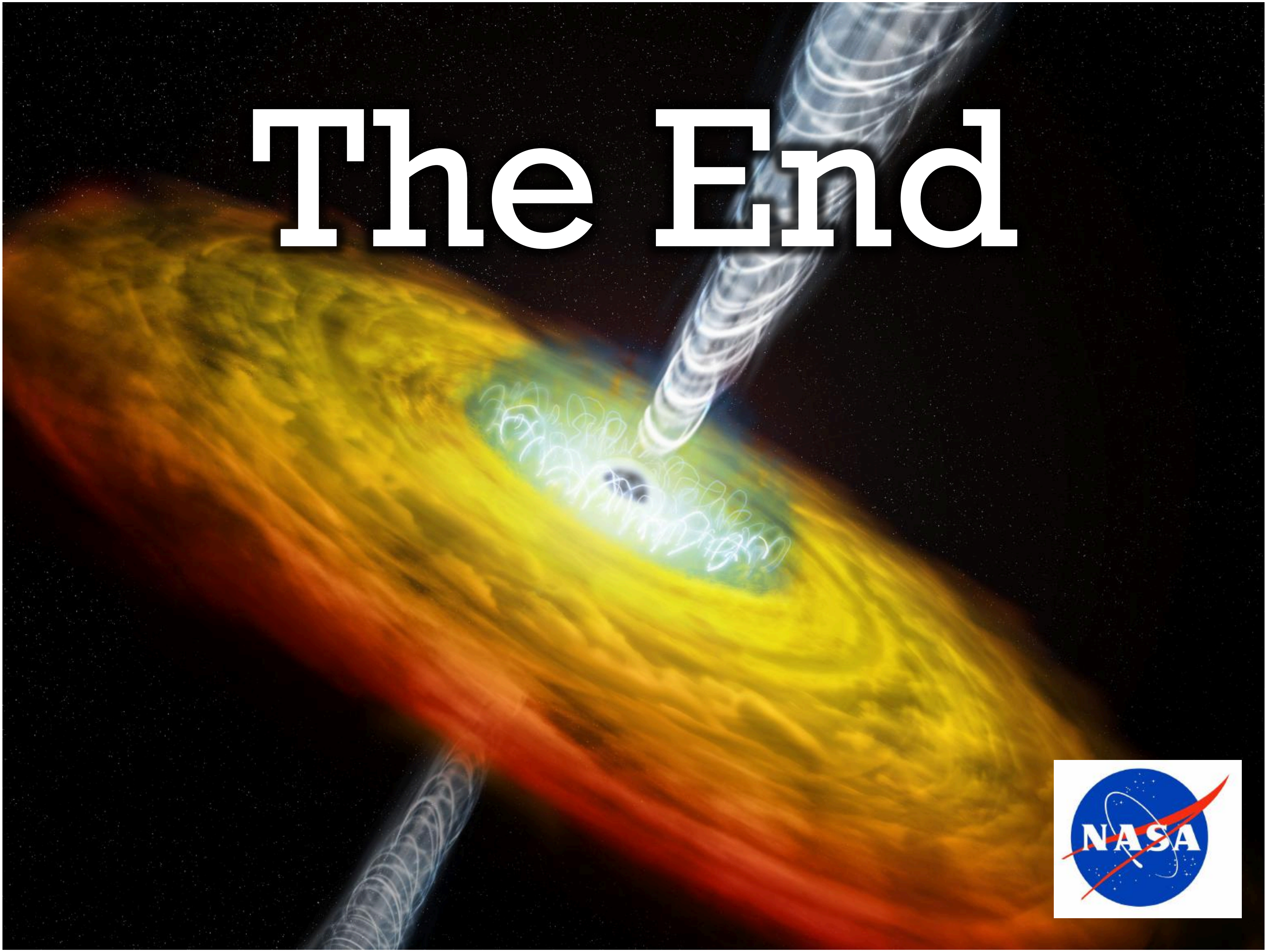
Additional Implications of Our Results

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/topology also likely critical.

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