The Fundamental Planes of Black Hole Activity for Radio-Loud and Radio-Quiet Quasars

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ABSTRACT
We examine the fundamental plane of black hole activity for correlations with redshift and radio loudness in both radio-loud and radio-quiet quasar populations. Sources are compiled from archival data of both radio-loud and radio-quiet quasars over redshifts 0.1 < z < 5.0 to produce a sample of 353 sources with known X-ray, radio, and black hole mass measurements. A fundamental plane of accretion activity is fit to a sample of radio-loud and radio-quiet quasars, and we find a dichotomy between radio-loud and radio-quiet sources. The set of best-fit equations that best describe the two samples are log $L_R = (1.12 \pm 0.06) \log L_X - (0.20 \pm 0.07) \log M - (5.64 \pm 2.99)$ for our radio-loud sample and $\log L_R = (0.48 \pm 0.06) \log L_X + (0.50 \pm 0.08) \log M + (15.26 \pm 2.66)$ for our radio-quiet sample. Our results suggest that the average radio-quiet quasar emission is consistent with advection dominated accretion, while a combination of jet and disc emission dominates in radio-loud quasars. We additionally examine redshift trends amongst the radio-loud and radio-quiet samples, and we observe a redshift dependence for the fundamental plane of radio-loud quasars. Lastly, we utilize the fundamental plane as a black hole mass estimation method and determine it useful in studying systems where standard spectral modeling techniques are not viable.

Key words: Accretion – Active Galaxies – Black Hole Physics – Galaxy Nuclei – High-Redshift Galaxies

1 INTRODUCTION
Black holes are exotic astrophysical objects with masses ranging from stellar mass up to $10^{10} M_\odot$, whose influence can be observed due to accretion processes that produce emissions across a broad range of different wavelengths. In particular, relativistic jets generated from the black hole will produce synchrotron radiation which is detectable at radio wavelengths (Begelman et al. 1984), while adiabatic compression within the inner accretion disc heats the surrounding material and produces X-ray emission (Heinz et al. 1998; Stawarz et al. 2008). Black hole luminosities can be as low as $10^{30} - 10^{33}$ erg s$^{-1}$ in quiescent stellar mass black holes (e.g., Gallo et al. 2003), and as high as $10^{47}$ erg s$^{-1}$ in the most luminous quasars. By deriving correlations between the observables, black hole properties such as accretion rate $M$, disc-jet coupling, and jet models can be extrapolated (e.g., Corbel et al. 2003; Gallo et al. 2003). Thus, multiwavelength observations of black holes are critical for studies of their unique physical properties.

The observational study by Merloni et al. (2003) examined physical properties of low-redshift black holes ($z < 0.3$) over broad mass and luminosity ranges in X-ray and radio wavelengths for any evidence of correlations between those parameters. By studying 116 black holes with known masses and luminosities, a “fundamental plane of black hole accretion activity” characterized by log $L_R = \xi_{RX} \log L_X + \xi_{RM} \log M + b_R$ was discovered. The result demonstrated that the radio luminosity of a black hole has a direct dependence on its mass and X-ray luminosity, regardless of local environmental effects. Furthermore, the fundamental plane provides a universal method of characterizing black hole behavior and properties that is scale invariant and independent of jet models (Heinz & Sunyaev 2003; Merloni et al. 2003). More recent works refined the fundamental plane parameters through the use of more precise radio and X-ray luminosities together with known masses obtained from direct dynamical measurements (Körding et al. 2006; Gültekin et al. 2009). The tighter constraints led to a relation between the luminosities and mass that was consistent with previous fundamental plane measurements but with 33% less scatter, further reinforcing the presence of a fundamental accretion process that is consistent across black holes in our nearby Universe.

Despite the merit of previous results, the majority of fundamental plane studies prioritized black holes at low redshifts ($z < 0.5$) since mass measurements and luminosities are well-constrained for those sources (e.g., Merloni et al. 2003; Falcke et al. 2004; Körding et al. 2006; Gültekin et al. 2009). Increased cosmic densities within the early Universe may have driven periods of rapid formation due to increased merger rates and gas consumption, giving rise to different accretion physics than what is presently observed (Volonteri 2012). In more recent timescales, the Universe has since undergone cosmological expansion which has also affected black hole formation and possibly accretion physics (Merloni et al. 2003; Merloni 2004;
Radio loudness is defined as the ratio of the radio luminosity to the bolometric luminosity of the AGN core, and an emissivity spectrum was extracted from the source. We explore such possible bias in the discussion of our redshift analysis (§ 4.2).

