

Constraining the Physical Properties of Quadruply Lensed Quasars using Optical-to-X-Ray Data

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ABSTRACT

Gravitational lensing of luminous active galactic nuclei (AGN; or quasars) can be used as a natural telescope to zoom in on their inner structures. With more and more lensed AGN being discovered, it is extremely important to have a homogeneous study focused on constraining their key physical properties, especially the bolometric luminosity. The primary limitation for such a study is the availability of observations for a representative sample of lensed AGN in at least the optical, ultraviolet (UV), and X-ray bands, where most of the AGN emission is concentrated. In this paper, we present one of the largest multiwavelength studies of lensed AGN with the aim of accurately measuring some of the fundamental quantities, such as their bolometric luminosities, black hole masses, and Eddington ratios. We compiled photometric and spectroscopic data in optical/UV and X-rays, for 27 quadruply lensed AGN ($0.6 < z < 3.1$) and calculated their bolometric luminosities by fitting their broadband spectral energy distributions (SEDs) with phenomenological models. We also performed spectral emission line fitting to estimate their black hole masses using the virial method. Additionally, we compared different prescriptions to calculate the bolometric luminosities of AGN from limited data, and our results show that the luminosity-dependent 2–10 keV X-ray bolometric corrections provide unbiased and reliable predictions of the bolometric luminosity, with a maximum scatter of ~ 0.5 dex. The predictions from optical bolometric corrections are generally overestimated but show a lower scatter once microlensing effects are taken into account. Thanks to the compiled optical/UV and X-ray data for our lensed AGN sample, we also present the well-known UV-X-ray luminosity relation for AGN as a novel way to determine uncertainty in the magnifications of lensed AGN induced by micro- and/or millilensing.

Key words. galaxies: active – galaxies: nuclei – quasars: general – quasars: supermassive black holes – gravitational lensing: strong – gravitational lensing: micro

1. Introduction

Over the years, one of the major challenges in the study of active galactic nuclei (AGN) has been to determine their bolometric luminosity (L_{bol}). The total accretion luminosity or the bolometric luminosity is one of the key physical properties of AGN, which is essential to understand their accretion and emission physics, as well as how they interact with their host galaxies. However, since AGN emit radiation at multiple wavelengths (from radio to X-rays) via various physical processes (e.g., Netzer 2013), a wealth of multiband data is needed to accurately measure their bolometric luminosity. This primarily requires access to their optical, ultraviolet (UV), and X-ray emission data, as these wavelengths are the major contributors to their bolometric luminosity. The optical/UV photons are emitted by the accretion disk surrounding the central supermassive black hole (SMBH), while the X-rays are produced in a plasma of hot electrons located close to the central black hole via Comptonization (e.g., Haardt & Maraschi 1991). Together, these two constitute the bolometric emission of the AGN. Additionally, the entire AGN structure is surrounded by a geometrically and optically thick torus-like

structure made up of dust and molecular gas, referred to as the ‘dusty torus’ (e.g., Urry & Padovani 1995). However, since the torus just reprocesses part of the optical/UV emission from the disk and re-emits in the infrared (IR), it does not contribute to the intrinsic emission of the AGN.

The difficulty of estimating L_{bol} further translates to the calculation of the accretion rate and the Eddington ratio (λ_{Edd} : mass-normalized accretion rate) of the AGN, which are crucial for black hole growth studies. The lack of reliable estimates of these fundamental properties of AGN is even more prominent for certain classes, such as obscured AGN, low-luminosity AGN, super-Eddington AGN, and lensed AGN. Most of these AGN types are relatively scarce in the general AGN population, due to their low brightness (especially in the optical/UV), which makes it a bit complicated to accurately quantify their bolometric luminosities. But in the case of gravitationally lensed AGN, even though we have large samples of optically selected, extremely bright AGN (quasars¹; Ducourant et al. 2018; Lemon et al. 2019, 2023), we are still missing a systematic multiwavelength study dedicated to constraining their physical properties. Additionally,

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¹ We use the terms quasars and AGN interchangeably throughout the text as most of the sources in our sample are intrinsically bright.

since lensed AGN provide a unique way to probe the inner structures of AGN (e.g., [Grieger et al. 1988](#)), which are otherwise difficult to resolve, it is extremely important to accurately characterize their key properties, including the bolometric luminosity. However, the available literature on lensed AGN consists only of source-specific studies or those with small samples and limited data (e.g., [Pooley et al. 2007](#); [Greene et al. 2010](#); [Sluse et al. 2012](#); [Melo et al. 2021, 2023](#)). Through this work, we aim to take a step towards solving this issue, by using available multi-band data to characterize the physical properties of lensed AGN.

Generally, the best way to calculate L_{bol} for an AGN is to construct and fit its broadband spectral energy distribution (SED). However, various other methods are employed to calculate the bolometric luminosity of AGN in the absence of multi-band data. The most common is to use bolometric corrections. Bolometric corrections (κ_{λ}) are defined as the ratio of the bolometric luminosity of the AGN to the luminosity at a specific wavelength/energy (L_{λ} ; $\kappa_{\lambda} = L_{\text{bol}}/L_{\lambda}$). Since they quantify the emission fraction of AGN at a particular wavelength, they can be easily used to estimate L_{bol} from limited data. Optical and X-ray bolometric corrections are widely used by the AGN community to compute L_{bol} for sources without multiwavelength data. Specifically, X-ray bolometric corrections in the 2–10 keV energy range (κ_{2-10}) are extremely useful as the X-rays (unlike optical/UV) are not contaminated by the host galaxy light and are less prone to dust extinction.

In the case of gravitationally lensed quasars, X-rays provide an additional advantage because they are also not affected by the light from the foreground lens. While acquiring reliable AGN flux in the optical/UV can be very technologically demanding, as it requires accurate modeling of the lens as well as the host galaxy (in some cases), the X-ray spectral extraction process is quite trivial. Therefore, X-ray bolometric corrections provide a useful tool for estimating the bolometric luminosity of lensed AGN, with far fewer sources of uncertainty compared to the optical. However, contrary to the optical bolometric corrections that are not luminosity dependent, κ_{2-10} increases with the AGN luminosity and Eddington ratio (e.g., [Lusso et al. 2012](#); [Duras et al. 2020](#); [Gupta et al. 2024](#)). Hence, one needs to be careful when using them to calculate L_{bol} , and, in turn, λ_{Edd} . As a result, most of the studies based on gravitationally lensed quasars commonly use optical bolometric corrections instead of the X-rays (e.g., [Sluse et al. 2012](#); [Melo et al. 2021, 2023](#)). Additionally, X-rays are more prone to microlensing due to the smaller physical scale of their emitting region, in which case they cannot be a reliable estimator of L_{bol} . Furthermore, optical instruments have better spatial resolution compared to X-ray telescopes, which is needed to resolve the multiple images of lensed AGN. In conclusion, both optical and X-rays have specific advantages (and disadvantages) over each other to be used as accurate L_{bol} estimators.

The aim of the work presented in this paper is three-fold. First, we have performed a comprehensive multiwavelength study of a sample of quadruply imaged lensed AGN, with the goal of measuring their important physical properties, such as bolometric luminosity (L_{bol}), black hole mass (M_{BH}), and Eddington ratio (λ_{Edd}). This was done by compiling optical, UV, and X-ray photometric and spectroscopic data for a sample of 27 lensed AGN systems ($0.6 < z < 3.1$). To date, this is the largest sample of quadruply lensed AGN for which such an analysis has been carried out in a consistent way. Moreover, for most of the systems in our sample, these measurements have been made for the first time. Second, we have explored the well-known UV-X-ray luminosity relation for AGN as a new method to identify

systematic uncertainties in the lensing magnification corrections of lensed AGN, caused by either incorrect lens models or by the presence of micro- or millilensing in one of the lens images. Finally, we have also used the available multiband data to perform specific tests to determine the best way to use the X-ray and optical/UV bolometric corrections as an estimator of the bolometric luminosities in lensed AGN in the absence of multiwavelength data.

The structure of the paper is as follows. In Sect. 2, we describe the sample of lensed AGN (Sect. 2.1) and the multiwavelength data (Sects. 2.2 and 2.3) used in this work, while in Sect. 3 we illustrate the data analysis process for the X-ray (Sect. 3.1) and optical/UV data (Sects. 3.2 and 3.3). In Sect. 4, we present our main results, including estimates of L_{bol} , M_{BH} , and λ_{Edd} . We present the UV-X-ray luminosity relation in the context of lensed AGN (Sect. 5.1) and show the most accurate method to use X-ray (Sect. 5.2) and optical/UV (Sect. 5.3) bolometric corrections as L_{bol} estimators in Sect. 5. Finally, in Sect. 6, we summarize the main takeaways from this paper. Throughout the paper, we assume a cosmological model with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{\text{M}} = 0.3$, and $\Omega_{\Lambda} = 0.7$. All magnitudes quoted throughout the text are AB magnitudes. All errors and uncertainties listed in the tables or shown as error bars or shaded regions in the figures are one sigma, unless otherwise stated. The correlations were obtained using various functions from the `statistics`² module of the Python library `scipy` ([Virtanen et al. 2020](#)) and the significance of the correlations is determined using the Pearson’s correlation test.