Radio fluxes were taken from the VLA-FIRST radio survey (Becker et al. 1995), or from independent VLA observations when FIRST data of the source was not available. A region was defined to isolate the AGN core in the radio observation, and the radio flux was measured from the region. The rest-frame 5 GHz radio luminosity of each source was extrapolated from the flux measurements. At the 5″ resolution of FIRST, the survey resolved radio features up to a separation distance of 31 kpc at \( z = 5 \), the maximum redshift of our quasar sample. We note that radio emission in nearby sources studied in the context of the fundamental plane reflects activity of the nucleus and generally does not include the extended radio emission from large scale jets (e.g., Merloni et al. 2003; Falcke et al. 2004). Since a priority of our sample is to investigate high-redshift sources, we anticipate a possible bias in our sample due to the inclusion of extended radio emission in our measurements. We explore such possible bias in the discussion of our redshift analysis (§ 4.2).

X-ray luminosities were derived using observations from Chandra, XMM-Newton, and Swift. A region was defined around the AGN core, and an emissivity spectrum was extracted from the source. Extended X-ray features potentially present in the regions may be ignored as they generally provide a negligible contribution to the total quasar luminosity (e.g., Marshall et al. 2018; Worrall et al. 2020). The observed X-ray flux was measured from a spectral model of the 0.5–7.0 keV energy band, and the rest-frame 2–10 keV luminosity was extrapolated from the best-fit model. We specifically selected quasars with radio and X-ray flux measurements and omitted any sources with upper limit estimates. Our quasar catalog was cross-referenced with the SDSS-DR14 catalog (Rakshit et al. 2020), where sources with confirmed spectroscopic mass measurements via SDSS spectra were included in our fundamental plane analysis.

Ultimately, our radio-loud quasar sample included 11 sources from Zhu et al. (2019), 6 sources from Snios et al. (2020), 12 sources from Snios et al. (2021), and 196 sources from Zhu et al. (2021). Radio luminosities for the sample ranged between \( 10^{30} - 10^{46} \) erg s\(^{-1}\), while X-ray luminosities ranged between \( 10^{43} - 10^{47} \) erg s\(^{-1}\). The masses of the sources ranged between \( 10^{6} - 10^{11} M_\odot \) with an average uncertainty of 0.342 \( M_\odot \). Consistent with Merloni et al. (2003), we also calculated for each source the ratio of the X-ray luminosity to the Eddington luminosity, which may be used as a proxy for the Eddington ratio. We defined the ratio as \( \log(L_X/L_{\text{Edd}}) \) where \( L_{\text{Edd}} = 1.3 \times 10^{38} M_\odot \), the range of \( \log(L_X/L_{\text{Edd}}) \) for our radio-loud sample is \([-3.31,-0.31]\) with a mean of \(-1.92\). In total, we obtained 225 unique radio-loud quasars at \( 0.1 < z < 5.0 \) with complete measurements over a broad range of observables, which is sufficient for our modeling analysis. Details on our radio-loud catalog are provided in Table 1, and Figure 1 shows the source distribution of our radio-loud sample across several different physical properties.
2.2 Radio-Quiet Quasars

Radio-quiet quasars comprise the majority of the known quasar population and are therefore commonly utilized in fundamental plane analyses (e.g., Merloni et al. 2003; Falcke et al. 2004; Körding et al. 2006; Gültekin et al. 2009; Plotkin et al. 2012). To obtain our radio-quiet quasar sample, we cross-referenced the radio-quiet quasar catalog from Timlin et al. (2020) with the X-ray fluxes of Zhu et al. (2021). Consistent with our sample selection method for the radio-loud catalog, we selected radio-quiet quasars with known radio and X-ray flux measurements. Radio and X-ray luminosities were provided from Timlin et al. (2020) and Zhu et al. (2021), where the derivation methods are the same as those described in § 2.1. Our quasar catalog was cross-referenced with the SDSS-DR14 catalog for spectroscopic mass measurements (Rakshit et al. 2020).

In total, we found 128 radio-quiet quasars with complete measurements which we included in our fundamental plane analysis. We note that although radio-quiet quasars comprise the majority of the known quasar population, our radio-loud sample is larger than our radio-quiet sample because relatively few radio-quiet sources have radio fluxes above current detector sensitivity limits. The sources span a redshift range of $0.1 < z < 4.0$, X-ray luminosities that ranged between $10^{42} - 10^{46}$ erg s$^{-1}$, radio luminosities that ranged between $10^{39} - 10^{43}$ erg s$^{-1}$, and masses that ranged between $10^6 - 10^{10} M_\odot$ with an average uncertainty of 0.341 $M$.

The ratio log($L_X / L_{Edd}$) was also calculated for our radio-quiet sample, finding a range of $[-4.87,-1.03]$ with a mean of $-2.43$. The radio-quiet sources possess similar physical parameters as our radio-loud sources, and both samples are comparable in size. This ensures that radio loudness is the primary difference between our two samples. Details on our radio-quiet catalog are provided in Table 1, Figure 1 shows the source distribution of our radio-quiet sample across different physical properties.
for their X-ray luminosities. For all of our radio luminosities, we adopted a 15\% uncertainty. We note that our adopted errors exceed those from similar studies (e.g., Gültekin et al. 2009; Gültekin et al. 2019), which reassures us that our error estimates are conservative. For the mass measurements obtained from Rakshit et al. (2020), we utilized the quoted uncertainties. Due to our model fitting method (described below), we adopted conservative symmetric uncertainties for all measurements.

Consistent with Merloni et al. (2003), we defined the fundamental plane of activity as

$$\log L_R = \xi_X \log L_X + \xi_M \log M + b,$$

where $L_R$ is the rest-frame 5 GHz luminosity, $L_X$ is the rest-frame 2–10 keV luminosity, and $M$ is the black hole mass. The dataset was fit using the multivariate orthogonal distance regression (ODR) method to estimate the best-fit regression coefficients (Boggs & Rogers 1990). ODR is a fitting scheme that modifies the ordinary least squares by accounting for uncertainties within both the dependent and independent variables, and the data is minimized by the sum of squared perpendicular distances from the data points to the best-fit line weighted by the uncertainty. Given the presence of measurement uncertainties for our three input parameters, ODR provided a more accurate best-fit than the commonly used ordinary least squares regression method.

Despite the robustness of the ODR method, a single run is not guaranteed to produce well-constrained best-fit coefficients with our data set as the maximally strict convergence conditions of the sums of squares and relative changes in the estimated parameters yield fits that are not necessarily located at the global minimum. We therefore ran ODR with $10^4$ iterations, producing a distribution of fitting coefficients. We used the mean of the resultant parameters as our best-fit coefficients, while their errors were calculated from the mean covariance matrices. We additionally implemented randomized initial conditions for each run to reduce input bias on the best-fit parameters.

For our analysis, we utilized our accumulated samples to construct a fundamental plane of black hole activity. Performing the ODR fit on our radio-loud and radio-quiet sources, we found a fundamental plane best-fit of $\log L_R = (1.12 \pm 0.06) \log L_X + (-0.20 \pm 0.07) \log M - (5.64 \pm 2.99)$ for our radio-loud sample and $\log L_R = (0.48 \pm 0.06) \log L_X + (0.50 \pm 0.08) \log M + (15.26 \pm 2.66)$ for our radio-quiet sample. Figure 2 shows the result of fitting across the two samples, and Table 2 displays the best-fit coefficients. For completeness, a best-fit was obtained for the entire dataset of radio-loud and radio-quiet quasars, which is also provided in Table 2. The residual variance $\sigma_{\text{res}}^2$, the y-intercept $b$, the best-fit residual variance $\sigma_{\text{res}}^2$, the adjusted R-squared of the best-fit model $R_{\text{adj}}^2$, and the scatter of the log($L_R$) parameter relative to the predicted value from the fundamental plane model $\sigma_R$.