2. Sample and data

2.1. Sample

Our parent sample consists of 31 quadruply lensed AGN systems from the JWST GO-2046 proposal (PI Nierenberg). As part of the JWST lensed quasar dark matter survey ([Nierenberg et al. 2024](#)), these sources were observed with JWST/MIRI. For details about the observations, see [Keeley et al. \(2024, 2025\)](#). As mentioned in [Keeley et al. \(2025\)](#), the lensed system J0457-7820 is a triplet, and the system J2107-1611 is doubly imaged. Therefore, we do not include these sources in our analysis, and moving forward, we work with 29 sources.

For the 29 quadruply lensed quasars in the original sample, we checked archival data and previous publications to compile all available optical, UV, and X-ray observations. Due to the difference in the availability of multiband photometric and spectroscopic data for the sources in our sample, we used various strategies to optimally utilize the available data and obtain the desired products. For a total of 17/29 (59%) sources, we were able to combine measurements from the literature (in optical/UV) and archival observations (for X-ray and optical/UV) to construct their broadband SEDs. For the remaining 10/29 (34%) sources, with limited optical/UV photometry (< 3 bands) or lacking X-ray observations, we were unable to model their broadband SEDs accurately (see Sect. 3.2 for details). In such cases, we used optical or X-ray bolometric corrections to estimate L_{bol} . In Sect. 5.2, we discuss in detail why this is the best approach to calculate L_{bol} for such sources. For the two remaining sources (B2045+265 and J2205-3727), we did not have sufficient data to include them in this multiwavelength study. Hence, our final sample consists of 27 lensed quasars that are listed in Table 1,

² <https://docs.scipy.org/doc/scipy/reference/stats.html>

Table 1: Lens systems in our sample.

Object	z_s	z_l^a	R.A.	Dec.	Distance	Optical/UV Photometry
RXJ1131-1231	0.66	0.30	172.9644	-12.5329	3922.4	Sluse et al. 2006
DESJ2038-4008	0.78	0.23	309.5113	-40.1371	4840.7	Agnello et al. 2018
SDSSJ1251+2935	0.80	0.40	192.7815	29.5946	5032.9	-
GRAL1131-4419	1.09	0.47	172.7502	-44.3332	7350.1	-
HE1113-0641	1.24	0.70	169.0981	-6.9608	8578.4	-
WISE2344-3056	1.30	0.5	356.0706	-30.9406	9123.0	This work
J0607-2152	1.30	0.56	91.7954	-21.8716	9183.9	-
SDSSJ0924+0219	1.52	0.39	141.2325	2.3236	11115.0	Floyd et al. 2009
J2145+6345	1.56	0.5	326.2713	63.7614	11449.0	-
WFI2033-4723	1.66	0.66	308.4257	-47.3956	12378.2	Morgan et al. 2004
PSJ1606-2333	1.70	0.92	241.5009	-23.5561	12635.4	Lemon et al. 2018
HE0435-1223	1.69	0.45	69.5619	-12.2875	12663.0	Kochanek et al. 2006
DESJ0405-3308	1.70	0.5	61.4988	-33.1475	12847.3	Anguita et al. 2018
J1537-3010	1.71	0.59	234.3556	-30.1713	12911.9	Lemon et al. 2019
J2017+6204	1.72	0.5	304.4544	62.0787	12911.9	-
PG1115+080	1.71	0.31	169.5704	7.7663	13050.6	Morgan et al. 2008
WISEJ0259-1635	2.16	0.91	44.9286	-16.5953	17069.5	This work
WFI2026-4536	2.23	0.5	306.5435	-45.6075	17746.5	Morgan et al. 2004
J0608+4229	2.35	0.5	92.1725	42.4935	18818.1	-
PSJ0147+4630	2.38	0.68	26.7923	46.5118	19180.6	Berghea et al. 2017
SDSSJ0248+1913	2.44	0.5	42.2031	19.2253	19800.0	-
J1042+1641	2.50	0.59	160.5921	16.6876	20560.8	This work
H1413+117	2.56	1.15	213.9427	11.4954	20987.3	Muñoz et al. 2011
MG0414+0534	2.64	0.96	63.6572	5.5786	21784.2	-
2M1134-2103	2.77	0.66	173.6688	-21.0563	23087.4	Rusu et al. 2019
J0803+3908	2.97	0.5	120.9905	39.1398	25111.6	-
J0659+1629	3.10	0.77	104.7670	16.4859	26265.0	This work

Notes. We have listed the lensed AGN systems along with their coordinates (in degrees, J2000), redshifts of the source and the lens, distances in Mpc, and reference for the optical/UV photometry. For sources with optical/UV photometry extracted in this work, we used HST observations in the F475X and F814W bands to calculate the AGN fluxes (described in Sect. 2.3).

^(a) For systems without any estimate for the lens redshift, we assumed $z_l = 0.5$ (to be consistent with Keeley et al. 2025 and Gilman et al. 2025).

along with their lens and source redshifts (for details see Gilman et al. 2025), coordinates, and distances. The image naming conventions for these quasars are shown in the appendix (Fig. C.1).

We also compiled rest-frame optical/UV spectra for 19/27 (70%) systems to estimate their black hole masses using the virial method (Sect. 3.3) and further calculate their Eddington ratios ($\lambda_{\text{Edd}} = L_{\text{bol}}/L_{\text{Edd}}$; $L_{\text{Edd}} = 1.5 \times 10^{38} \times \frac{M_{\text{BH}}}{M_{\odot}} \text{ erg s}^{-1}$).

2.2. X-ray data

To compile the publicly available X-ray observations for our lensed AGN sample, we used the HEASARC archive³. For this study, we only used observations with the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003) on board the *Chandra* X-ray Observatory⁴, due to its high angular resolution

($\sim 0.5''$). This is important because unlike nonlensed AGN, lensed AGN have multiple images that need to be distinguishable on the sky to precisely extract and model their X-ray spectra. We recovered X-ray observations for 26/27 ($\sim 96\%$) sources (listed in Table 2). In case of multiple observations for the same source, we used the one with the largest exposure time to have a significant number of photons in the spectrum.

We used the official software package developed by the Chandra X-Ray Center (CXC) for data analysis: CIAO⁵ (Chandra Interactive Analysis of Observations; Fruscione et al. 2006) v4.15 with CALDB v4.10.4, to reduce the X-ray observations and extract the X-ray spectra. For the quadruply lensed AGN in our sample, the images have separations ranging from $0.3''$ to $5''$ (see Fig. C.1 for reference). Whenever possible, we tried to get the spectra for all the four lensed images. However, in cases where two or more lensed images were within $\sim 1.5''$ (~ 3 pixels) of each other and could not be resolved, we worked with

³ <https://heasarc.gsfc.nasa.gov/cgi-bin/W3Browse/w3browse.pl>

⁴ <https://chandra.harvard.edu/>

⁵ <https://cxc.cfa.harvard.edu/ciao/>

unresolved images. Additionally, for some sources with low exposure times (< 5 ks), it was impossible to distinguish individual lensed images due to low counts, so we could only extract one spectrum for such systems. For 7/26 (27%) sources, we successfully extracted the X-ray spectra for all images; for 10/26 (38%) sources, only one spectrum per source was extracted, as the lens system was unresolved; for the remaining 9/26 (35%) sources, we had a combination of resolved and unresolved images (see Table 2 for details).

We followed the steps prescribed by the Chandra analysis guide⁶ to extract the X-ray spectra. We first used the `chandra_repro` command to reprocess the downloaded observations. The reprocessed event files were then used to create circular source regions around each resolved image (whenever possible) so that there was no contamination from other images. Finally, we used the `specextract` command to extract the source spectra (.pi) in the specified regions, along with their ancillary (.arf) and response (.rmf) files. A similar procedure was followed in the case of unresolved images for certain lens systems, as well as for completely unresolved systems. All extracted spectra were rebinned to include at least one count per bin.

2.3. Optical/UV data

For optical/UV photometry, we mainly relied on published data from the literature. Primary preference was given to studies that reported flux estimates in at least three bands for all resolved images for each system. A minimum of three bands were needed to eventually construct statistically reliable SEDs (see Sect. 3.2 for more details). This was available for 13/27 (48%) sources in our sample (see Table 1). For 4/27 (15%) sources⁷, we measured the AGN fluxes from archival observations⁸ with the Wide Field Camera 3 (WFC3) of the *Hubble* Space Telescope (HST), in the F475X and F814W bands. The third photometric point was estimated from the available spectroscopy for these systems (listed in Table 3). We calculated the third band flux in the wavelength range 6065 Å – 7062 Å, to complement the fluxes in HST bands F475X and F814W, and to create a continuous SED.

The AGN fluxes in the two HST bands were calculated by performing lens/source decomposition with four Moffat profiles and a Sérsic profile, to fit the four lensed images and the lensing galaxy, respectively. All lensed quasars in our sample are optically selected and hence significantly brighter than their host galaxies. For three of the lenses, we did not detect any host light in the fit residuals, and for one system, the host contribution was as low as 10%. So we fit the four point-like lensed quasar images with only a Moffat profile. The input parameters for the Moffat profile include the coordinates and intensity of the source (lensed image), width and slope of the profile. In all four lensed systems, the input value of the model parameters was estimated by fitting one lensed image at a time, in order of decreasing brightness. For each system, we started by fitting the brightest lensed image with a Moffat profile. After obtaining a good fit for the first image, the corresponding fit parameters were fixed to their best-fit values, and a second Moffat profile was added to the model to fit

Table 2: X-ray observations for the lens systems in our sample.