Table 2. Best-fit Parameters of the Fundamental Plane of Black Hole Activity Analysis

| Number of Sources | $\xi_X$ | $\xi_M$ | $b$ | $\sigma_{\text{res}}^2$ | $R_{\text{adj}}^2$ | $\sigma_R$ |
|------------------|--------|--------|-----|----------------|-----------------|--------|
| Total Dataset    | 353    | 1.44 ± 0.08 | 0.16 ± 0.10 | -23.85 ± 3.49 | 54.97 | 0.5207 | 0.85 |
| **Radio Loudness Dependence** | | | | | | | |
| Radio-Loud Quasars | 225    | 1.12 ± 0.06 | -0.20 ± 0.07 | -5.64 ± 2.99 | 20.09 | 0.4629 | 0.62 |
| Radio-Quiet Quasars | 128    | 0.48 ± 0.06 | 0.50 ± 0.08 | 15.26 ± 2.66 | 17.77 | 0.5866 | 0.39 |
| **Redshift-dependence (Radio-Loud Quasars)** | | | | | | | |
| $z < 1$      | 87     | 1.32 ± 0.15 | -0.06 ± 0.13 | -16.20 ± 6.59 | 18.58 | 0.3390 | 0.55 |
| $1 < z < 3$  | 94     | 1.06 ± 0.13 | -0.17 ± 0.10 | -3.27 ± 6.00 | 21.66 | 0.3564 | 0.52 |
| $z > 3$      | 44     | 0.63 ± 0.15 | -0.27 ± 0.15 | 17.55 ± 6.64 | 22.63 | 0.2779 | 0.48 |
| **Redshift-dependence (Radio-Quiet Quasars)** | | | | | | | |
| $z < 1$      | 66     | 0.38 ± 0.08 | 0.40 ± 0.11 | 20.20 ± 3.32 | 22.68 | 0.5035 | 0.42 |
| $z > 1.5$    | 62     | 0.18 ± 0.09 | 0.22 ± 0.08 | 31.49 ± 4.12 | 11.17 | 0.4460 | 0.26 |

Note: The reported parameters for the fundamental plane best-fits correspond to the X-ray luminosity slope $\xi_X$, the black hole mass slope $\xi_M$, the y-intercept $b$, the best-fit residual variance $\sigma_{\text{res}}^2$, the adjusted R-squared of the best-fit model $R_{\text{adj}}^2$, and the scatter of the log($L_R$) parameter relative to the predicted value from the fundamental plane model $\sigma_R$.

for our radio-quiet sample. Figure 2 shows the result of fitting across the two samples, and Table 2 displays the best-fit coefficients. For completeness, a best-fit was obtained for the entire dataset of radio-loud and radio-quiet quasars, which is also provided in Table 2. The residual variance $\sigma_{\text{res}}^2$, the y-intercept $b$, the best-fit residual variance $\sigma_{\text{res}}^2$, the adjusted R-squared of the best-fit model $R_{\text{adj}}^2$ were measured for each best-fit model, and the results are shown in Table 2. A positive correlation is observed for each best-fit, while the fit statistics demonstrate a preference towards utilizing separate models for the radio-loud and radio-quiet samples.

We compared our best-fit parameters to the result from Merloni et al. (2003), and found that the radio-quiet and Merloni et al. (2003) best-fit parameters agree with one another within 1σ despite different data selection criteria (e.g., redshift and mass). This agreement is unsurprising given that the sample from Merloni et al. (2003) was primarily comprised of radio-quiet sources. In comparison, the radio-loud best-fit parameters each diverge from the Merloni et al. (2003) result by $>3\sigma$. The measured scatters of the fit in the log($L_R$) parameter relative for radio-loud and radio-quiet quasar samples are $\sigma_R = 0.62$ and $\sigma_R = 0.39$, which is at least 68% less than the scatter found by Merloni et al. (2003) and at least 75% less than the scatter found by Gültekin et al. (2009). Hence, the thickness of our radio-quiet fundamental plane is less than previous work that focused on radio-quiet sources.

Our results suggest that the dichotomy between radio-loud and radio-quiet quasars is also found within the fundamental plane, hence, two fundamental planes are better descriptors of quasar populations. In § 4, we discuss the physical impacts of trends observed within the fundamental planes.

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2 We define the coefficient of determination as $R_{\text{adj}}^2 = 1 - \frac{(1-R^2)(N-1)}{N-p-1}$, where $N$ is the total sample size and $p$ is the number of independent variables.
Figure 2. An edge-on view of the fundamental planes of black hole activity, where the sample is separated into radio-loud and radio-quiet quasars. The x-axis is defined in accordance with the best-fit parameters to the total quasar dataset. Best-fit lines for the radio-quiet (blue) and radio-loud (red) are shown. The data demonstrates a clear dichotomy between the fundamental plane best-fit for the two populations.

4 DISCUSSION

4.1 Radio-Loud Dependence on Fundamental Plane

The fundamental plane comparisons performed in §3 reveal several key properties within our quasar samples. First, the fundamental plane from Merloni et al. (2003) with their predominantly radio-quiet heterogeneous sample is consistent with our more homogeneous radio-quiet quasar sample. Second, the Merloni et al. (2003) fundamental plane underpredicts the radio luminosity of the radio-loud quasar sample, resulting in a divergence between the two best-fits over our examined physical parameter space. Radio loudness has previously been shown to impact accretion rates (Sikora et al. 2007; Baloković et al. 2012), so it follows that it should also impact the fundamental plane of black hole activity. Furthermore, studies of radio loudness could help constrain jet formation, acceleration, and collimation (Sikora et al. 2007). Motivated by our observation and its physical significance, we explored the fundamental plane within the context of radio loudness.

The fundamental plane best-fit parameters for the two radio loudness samples are shown in Table 2, and Figure 2 displays our results. Comparing the two best-fits, we find that their difference exceeds the measured scatter $\sigma_R$ of 0.62 and 0.39 for the radio-loud and radio-quiet fits, respectively. Thus, we observe a dichotomy between the black hole activity of radio-loud and radio-quiet sources. The observed separation between the radio-loud and radio-quiet samples is consistent with previous studies that have demonstrated a bimodal distribution of radio loudness amongst the quasar population (e.g., Kellermann et al. 1989; Miller et al. 1990; Ivezić et al. 2004; White et al. 2007; Zamfir et al. 2008; Baloković et al. 2012).

The measured correlation coefficients from our fundamental plane best-fits provide insight into the different emission mechanisms within the quasar samples, where the ratio of these observables can correspond to predicted values from different emission models (Merloni et al. 2003; Plotkin et al. 2012). We therefore plotted the correlation coefficients from our radio-loud and radio-quiet best-fits, which is shown in Figure 3, left. This image further illustrates the dichotomy between our radio-loud and radio-quiet quasar samples as the two best-fits are separated by $>3\sigma$ for both $\xi_X$ and $\xi_M$ parameters. Furthermore, these results indicate that the dominant emission mechanism differs between the two samples.

To assess the probable emission mechanism for our quasar samples, we compared our correlation coefficients to those predicted by different emission models from Merloni et al. (2003). The predicted coefficients are also overlaid on Figure 3. We stress that the plotted model parameters represent a small subsample of the possible quasar emission models, so any emission mechanism predictions and subsequent comparisons should be regarded as approximate. Based on the different model parameterizations from Merloni et al. (2003) that were tested, we found that the radio-quiet sample, on average, favors the advection dominated accretion flows (ADAF) instead of
the standard jet or disc models, which agrees with previous fundamental plane studies for radio-quiet black holes (e.g., Merloni et al. 2003; Gültekin et al. 2009; Plotkin et al. 2012). The distribution of $L_x / L_{Edd}$ values for the radio-quiet sample, shown in Figure 1, is also broadly consistent with radiatively inefficient emission based on the model results of Merloni et al. (2003). In comparison, the radio-loud quasar sample is, on average, more consistent with the standard jet emission model, or a disc model, or a combination of the two. Our finding agrees with previous quasar studies where jet contributions are invoked to explain the radio-loud phenomenon (Worrall et al. 1987; Kellermann et al. 1989; Urry & Padovani 1995).

Overall, our results demonstrate that two fundamental planes are necessary to accurately reflect the different physical mechanisms that govern radio-loud and radio-quiet quasars. These two separate models will help better constrain and predict physical properties of quasar populations such as the nature of jets, accretion processes, and their local environments.

### 4.2 Redshift Dependence on Fundamental Plane

Previous works, due to observational constraints, focused on the fundamental plane within the context of low-redshift sources $z < 0.5$ (e.g., Merloni et al. 2003; Falcke et al. 2004; Körding et al. 2006; Gültekin et al. 2009). As a result, the fundamental plane at high-redshifts is not well-understood. Furthermore, whether the fundamental plane model is constant over the age of the Universe is not well-constrained. We therefore investigated the fundamental plane model across varying redshift.