Object	Obs. ID	Exposure	Resolved Images
RXJ1131	4814	10180	All
DESJ2038	21440	6050	All
SDSSJ1251	22016	1610	Unresolved
GRAL1131	25405	29710	A, B, C+D
HE1113	14961	29560	Unresolved
WISE2344	22017	1610	Unresolved
J0607	25408	5380	A, B+C, D
SDSSJ0924	11564	22160	A+C+D, B
J2145	28209	10080	A, B, C+D
WFI2033	5603	15620	A1+A2, B, C
PSJ1606	20490	30110	Unresolved
HE0435	14489	38060	All
DESJ0405	26343	13950	Unresolved
J1537	23828	23050	All
PG1115	363	26830	A, B, C+D
WISEJ0259	21444	25090	A+D, B, C
WFI2026	7758	10170	A1+A2+C, B
J0608	25407	4960	Unresolved
PSJ0147	21443	10660	All
SDSSJ0248	23824	4950	Unresolved
J1042	23135	24490	Unresolved
H1413	5645	90040	Unresolved
MG0414	12800	30050	A+B, C, D
2M1134	21442	30070	All
J0803	29168	11760	Unresolved
J0659	23825	15070	All

Notes. We have listed the observation IDs and exposure times (in seconds) for the Chandra X-ray observations for the lens systems in our sample. In the last column, we report the images for each system that were resolved in these observations.

the second brightest lensed image. This procedure was repeated for every consecutively faint image and finally for the lensing galaxy, which was fitted using a Sérsic profile. In the final step, the best-fit values obtained so far for the five profiles (four Moffats and one Sérsic) were used as input values for the model parameters (and left free to vary), and all five sources (four lensed images and one lensing galaxy) were fit simultaneously to obtain the best-fit model for the entire lensed system. All residuals were visually inspected, and the least-squares statistics was employed to obtain the best-fit model. The lensed quasar fluxes thus obtained (listed in Table C.1) were used to construct the optical/UV SEDs, which were used to complement the X-ray spectra and perform a broadband SED fit for these four systems (Sect. 3.2). For the remaining 10/27 (37%) sources, there was no useful multiband photometry available.

To estimate the black hole masses of the lensed AGN using the virial method (discussed in Sects. 3.3 and 4.2), we also compiled the rest-frame optical/UV spectra for 19/27 (70%) systems from various astronomical facilities (see Table 3 for details). For 12/19 (63%) systems, we acquired spectra from ~ 1500 Å to $\sim$

⁶ <https://cxc.cfa.harvard.edu/ciao/guides/index.html>

⁷ HST flux measurements for these sources were published in Schmidt et al. (2023), where the lens models were optimized for time delay cosmography and the noise of the PSF was boosted to avoid overfitting in the PSF reconstruction. Obtaining accurate point source fluxes was not a goal of that paper, but it is important for this work. Therefore, we did not use those values and re-measured the fluxes ourselves using a procedure optimized for point source flux measurements.

⁸ Cycles 25 and 26 programs HST-GO-15320 and HST-GO-15652

Table 3: Rest-frame optical and UV spectroscopy for the lens systems in our sample.

Object	Telescope/Instrument	Emission Line	Images
DESJ2038	VLT/MUSE	Mg II	All
WISE2344	VLT/XSHOOTER	Mg II	A+D, B+C
J0607	Keck/LRIS	Mg II	A, D
SDSSJ0924	Keck/ESI	Mg II	A, B
WFI2033	VLT/MUSE	Mg II	All
PSJ1606	VLT/MUSE	Mg II	All
HE0435	VLT/FORS1	Mg II	B, D
DESJ0405	Magellan/IMACS	C IV	B, C
J1537	VLT/MUSE	Mg II	All
J2017	Keck/LRIS	Mg II	B
PG1115	VLT/MUSE	Mg II	All
WISEJ0259	VLT/XSHOOTER	Mg II	A+C, B+D
WFI2026	VLT/FORS1	C IV	A1+A2, B
J0608	Keck/LRIS	C IV	Unresolved
PSJ0147	GTC/EMIR	H α	B, C, D
SDSSJ0248	Keck/ESI	Mg II	B, C
H1413	VLT/SINFONI	H α	All
2M1134	VLT/MUSE	C IV	All
J0659	Keck/LRIS	C IV	All

Notes. We have listed the telescope and instrument pair used to obtain the optical/UV spectroscopy for the lens systems in our sample. We also report the emission line used to estimate the black hole mass of the system. The last column indicates the individual lensed images (or pair of images in case of compact systems) for which the spectra were available.

3500 Å rest-frame, which included the Mg II λ 2798 broad emission line. For 5/19 (26%) systems, we used the broad C IV λ 1549 from their rest-frame spectra in the wavelength range ~ 1000 Å to ~ 2500 Å. Finally, for 2/19 (11%) sources with spectra available at longer wavelengths (~ 4000 Å to ~ 7000 Å rest-frame), we used the H α line to estimate their black hole mass.

3. Data analysis

To calculate the bolometric luminosity of lensed AGN, we first need to obtain their intrinsic X-ray and optical/UV luminosity corresponding to the coronal and disk emission, respectively. In Sect. 3.1, we describe the procedure we followed to fit the X-ray spectra and obtain the X-ray luminosity. Sect. 3.2 discusses the method used to convert the optical/UV magnitudes into the total emission from the accretion disk. Finally, in Sect. 3.3 we derive the black hole mass from optical/UV spectroscopy for each system.

3.1. X-ray spectral fitting

To fit the 0.3–10 keV X-ray spectra for our lensed AGN systems, we used the X-ray spectral fitting package XSPEC (Arnaud 1996). We extracted the X-ray spectra for individual lensed images (whenever possible) and for unresolved images for a total of 26 systems (see Sect. 2.2). We used a simple powerlaw

(POWERLAW) model with Galactic absorption (TBABS) to fit these spectra. The column density (N_H) for Galactic absorption was fixed at the value obtained at the coordinates of the source from the HI 4-PI Survey (HI4PI; HI4PI Collaboration et al. 2016), a 21-cm all-sky survey of neutral atomic Hydrogen. The spectra were fit using Cash statistics (C-stat; Cash 1979). The best-fit values of all free parameters (photon index: Γ and normalization: K_x) were checked using the `steppar` command in XSPEC to avoid fits corresponding to local minima. Additionally, the 90% confidence intervals for all parameters were estimated using the `error` command in XSPEC. All the fit residuals were visually inspected and their goodness was checked using the reduced chi-square value.

Based on the best fit models, we calculated the total intrinsic (rest-frame and absorption corrected) X-ray flux (F_x) in the 0.1 to 500 keV energy range for all our lensed AGN (resolved and unresolved). The uncertainties in the flux were calculated using the upper and lower limits of K_x . The corresponding luminosities were calculated using the distances listed in Table 1. Finally, all X-ray luminosities were corrected for lensing macro magnifications (listed in Table B.1). This final magnification corrected estimate of the total X-ray luminosity (L_x) will be later combined with the optical/UV disk luminosity, to estimate the bolometric luminosity of the 17 lensed AGN with multiband optical/UV photometry. For the remaining nine systems, we calculated their intrinsic, magnification corrected luminosities in the 2–10 keV energy band (L_{2-10}) to calculate the bolometric luminosity using the 2–10 keV bolometric correction ($L_{bol} = \kappa_{2-10} \times L_{2-10}$; see Sect. 4.1). We provide a detailed discussion and specific tests in Sect. 5.2 to justify this approach.

3.2. Optical/UV SED fitting

We used the optical and UV magnitudes compiled for each system in Sect. 2.3 to populate the optical/UV part of their SEDs. The optical/UV SEDs were fitted in XSPEC using the DISKPN model, which is a thermal accretion disk model comprising multiple blackbody components (e.g., Mitsuda et al. 1984; Makishima et al. 1986). This model follows the assumptions of the standard Shakura & Sunyaev (1973) disk around an accreting black hole. Although this model is known to have its own limitations, mainly for sources with higher and lower accretion rates (see Beloborodov 1999 for a review), it can still successfully reproduce the observed optical/UV emission of most AGN (e.g., Capellupo et al. 2015, 2016; Gupta et al. 2024). Moreover, because of the heterogeneity⁹ in the multiband optical/UV photometry available for our sample, we avoid using more complex disk models to fit the SEDs and instead follow a simple but consistent approach throughout our sample. This approach makes it possible to compare results across our sample in a consistent way. The free parameters for DISKPN include the normalization (K_{uvo}) and the maximum temperature of the disk (kT_{max} ; in units of keV). The inner radius of the disk (R_{in} ; in units of $R_g = GM/c^2$) is fixed to 6.0 gravitational radii¹⁰. We use the convolution model ZASHIFT to shift the disk spectrum to the redshift of the respective source. In addition to the disk model, we include a compo-

⁹ We checked if the heterogeneity in the methods used to calculate the AGN fluxes in the literature affects our SED fits and outputs. We found that our SED fits are not sensitive to errors as low as 0.5 mag in the AGN fluxes, which is the extent of differences in the AGN photometry estimated using different methods.