Due to the observed differences between the population of our radio-loud and radio-quiet sample, we analyzed redshift dependencies of each sample separately. We binned the radio-loud sources across three redshift ranges ($z < 1.5, 1.5 < z < 3.0,$ and $z > 3$), where each redshift bin was selected to ensure similar sample statistics for our analysis. In contrast, we binned the radio-quiet sources across two redshift ranges ($z < 1.5, z > 1.5$), due to its smaller sample size. The best-fit results from these additional tests are shown in Table 2. We note that the measured scatter $\sigma_R$ demonstrates consistency between the different models over the parameter space investigated with our sample (Table 2). Figure 4, left displays the fundamental plane best-fit for the radio-loud quasars, while Figure 4, right displays the best-fit for the radio-quiet quasars.

From our analysis, the radio-quiet best-fits demonstrate broad consistency with one another across the examined redshift range, where the correlation coefficients are in agreement to within $2\sigma$ in all scenarios. Additionally, Figure 3, right illustrates the consistency between the two radio-quiet subsamples while also indicating that each subsample is most consistent with ADAF from the emission models tested. Our result agrees with optical–X-ray studies of quasars that have shown constant trends in power output and accretion rates within radio-quiet quasars up to redshifts $z = 6$ (Just et al. 2007; Nanni et al. 2017; Vito et al. 2019). Ultimately, our current data which spans a redshift range of $0.1 < z < 5.0$ suggests that the radio-quiet fundamental plane model is independent of redshift. Hence, low-redshift fundamental plane models from previous works (e.g., Merloni et al. 2003; Falcke et al. 2004; Körding et al. 2006; Gültekin et al. 2009; Plotkin et al. 2012) may be valid for radio-quiet black holes extending all the way to 9% of the present age of the Universe.

In contrast to the radio-quiet sample, examination of the radio-loud quasar subsamples indicates a decreasing X-ray luminosity dependence for increasing redshift at $\sigma > 3\sigma$ significance. This result is also illustrated in Figure 3, right, where the radio-loud samples clearly demonstrate a decreasing X-ray luminosity dependence versus redshift while mass dependence remains constant to within $1\sigma$. As noted in § 2, the radio luminosity measurements of the high-redshift radio-loud quasar cores may include contributions from extended features due to instrument resolution limits, which would elevate $L_R$ with increasing redshift. Comparatively, extended emission, on average, accounts for $< 2\%$ the total X-ray luminosity of a quasar (e.g., Marshall et al. 2018; Worrall et al. 2020; Snios et al. 2021), which is below other sources of measurement error. If extended emission contamination is present in our radio-loud sample, the $L_R$ values of the high-redshift quasars should be regarded as upper limits on the true AGN core luminosity. Reducing $L_R$ to account for such effects.
Figure 4. An edge-on view of the fundamental planes of black hole activity across different redshift bins for the radio-loud quasars (left) and radio-quiet quasars (right). The best-fit lines for each redshift bin (colored) and the total sample (black) are plotted. The fundamental plane best-fit parameter are found to be broadly consistent across redshifts for both the radio-loud and radio-quiet samples.

would also reduce the measured slope of the fundamental plane for sources at \( z > 3 \), increasing the statistical significance of the inverse relationship between X-ray luminosity and redshift for the fundamental plane. Thus, the presence of contamination would serve to enhance the observed redshift trend for the fundamental plane of the radio-loud quasar population.

Comparing the samples to different emission models from Merloni et al. (2003), we found that the low-redshift radio-loud sample agrees well with the disc model. However, the high-redshift sample is more consistent with a jet model, indicating a possible evolution of the primary emission mechanism for radio-loud quasars. Such an effect would be consistent with the recent theory that inverse Compton upscattering of the cosmic microwave background radiation (IC/CMB) will increase the observed jet intensity for quasars at \( z \geq 3 \) as the energy density of the CMB exceeds the magnetic energy density for the quasar jets (Schwartz et al. 2020).

We stress that the observed redshift dependence in the radio-loud sample is indicative given the limited sample size and coarse redshift binning utilized in our analysis, and a greater sample size across all redshifts is necessary to accurately constrain the existence of a redshift dependence on the primary emission mechanism. Nonetheless, our analysis does suggest a redshift dependence for the fundamental plane of radio-loud quasars.