¹⁰ <https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/node171.html>

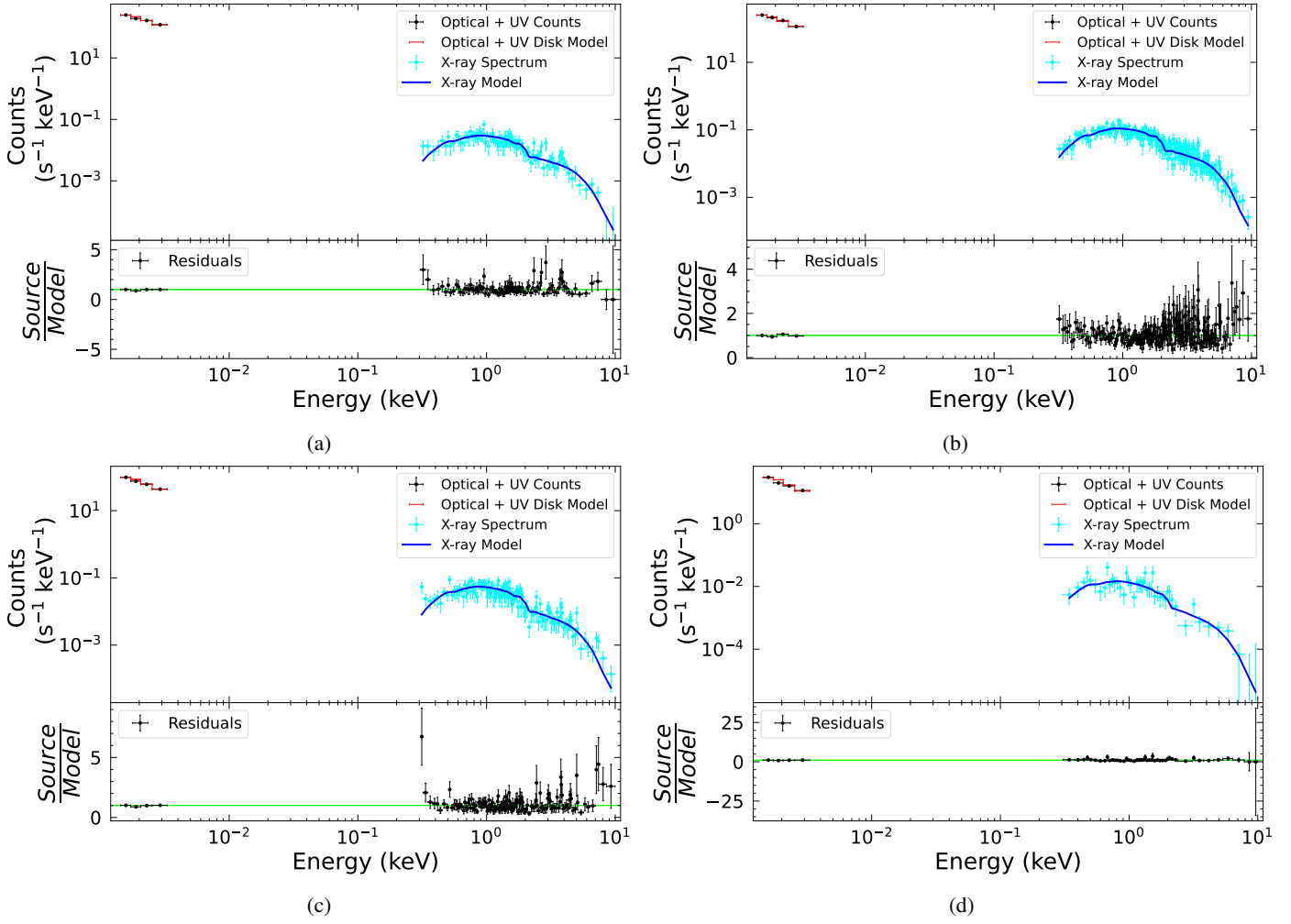


Fig. 1: An example of the optical-to-X-ray SED fitting of the four resolved images of the lensed system RXJ1131. Each of the individual panels show the counts in the optical/UV filters (black points) and the 0.3–10 keV X-ray spectrum (cyan points). They also show the best-fit obtained using the optical/UV disk model including dust extinction (in red) and the X-ray powerlaw model with Galactic absorption (in blue). The fit residuals are shown in the bottom of each panel.

nent of the ZDUST model to take into account the extinction due to dust grains (Pei 1992) in the optical and UV bands, associated with the Milky Way (ZDUST). For this reddening component, we adopt a Milky Way extinction curve with $R_V = 3.08$. We fix the $E(B - V)$ value to those estimated by Schlegel et al. (1998), who combined the results of IRAS and COBE/DIRBE to create a 100-micron intensity map of the sky.

Based on the number of free parameters in our model, we require optical/UV photometry in at least three bands to obtain a statistically reliable SED fit. These data were available for 17 systems in our sample (see Sect. 2.3). We fitted the optical/UV SEDs of all four lensed images for these systems with the model described above. The goodness of fit was checked using the reduced chi-square value (~ 1) and all residuals were visually inspected. The best-fit values of all free parameters were checked using the `steppar` command to avoid fits corresponding to local minima. The errors in the free parameters (kT_{max} and K_{uvo}) were calculated using the `error` command to give 90% confidence intervals. An example of our SED fit, along with the best-fit model and residual, is shown in Fig. 1. The final best fits were used to calculate the intrinsic (rest-frame and absorption-corrected) model fluxes and luminosities. The upper and lower limits of these fluxes were calculated considering the upper and

lower bounds of K_{uvo} . The total intrinsic optical + UV luminosity was estimated in the $1000\mu\text{m}$ to 0.1 keV range, since the standard Shakura & Sunyaev (1973) disk typically has very little to no emission in the X-rays. All luminosities were corrected for the respective lens magnifications (listed in Table B.1). The corrected disk luminosity (L_{uvo}) was combined with L_x (see Sect. 3.1) to estimate the total accretion luminosities ($L_{\text{bol}} = L_{\text{uvo}} + L_x$) of the 17 lensed AGN in our sample with optical-to-X-ray data.

3.3. Optical/UV spectral fitting

In this section, we describe the spectral emission line fitting method employed to estimate the black hole masses of the 19 lensed AGN systems with good-quality spectra in our sample. To fit and calculate the width of the available broad emission line in the rest-frame optical/UV spectra, we used a Levenberg-Marquardt optimization implemented in the `mpfit` method (Markwardt 2009) of the Python package `pyspeckit`¹¹ (Ginsburg & Mirocha 2011; Ginsburg et al. 2022). We followed the step-by-step procedure described by Mejía-Restrepo et al. (2016) to perform the spectral emission line fitting. First, the

¹¹ <https://pyspeckit.readthedocs.io/en/latest/>

local continuum surrounding the specific emission line was fitted using a single powerlaw. These continuum windows extends from 2650 – 2670 Å and 3030 – 3070 Å for Mg II λ 2798, from 1420 – 1460 Å and 1680 – 1720 Å for C IV λ 1549, and from 6150 – 6250 Å and 6950 – 7150 Å for H α . Next, we modeled the blended iron line emission in the spectra using various iron templates. For the optical region around H α (4000 – 7000 Å), we used the Boroson & Green (1992) template. For the UV region around C IV and Mg II, we used the iron templates from Vestergaard & Wilkes (2001) and Mejía-Restrepo et al. (2016) in the wavelength range 1250–3090 Å and 2200–3646 Å, respectively. For the overlapping wavelength range, preference was given to the Mejía-Restrepo et al. (2016) template for consistency with the fitting method. Finally, after subtracting the continuum and iron emissions, the broad emission line of interest was fitted using a Gaussian profile. In the case of visible doublets (for C IV and Mg II), two Gaussian profiles were used. In a few cases, a third Gaussian was used to fit an additional narrow emission arising from the narrow line region.

The full width at half maximum (FWHM) of the broad emission lines extracted from the spectral fitting procedure mentioned above is later used to estimate the black hole mass of the lensed AGN systems using the virial method (Sect. 4.2). Additionally, the intrinsic monochromatic luminosity of the AGN continuum (L_λ ; where $\lambda = 1450$ Å, 3000 Å, and 5100 Å for C IV, Mg II, and H α , respectively) is also calculated from the spectral fitting. For 3 systems (J0607, J2017, and J0608) with no photometric data in the optical/UV but available spectroscopy, we also estimated the intrinsic 2500 Å luminosity from their spectra. All the luminosities are corrected for lensing magnification.

4. Results

In this section, we present the main results of our multiwavelength analysis of 27 quadruply lensed AGN, including the bolometric luminosities (in Sect. 4.1), and the black hole masses and Eddington ratios (in Sect. 4.2) of our lensed AGN sample.

4.1. Bolometric luminosity

For 17/27 systems with multiband optical/UV photometry and X-ray spectroscopy, we used their optical-to-X-ray SED fits to calculate the bolometric luminosity. This was done by adding the X-ray luminosity in the 0.1 to 500 keV energy range (L_x) and the optical/UV disk luminosity in the 1000 μ m to 0.1 keV range (L_{uvo}). A possible caveat of this method arises from the fact that AGN are known to show variability at different wavelengths with different timescales (e.g., Ulrich et al. 1997). Since the multiwavelength data used in this study have been compiled from different instruments, they are spread over a few years; specifically, the time difference between the X-ray and optical/UV observations in a few cases is as large as six years. To quantify the impact of using non-simultaneous observations for SED fitting on our final results, we selected the five most variable sources in our sample, based on their optical light curves obtained from the Zwicky Transient Facility¹² and redid the SED fitting for their brightest and faintest state. We then calculated the intrinsic luminosities (L_x , L_{uvo} , L_{bol}) at the two states to determine how much they deviate from our original estimate made using non-simultaneous SEDs. We found that the maximum scatter in L_{bol} due to variability is 0.2 dex, which is similar to the typical uncertainties

Table 4: Summary of available data and L_{bol} estimators for our lensed AGN sample.

Object	X-Ray Spectra	Optical/UV Photometry	Optical/UV Spectra	SED Fits	L_{bol} Estimator
RXJ1131	✓	✓	✗	✓	SED fit
DESJ2038	✓	✓	✓	✓	SED fit
SDSSJ1251	✓	✗	✗	✗	κ_{2-10}
GRAL1131	✓	✗	✗	✗	κ_{2-10}
HE1113	✓	✗	✗	✗	κ_{2-10}
WISE2344	✓	✓	✓	✓	SED fit
J0607	✓	✗	✓	✗	κ_{2-10}
SDSSJ0924	✓	✓	✓	✓	SED fit
J2145	✓	✗	✗	✗	κ_{2-10}
WFI2033	✓	✓	✓	✓	SED fit
PSJ1606	✓	✓	✓	✓	SED fit
HE0435	✓	✓	✓	✓	SED fit
DESJ0405	✓	✓	✓	✓	SED fit
J1537	✓	✓	✓	✓	SED fit
J2017	✗	✗	✓	✗	$\kappa_{3000\text{\AA}}$
PG1115	✓	✓	✓	✓	SED fit
WISEJ0259	✓	✓	✓	✓	SED fit
WFI2026	✓	✓	✓	✓	SED fit
J0608	✓	✗	✓	✗	κ_{2-10}
PSJ0147	✓	✓	✓	✓	SED fit
SDSSJ0248	✓	✗	✓	✗	κ_{2-10}
J1042	✓	✓	✗	✓	SED fit
H1413	✓	✓	✓	✓	SED fit
MG0414	✓	✗	✗	✗	κ_{2-10}
2M1134	✓	✓	✓	✓	SED fit
J0803	✓	✗	✗	✗	κ_{2-10}
J0659	✓	✓	✓	✓	SED fit

Notes. We provide a final summary of the multi-wavelength photometric and spectroscopic data available/compiled in this study for our 27 lensed AGN system. We also show whether reliable SED fits were obtained for a system and the method used to calculate the bolometric luminosity for each system, i.e., using the SED fits, X-ray bolometric corrections (κ_{2-10}), or optical bolometric corrections ($\kappa_{3000\text{\AA}}$).

we obtained in L_{bol} from the SED modeling. Considering that the scatter of 0.2 dex is measured for the most variable source of our sample, we can safely assume that for all other sources, any scatter due to variability is much smaller than the existing uncertainties in L_{bol} from the SED fitting.

For 9/27 systems lacking optical/UV photometry, we used X-ray bolometric corrections in the 2–10 keV (κ_{2-10}) to estimate their bolometric luminosities from the 2–10 keV X-ray luminosity ($L_{\text{bol}} = \kappa_{2-10} \times L_{2-10}$). Studies have shown that κ_{2-10} does not show any significant dependence on redshift (e.g., Duras et al. 2020; Gupta et al. 2024). However, they strongly correlate with the bolometric luminosity, especially for $L_{\text{bol}} > 10^{45}$ erg s^{−1} (e.g., Duras et al. 2020; Gupta et al. 2024). Hence, we employ luminosity-dependent κ_{2-10} (using Eq. 1 from Gupta et al. 2025) to calculate L_{bol} for these nine lensed systems (see Sect. 5.2 for

¹² ZTF: <https://irsa.ipac.caltech.edu/Missions/ztf.html>

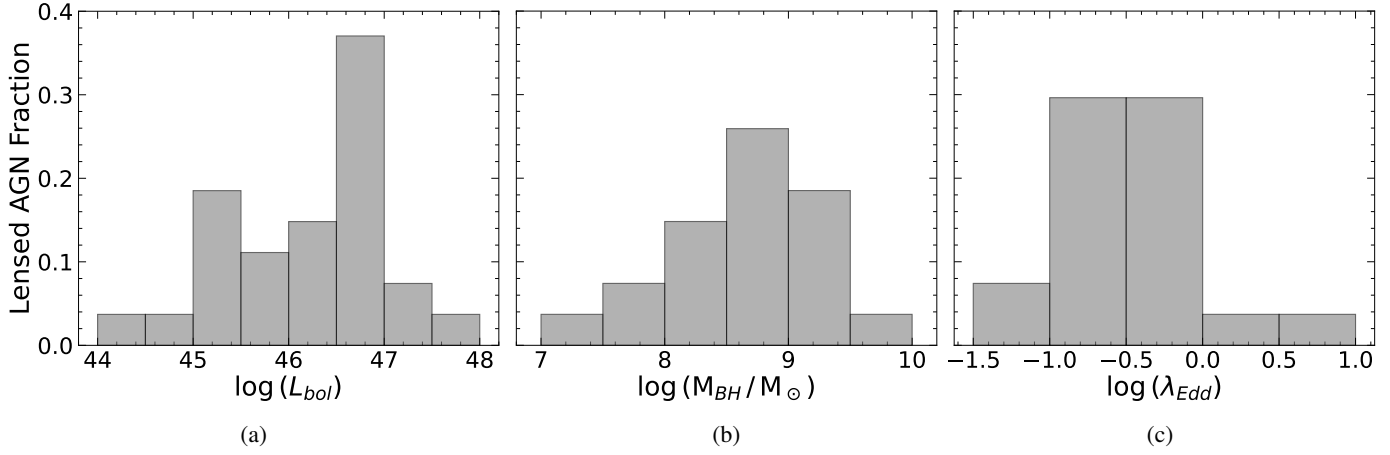


Fig. 2: Distribution in the (a) bolometric luminosities, (b) black hole masses, and (c) Eddington ratios of our quadruply lensed AGN sample. We have included one measurement per lensed system by averaging over the values for available lensed images for each system.

more details). For one system, we used the optical bolometric correction (at 3000Å) to estimate L_{bol} (more details in Sect. for 5.3). The individual methods used to estimate L_{bol} for each system are summarised in Table 4.

4.2. Black hole mass and Eddington ratio

Next, to calculate the black hole mass of our lensed AGN, we used the virial method. This method basically assumes virialized motion of the gas in the broad line region (BLR) and by employing the empirical relations between the continuum luminosity (L_{λ}) and the size of the BLR (from reverberation mapping), the mass of the black hole can be calculated using the width (FWHM) of certain broad emission lines. In this study, based on the wavelength ranges of the available rest-frame optical/UV spectra, we used the broad C IV, Mg II, and H α lines (see Table 3 for details). The following relation was used to estimate M_{BH} :

$$M_{\text{BH}} = f G^{-1} \times R_{\text{BLR}} \times V_{\text{BLR}}^2 = K (\lambda L_{\lambda})^{\alpha} \text{FWHM}^2 \quad (1)$$

where, R_{BLR} and V_{BLR} are the radius and velocity of the BLR, respectively, and f is a general geometric function (assumed to be 1; Mejía-Restrepo et al. 2016). In agreement with our fitting procedure, we used values of K and α corresponding to a local fit in Mejía-Restrepo et al. (2016; listed in columns 1–3 of Table 7) to calculate M_{BH} . The typical uncertainties on our M_{BH} estimates are dominated by those introduced due to the relation used (Eq. 1). This corresponds to errors of 0.25 dex (for Mg II), 0.33 dex (for C IV), and 0.16 dex (for H α), as reported by Mejía-Restrepo et al. (2016). Finally, we also estimated the Eddington ratios for the 19 systems with M_{BH} and L_{bol} measurements. We have reported the bolometric luminosities, black hole masses, and Eddington ratios for the resolved lensed images (whenever possible) for all 27 quasar systems in Table B.1. We show the distribution in these physical properties of lensed quasars (averaged over available lensed images) in Fig. 2.

5. Discussion

In this section, we look at some of the established relations for AGN in the context of lensed AGN and their implications. We

first investigate the well-known UV-X-ray luminosity relation to see if lensed AGN follow the same trends as nonlensed AGN (in Sect. 5.1). Next, we study the evolution of X-ray bolometric corrections from lensed AGN with their physical properties (specifically luminosity) to determine the best and most accurate method to use them as L_{bol} estimators (Sect. 5.2). We also briefly explore the scatter in L_{bol} when predicted from optical/UV bolometric corrections (Sect. 5.3).