### 4.3 Using the Fundamental Plane as a Mass Estimator

Historically, fundamental plane studies have focused on investigating the accretion properties of black holes across broad mass and luminosity ranges. However, the fundamental plane may also be used as an estimator of black hole masses due to the scale-invariant nature of the model (e.g., Merloni et al. 2003; Gültekin et al. 2019). Motivated by this fact, we examined the fundamental plane in the context of mass prediction for our quasar sample.

Using the ODR fitting method described in §3, we defined our model as the expression

\[
\log M = \xi_{MX} \log L_X + \xi_{MR} \log L_R + b_M.
\]

Due to the observed dichotomy between radio-loud and radio-quiet quasars described in §4.1, we fit the model to each sub-sample separately. The results for all our fits are shown in Table 3, and Figure 5 displays the best-fit results of our analysis. The results indicate a dichotomy between the radio-loud and radio-quiet sample when fitting the fundamental plane defined in Equation 2, where the best-fit slope parameters \( \xi_{MX} \) and \( \xi_{MR} \) differed by \( > 3\sigma \) between the two best-fits. The measured scatter of the \( \log(M) \) parameter between the measured and predicted values \( \sigma_M \) are determined to be 0.43 and 0.45 for the radio-loud and radio-quiet samples, respectively. The scatter is consistent between the two datasets, and both samples cover a comparable physical parameter range. Altogether, we find that the fundamental plane model for mass measurements is dependent on radio loudness.

To assess the accuracy of the fundamental plane as a black hole mass predictor, we compared the predicted masses determined by our fundamental plane fits with the spectroscopically measured values from the SDSS-DR14 emission line analysis compiled by Rakshit et al. (2020). We found that, on average, the predicted \( \log(M) \) values from the fundamental planes differs from those values determined from spectroscopic modeling by a percent difference of 3.9% and 4.1% for the radio-loud and radio-quiet quasars, respectively. We additionally calculated the root mean square error (RMSE), also known as the standard deviation of the residuals, between the predicted black hole mass from the fundamental plane model and the spectrum-measured mass from Rakshit et al. (2020). We find that the radio-loud and radio-quiet quasars have an RMSE of 0.43 log(\( M_\odot \)) (5.0%) and 0.45 log(\( M_\odot \)) (5.5%), respectively. Our method of black hole mass estimation is broadly consistent with previous studies that

\[\text{RMSE} = \sqrt{\frac{1}{N} \sum (P_i - \hat{P}_i)^2/N} \]

3 We define the percent difference of the sample as \( \frac{100}{\sigma_i} \frac{P_i - \hat{P}_i}{\hat{P}_i} \), where \( O \) is the measured value from the fundamental mass plane, \( P \) is the mass value from Rakshit et al. (2020), and \( N \) is the sample size.

4 We define the root-mean square error as \( [\Sigma_i^N (O_i - P_i)^2/N]^{1/2} \), where \( O \) is the measured value from the fundamental mass plane, \( P \) is the mass value from Rakshit et al. (2020), and \( N \) is the sample size.
utilized the fundamental plane as a mass estimator (e.g., Gültekin et al. 2019), despite our study focusing on high-mass quasars ranging between $10^6 - 10^{10} M_\odot$ while previous works prioritized low-mass, low-redshift sources.

The accuracy of black hole mass estimates from spectroscopic modeling is known to worsen with increasing redshift due to a reduction in the available emission lines in the optical band as well as a greater reliance on low signal-to-noise emission lines, such as Mg II and C IV (Shen 2013). We theorize that the mass estimates from the fundamental plane would not suffer from a similar degradation in accuracy with increasing redshift given the comparable radio and X-ray flux errors across our sample. To test this theory, we divided our total quasar sample into low-redshift ($z < 3$) and high-redshift ($z > 3$) subsamples. For the fundamental plane mass measurements, we found an average RMSE of 5.1% for quasars at $z < 3$ and 5.4% for quasars at $z > 3$. In contrast, the spectroscopic mass measurements taken from Rakshit et al. (2020) have an average error percentage of 1.6% for quasars at $z < 3$ and 2.5% for quasars at $z > 3$.