5.1. UV-X-ray luminosity relation

It is well known that the monochromatic X-ray and UV luminosities at 2 keV and 2500 Å, respectively show a strong nonlinear correlation for AGN (e.g., Avni & Tananbaum 1986; Wilkes et al. 1994; Steffen et al. 2006; Lusso et al. 2010; Gupta et al. 2024). Although the exact physics driving this relation is still under debate (e.g., Lusso & Risaliti 2017), it is useful to better understand the link between the optical/UV disk and X-ray coronal emission. Moreover, the absence of any significant redshift evolution of this relation (e.g., Lusso et al. 2010; Risaliti & Lusso 2015, 2019) further confirms its universality for all AGN populations. In the case of gravitationally lensed AGN, this relation requires a prior magnification correction for the lensed image luminosities, which is usually calculated from the macro-model (corresponding to the foreground lens). However, since this relation is non-linear, the same, but incorrect, multiplicative factor (i.e., magnification) applied to the luminosities can move an object away from the expected relation. There are two main reasons that could lead to wrong magnification corrections: (a) the macro-model being biased due to incorrect modeling assumptions or (b) one or more of the lensed images being subject to a strong micro- or millilensing event. In the first case, it is more likely that all the lensed images will be similarly shifted in the same direction, whereas the effect of micro-/millilensing is expected to dominate for only one image. However, it is important to realize that to shift an object off the relation based on just the macro-model bias, relatively large changes of the magnification would be needed. One can easily show that a bias of a factor 10 in magnification (corresponding to a change of 0.1 dex in $L_{2500\text{Å}}$) translates into a change of 0.15 dex in $L_{2\text{keV}}$. On the contrary, because the optical and X-ray emitting regions in AGN have different physical scales and could potentially not be co-spatial (e.g.,

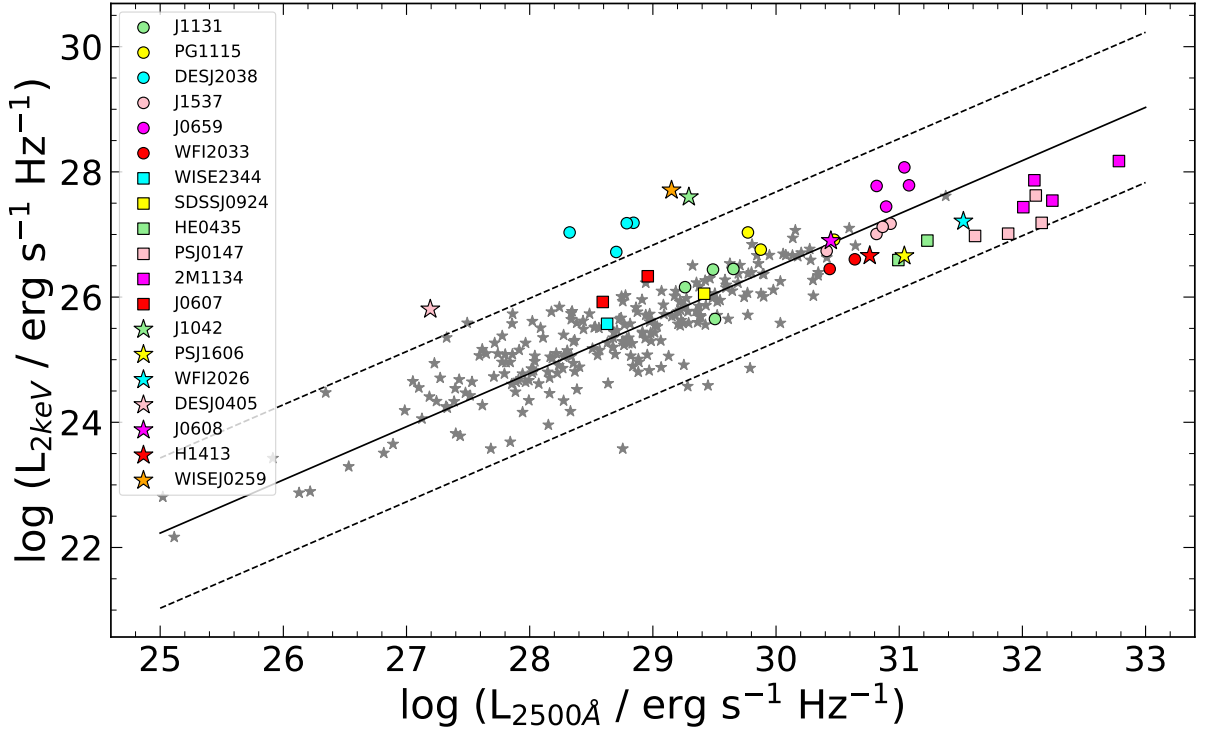


Fig. 3: Monochromatic luminosity at 2500 Å versus the monochromatic luminosity at 2 keV. Both luminosity estimates are intrinsic and have been corrected for macro-magnification. The best-fit relation (Eq. 6 from Gupta et al. 2024) with 3σ uncertainty are shown as solid and dashed black lines, respectively. Individual systems are shown as different markers as listed in the legend. Multiple measurements for the same system correspond to each resolved image for that system.

Spingola et al. 2022; Rogers et al. 2025), microlensing (and its time variability) could produce larger shifts of the object luminosities in the $L_{2\text{keV}} - L_{2500\text{Å}}$ plot. In this section, we investigate whether the lensed AGN systems with multiple images show a similar trend as nonlensed AGN between their X-ray and UV luminosity and use their position on this relation as a diagnostic for macro-model bias and/or possibility of micro-/millilensing in the lensed AGN.

In Fig. 3, we plot the rest-frame monochromatic luminosity at 2 keV ($L_{2\text{keV}}$) as a function of the rest-frame monochromatic luminosity at 2500 Å ($L_{2500\text{Å}}$) for all the lensed images (if resolved) for our lensed AGN sample (values are listed in Table B.1). We also show local, nonlensed AGN in the background (as gray stars), along with the linear fit from Gupta et al. (2024; Eq. 6). The dashed lines mark the 3σ scatter around this relation. Most of the lensed AGN images occupy the region within 3σ of the UV-X-ray luminosity trend observed for nonlensed AGN. This is not surprising, as we do not expect lensing to change the intrinsic accretion and emission physics of AGN. However, we do find some outliers. Three of these are from the unresolved systems DESJ0405 (pink star), J1042 (green star), and WISEJ0259 (orange star). Very few observations of these systems exist in the literature, which limits our ability to identify the origin of the deviation. However, it is worth noting that both DESJ0405 and J1042 show evidence of flux anomalies due to microlensing in at least one of their images, which could possibly shift the points away from the expected relation. In the case of DESJ0405, the chromatic study of the flux ratios by Nierenberg et al. 2024 suggests some microlensing in the optical/UV, but it is of too small amplitude to shift the object out of the relation. A plausible scenario to explain the observed deviation would be a large differential microlensing between the UV and X-ray domains. For

instance, microlensing demagnification of an image in UV and microlensing magnification in X-ray would move a system towards lower $L_{2500\text{Å}}$ but higher $L_{2\text{keV}}$, as observed for DESJ0405. A shift of 0.5 dex in $L_{2\text{keV}}$ (but negligible microlensing in UV) is roughly needed to reconcile DESJ0405 with the relation. This corresponds to a micro-magnification factor ~ 3 (1.25 mag), that has been previously observed for a single lensed image in other systems (e.g., see Fig. 3 of Pooley et al. 2007). A similar amplitude of differential microlensing between X-ray and UV is also possible if the two epochs of observations are not exactly simultaneous, as is the case for DESJ0405 (e.g., see Fig. 4 and 5 of Dai et al. 2010). For J1042, the HST data from Schmidt et al. (2023) indicates some flux ratio anomaly in one of the images, further supporting the important role of microlensing in this system. In short, the common occurrence of microlensing in quadruply lensed quasars suggests that strong-amplitude microlensing may be at work in the three unresolved systems, pushing them away from the observed UV-X-ray relation.

In contrast, for the lensed system of DESJ2038 (blue circles), microlensing does not seem to be a likely explanation because all four images occupy a similar region outside of the 3σ scatter of the expected trend, such that they either show a higher X-ray luminosity or a lower UV luminosity.

Finally, in the case of systems PSJ0147 (pink squares) and 2M1134 (magenta squares), although both agree with the expected UV-X-ray relation, they are clearly more luminous compared to the rest of the sample. The four images of PSJ0147 have roughly the same luminosity within uncertainties, suggesting that microlensing is not a major source of the visible systematic offset. In fact, PSJ0147 is one of the brightest lensed quasars known, suggesting that it is genuinely an intrinsically bright source (e.g., Bergea et al. 2017; Shalyapin et al. 2023).

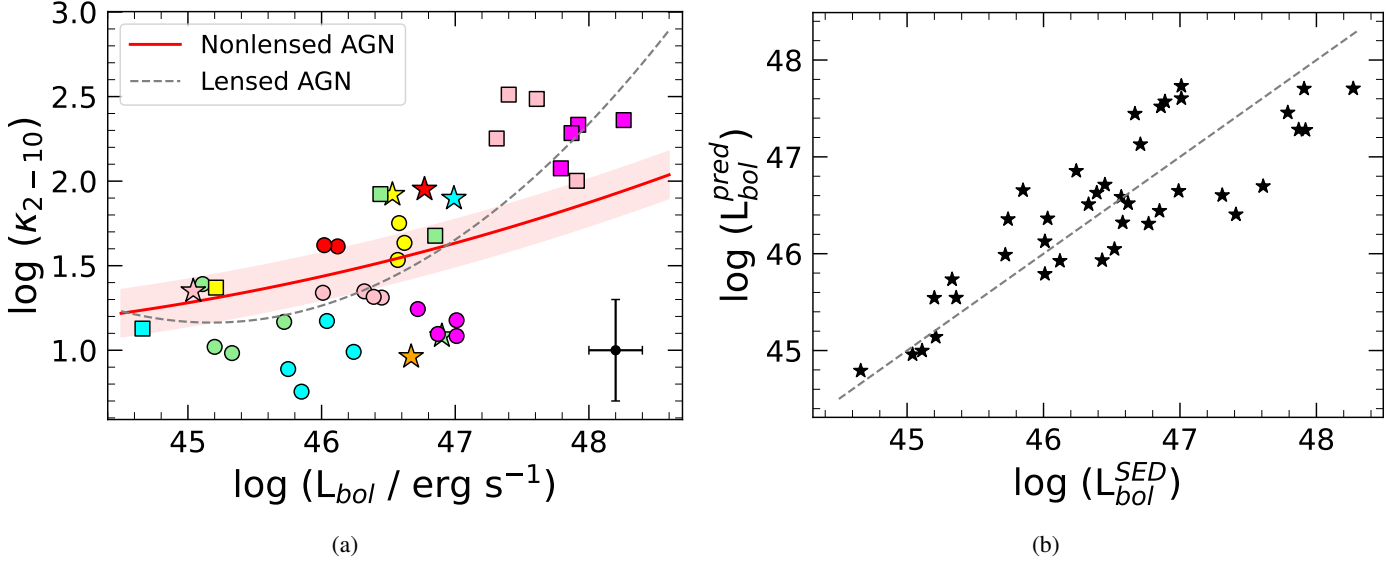


Fig. 4: (a) The 2–10 keV X-ray bolometric correction (κ_{2-10}) as a function of the bolometric luminosity. The best-fit relation for nonlensed AGN from Gupta et al. (2025) is shown as a solid red line. The shaded region (in light red) marks the 1σ scatter on the best-fit relation. For visual aid, we also show the linear fit for our lensed AGN sample (as dashed gray line). Individual systems are shown as different markers as listed in the legend of Fig. 3 and there is one point per resolved image. The marker at the bottom right corner shows the typical uncertainties on the quantities. (b) Comparison between the predicted bolometric luminosity (from luminosity-dependent κ_{2-10}) and that obtained from the broadband SED analysis. The dashed gray line shows the 1:1 relation.

For 2M1134, there might be two effects in place. Firstly, one of the images seems to be much brighter than the others, which could possibly be due to micro- or millilensing. Secondly, this system is suspected to have a galaxy cluster nearby ($\sim 30''$), whose mass is not explicitly accounted for in the lens model and would affect its accuracy (e.g., Rusu et al. 2019). Therefore, the high brightness of the whole system may be caused by a large underestimation of the resultant magnifications.

5.2. X-ray bolometric correction

In this section, we check the reliability of X-ray bolometric corrections to predict the bolometric luminosity of lensed AGN. To do so, we first confirmed that the 2–10 keV X-ray bolometric corrections for our lensed AGN sample show a similar evolution with luminosity to the one expected from nonlensed AGN. Thanks to the broadband SED analysis of the 17 lensed systems in our sample, we could calculate their 2–10 keV X-ray bolometric corrections. Here, we have included measurements from both resolved and unresolved systems to maximize our sample size. We illustrate the evolution of κ_{2-10} with the bolometric luminosity in Fig. 4a. Individual lensed AGN are shown by different markers and colors (similar to Fig. 3). We clearly see an increase in κ_{2-10} with L_{bol} , as expected from previous studies using nonlensed AGN. For comparison, we show the best-fit relation reported by Gupta et al. (2025) based on a large study of hard-X-ray-selected AGN in the local Universe (solid red line). The visible scatter in Fig. 4a is consistent with the expected 3σ dispersion in κ_{2-10} (Gupta et al. 2025). The primary outliers to the relation are systems with $L_{\text{bol}} > 10^{47} \text{ erg s}^{-1}$ (2M1134 and PSJ0147), which systematically show high optical luminosities, leading to high κ_{2-10} values. We also show the fit obtained for our lensed AGN sample (dashed gray line), but purely for visual aid, as this relation is heavily biased (discussed in detail in Appendix A).

Next, we used the best-fit relation from Gupta et al. (2025) to estimate κ_{2-10} based on the already calculated L_{bol} (from SED analysis) to check if the resultant value of L_{bol} agrees with the expected one from the broadband SEDs. We solved the following equation to obtain the bolometric luminosity:

$$L_{\text{bol}} = \kappa_{2-10} \times L_{2-10} ; \text{ where, } \kappa_{2-10} = f(L_{\text{bol,G25}}) \quad (2)$$

Here, $f(L_{\text{bol,G25}})$ is the equation that describes κ_{2-10} as a function of L_{bol} from Gupta et al. (2025; Eq. 1). This method only requires, as input, the 2–10 keV X-ray luminosity of the source to finally obtain the bolometric luminosity for that source. In Fig. 4b, we compare the values of L_{bol} obtained from the SED fitting ($L_{\text{bol}}^{\text{SED}}$) with the predicted value of L_{bol} ($L_{\text{bol}}^{\text{pred}}$) calculated from the luminosity-dependent X-ray bolometric corrections. As visible in Fig. 4b, the predicted value of L_{bol} matches quite well with the one from the SED fitting, with a scatter of only ~ 0.5 dex. Moreover, the predictions are uniformly spread around the 1:1 line (gray dashed), without significant evidence for bias towards over- or under-estimation. For points at $L_{\text{bol}} > 10^{47} \text{ erg s}^{-1}$, the predictions might appear to be underestimated. However, these points correspond to the four images of the two lensed sources, 2M1134 and PSJ0147, with higher than usual optical luminosities contributing significantly to their total bolometric luminosity estimated from the SED (see Sect. 5.1). Therefore, their L_{bol} predictions from κ_{2-10} are generally lower.

We also checked if other estimates of κ_{2-10} give a better prediction of the bolometric luminosity compared to the one discussed above. We first tested constant bolometric corrections with $\kappa_{2-10} = 15$ (Gupta et al. 2024) and $\kappa_{2-10} = 20$ (Vasudevan & Fabian 2009). For both cases the bolometric luminosity predictions agreed well with the real values for low luminosity sources ($L_{\text{bol}} < 10^{46} \text{ erg s}^{-1}$). However, as we go to higher luminosities, L_{bol} was underestimated by up to ~ 1 dex. This is expected as the constant bolometric corrections only apply for a small range of bolometric luminosities and do not include the obvious effects of

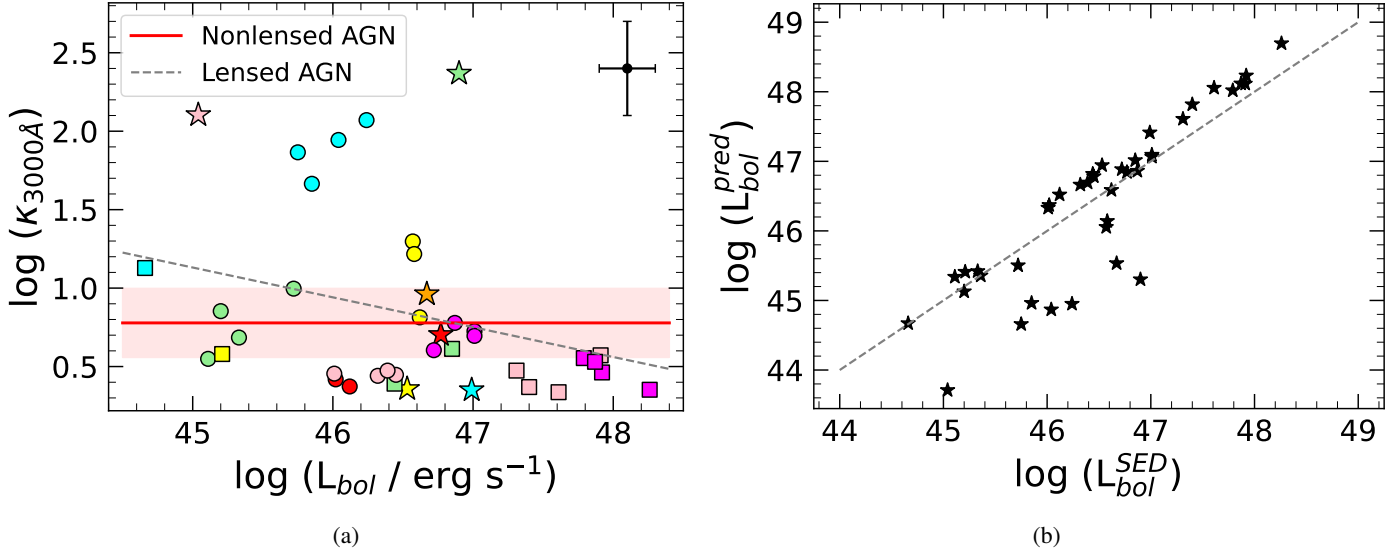


Fig. 5: (a) The 3000 Å bolometric correction ($\kappa_{3000\text{\AA}}$) as a function of the bolometric luminosity. The best-fit relation for nonlensed AGN from Gupta et al. (2024) is shown as a solid red line. The shaded region (in light red) marks the 1σ scatter on the best-fit relation. For visual aid, we also show the linear fit for our lensed AGN sample (as dashed gray line). Individual systems are shown as different markers as listed in the legend of Fig. 3 and there is one point per resolved image. The marker at the top right corner shows the typical uncertainties on the quantities. (b) Comparison between the predicted bolometric luminosity (from constant $\kappa_{3000\text{\AA}}$) and that obtained from the broadband SED analysis. The dashed gray line shows the 1:1 relation.

increasing luminosity on the X-ray bolometric corrections. Finally, we tested another $\kappa_{2-10} - L_{\text{bol}}$ relation from Duras et al. (2020) to see if it could decrease the scatter in the values L_{bol} predicted by the Gupta et al. (2025) relation. We used the general relation reported in Duras et al. (2020; Table 1) to estimate L_{bol} from L_{2-10} using the same iterative method mentioned previously. On comparing the resultant $L_{\text{bol}}^{\text{pred}}$ with $L_{\text{bol}}^{\text{SED}}$, we found that the value of the bolometric luminosity was severely overestimated with a deviation up to ~ 2 dex.