Given our selection of conservative errors for the radio and X-ray fluxes (§ 3), the precision of the fundamental plane method could improve if more accurate uncertainties are utilized. Nonetheless, our results demonstrate that the accuracy of the fundamental plane mass model is predominantly redshift invariant, while the accuracy of spectrum-measured masses worsens with redshift. Thus, our derived fundamental plane for black hole mass may prove useful in studying high-redshift quasars as well as situations where more standard mass estimation techniques, such as spectral modeling, are not possible.

5 CONCLUSION

We examined the fundamental plane of black hole activity for correlations with redshift and radio loudness in both radio-loud and radio-quiet quasar populations. Utilizing archival observations, we compiled quasar data that varied across radio loudness, mass, and redshift to obtain a sample of 353 sources. We constructed a fundamental plane of black hole activity, and our best-fit for the two samples are $log L_R = (1.12 \pm 0.06) log L_X - (0.20 \pm 0.07) log M - (5.64 \pm 2.99)$ for our radio-loud sample and $log L_R = (0.48 \pm 0.06) log L_X + (0.50 \pm 0.08) log M + (15.26 \pm 2.66)$ for our radio-quiet sample.

We examined the impact of radio loudness on the fundamental plane best-fit for within our quasar sample. Our results demonstrate that two different fundamental planes are required to accurately model the dichotomy of radio-loud and radio-quiet quasar populations. Thus, we concluded that the radio-loud and radio-quiet quasar populations are governed by different fundamental plane models. Comparing the best-fit correlation coefficients to values predicted from different emission models, we found that a possible emission mechanism for the radio-quiet sample is advection dominated accretion flows while the radio-loud sample is likely a combination of jet and disc emission.

We also explored the dependencies of redshift on the fundamental plane as well as situations where more standard mass estimation techniques, such as spectral modeling, are not possible.

Table 3. Best-Fit Parameters of Black Hole Mass Fundamental Plane Analysis

| Number of Sources | $\xi_{MX}$ | $\xi_{MR}$ | $b_M$ | $\sigma_{\text{res}}^2$ | $R_{\text{adj}}^2$ | $\sigma_M$ |
|------------------|-----------|-----------|-------|-----------------|-----------------|-----------|
| Radio-Loud Quasars | 225       | 0.63 ± 0.05 | -0.21 ± 0.04 | 10.47 ± 2.09 | 15.56 | 0.1474 | 0.43 |
| Radio-Quiet Quasars | 128       | 0.08 ± 0.07 | 0.41 ± 0.06 | 11.42 ± 3.61 | 32.00 | 0.3281 | 0.45 |

Note: The reported parameters for the fundamental plane best-fits correspond to the X-ray luminosity slope $\xi_{MX}$, the radio luminosity slope $\xi_{MR}$, the y-intercept $b_M$, the best-fit residual variance $\sigma_{\text{res}}^2$, the adjusted R-squared of the best-fit model $R_{\text{adj}}^2$, and the scatter of the log($L_R$) parameter relative to the predicted value from the fundamental plane models $\sigma_M$. 

Figure 5. An edge-on view of the fundamental planes of black hole activity where log $M_{BH}$ is the predicted variable, where the sample is separated into radio-loud (left) and radio-quiet quasars (right). Best-fit lines for the radio-quiet and radio-loud are shown. The derived mass measurements are found to be consistent with spectroscopic mass estimation techniques for black holes, where the accuracy of the fundamental plane mass estimates is comparable to those obtained from spectroscopic mass measurements of high-redshift quasars.
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Leveraging our fundamental plane results, we derived a best-fit expression for black hole mass estimation that used only the radio and the X-ray luminosities. We found a best-fit of log M = (0.63 ± 0.05) log L_X − (2.21 ± 0.04) log L_R − (10.47 ± 2.09) for the radio-loud quasars and log M = (0.08 ± 0.07) log L_X − (0.41 ± 0.06) log L_R − (11.42 ± 3.61) for the radio-quiet quasars. The accuracy of our fundamental plane mass estimation method was assessed for each sample, and we found an average 4.0% difference between it and standard estimates from optical spectrum emission lines. Thus, this method may prove useful in studying the high-redshift quasar population as well as situations where high signal-to-noise emission lines utilized for spectral modeling are not present at standard observing wavelengths.

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DATA AVAILABILITY
The data used in this investigation are available with the article in a machine-readable format.

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