Based on the tests discussed in this section, we strongly recommend the use of luminosity-dependent X-ray bolometric corrections for the estimation of L_{bol} in the case when only X-ray data is available. Additionally, our analysis shows that using the $\kappa_{2-10} - L_{\text{bol}}$ function reported by Gupta et al. (2025) to estimate the bolometric luminosity results in the least scatter (~ 0.5 dex) in the value of L_{bol} . Therefore, we used the same method for the nine lensed AGN in our sample (without optical/UV data) to estimate their bolometric luminosities (listed in Table B.1).

5.3. Optical/UV bolometric correction

For sources lacking X-ray data, constant bolometric corrections at 1250 Å, 3000 Å, and/or 5100 Å are commonly used to estimate the bolometric luminosity. In this section, we investigate the goodness of the L_{bol} estimates from these corrections. Going forward, we present all results using the 3000 Å bolometric correction ($\kappa_{3000\text{\AA}}$). However, they are also applicable for other wavelengths in the optical/UV. We first checked the dependence of $\kappa_{3000\text{\AA}}$ on L_{bol} for our sample of 17 lensed AGN (with both resolved and unresolved images) in Fig. 5a. In agreement with previous studies, we did not obtain any significant trend in $\kappa_{3000\text{\AA}}$ with luminosity. For reference, we plot the constant $\kappa_{3000\text{\AA}} = 6$ line from Gupta et al. (2024), who reported a median value of $\kappa_{3000\text{\AA}}$ based on the broadband SED analysis of nearby AGN. Comparing to the expected 3σ scatter in $\kappa_{3000\text{\AA}}$ (Gupta et al.

2024), we obtain three systems as outliers. Two of these systems (DESJ0405 and J1042) show signatures of microlensing (see Sect. 5.1), which could explain their large deviation from the expected trend. The last outlier (DESJ2038) is already identified as an unusual system based on Fig. 3 (discussed in Sect. 5.1) and requires a dedicated study to determine why it behaves differently.

Next, we used $\kappa_{3000\text{\AA}} = 6$ to calculate L_{bol} from $L_{3000\text{\AA}}$ ($L_{\text{bol}}^{\text{pred}} = 6 \times L_{3000\text{\AA}}$) and checked these predictions against the more accurate values of L_{bol} measured from the SED fitting ($L_{\text{bol}}^{\text{SED}}$). Fig. 5b shows that the use of a constant $\kappa_{3000\text{\AA}}$ leads to a slight overestimation of the predicted L_{bol} in most cases. But the scatter in $L_{\text{bol}}^{\text{pred}}$ is generally very small, except for certain sources where the scatter is as high as ~ 1 dex. On closer inspection, we find that these sources are specifically the ones that are outliers in the UV-X-ray relation shown in Fig. 3 (discussed in Sect. 5.1). Therefore, we can attribute this large deviation in the predicted L_{bol} to a microlensing event or biases in the lens model. If luminosities are corrected for these effects in advance, optical bolometric corrections can provide extremely reliable estimates of L_{bol} , although biased toward overprediction. Similar results were also obtained when using $\kappa_{3000\text{\AA}} = 5.15$, as reported by Shen et al. 2008.

6. Summary

In this paper, we present one of the largest multiwavelength studies of 27 quadruply lensed AGN ($0.6 < z < 3.1$), with the aim to calculate their bolometric luminosities, black hole masses, and Eddington ratios. We compiled optical, UV, and X-ray photometric and spectroscopic observations for all sources. We constructed and fit the optical-to-X-ray SEDs (from 1000 μm to 500 keV) for 17 lensed AGN using a dust-reddened multi-temperature blackbody to model the optical/UV accretion disk and a simple X-ray powerlaw model with Galactic absorption to model the coronal emission. We then used the best-fit SED

models to calculate the total accretion luminosity of our sources. We also performed spectral emission line fitting in rest-frame optical/UV to measure the black hole masses and eventually the Eddington ratios of 19 systems. We list all these important quantities in Table B.1.

For ten sources with limited data, we used bolometric corrections to estimate their bolometric luminosities. We performed multiple tests to determine the best method to use X-ray bolometric corrections as L_{bol} estimators. Our analysis showed that using luminosity-dependent 2–10 keV bolometric corrections (from Eq. 1 in Gupta et al. 2025) results in L_{bol} predictions within ~ 0.5 dex of the value calculated from SED fitting. Using other methods could bias the predictions towards over- or under-estimation with deviations up to $\sim 1 - 2$ dex. We also showed that using constant optical/UV bolometric corrections (at 1250 Å, 3000 Å, or 5100 Å) to calculate L_{bol} results in a lower scatter in the predictions, if one has already corrected the luminosities for microlensing events. However, these predictions are generally biased towards overestimation.

We also investigated the well-known UV-X-ray luminosity relation for AGN in the context of lensed systems. As expected, we found that lensed AGN majorly occupy a similar parameter space in terms of the monochromatic 2 keV and 2500 Å luminosity. However, we also find some sources that deviate from the expected trend. We suspect that the main reason for this offset is large differential microlensing between the UV and X-ray domains, which could also be enhanced by the lack of simultaneous UV and X-ray data. As a result, we propose that the UV-X-ray relation for AGN can be a useful tool for identifying microlensing events in lensed AGN.

Through this multiwavelength study, we have performed a comprehensive broadband SED fitting analysis of a sample of lensed AGN, to provide the community estimates of some useful quantities, such as bolometric luminosities, black hole masses, and Eddington ratios. We have explored possible sources of errors that might affect our analysis, including AGN variability, dust extinction, and host galaxy contamination. We have also presented and compared prescriptions to derive bolometric luminosities for lensed AGN from limited data, which we believe would be extremely useful for the community.

7. Data availability

All the optical-to-X-ray SEDs and optical/UV spectral fits generated in this work are available upon reasonable request to the corresponding author.

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Appendix A: κ_{2-10} vs L_{bol} for lensed AGN

As expected, the 2–10 keV X-ray bolometric corrections for the lensed AGN show an increasing trend with the bolometric luminosity (Fig. 4a). The best-fit relation corresponding to the lensed images (dashed gray line) agrees within uncertainties with the fit (solid red line) reported for nonlensed AGN by Gupta et al. (2025). However, the relation obtained from the current study is biased due to many factors and therefore cannot be used to estimate L_{bol} for other lensed AGN. Firstly, it is based on a statistically small sample. Secondly, as discussed in Sect. 5.1, certain resolved or unresolved lensed images do not represent the intrinsic properties of the entire system. In some cases, they can be affected by micro-/millilensing, while sometimes the lens model might be poorly constrained. As a result, based on the study and sample presented in this paper, we cannot provide a one-to-one relation between κ_{2-10} and L_{bol} specific to lensed AGN. However, lensing should not affect the intrinsic accretion mechanisms of AGN and therefore, we can use the established $\kappa_{2-10} - L_{\text{bol}}$ relations from the literature to estimate L_{bol} for lensed AGN from limited data.

Appendix B: Physical properties of lensed AGN

Table B.1: Outputs from the optical-to-X-ray SED and optical/UV spectral fitting.

Object	Image	Macro-Magnification ^a	$L_{2500\text{Å}}$	$L_{2\text{keV}}$	L_{bol}	M_{BH}	λ_{Edd}
RXJ1131	A	18.86	44.58	43.33	45.11	8.11 ^b	-1.17
	B	12.05	44.73	44.13	45.72	8.11 ^b	-0.57
	C	9.95	44.34	43.84	45.20	8.11 ^b	-1.08
	D	1.05	44.57	44.12	45.33	8.11 ^b	-0.96
DESJ2038	A	3.04	43.92	44.87	45.85	8.49	-0.82
	B	3.65	43.78	44.40	46.04	8.53	-0.67
	C	2.85	43.87	44.86	46.24	8.58	-0.51
	D	1.33	43.40	44.72	45.75	8.68	-1.11
SDSSJ1251	A+B+C+D	23.00	-	42.66	44.45	-	-
GRAL1131	A	2.62	-	43.95	45.60	-	-
	B	4.17	-	43.54	45.33	-	-
	C+D	18.63	-	44.02	45.71	-	-
HE1113	A+B+C+D	54.60	-	43.64	45.16	-	-
WISE2344	A+B+C+D	33.00	43.71	43.26	44.66	7.66	-1.17
J0607	A	7.84	44.04	44.02	45.48	8.17	-0.87
	D	17.55	43.67	43.61	45.22	7.95	-0.91
SDSSJ0924	B	4.08	44.50	43.74	45.21	8.48	-1.45
J2145	A	16.23	-	44.35	46.07	-	-
	B	18.03	-	43.55	45.38	-	-
	C+D	6.3	-	44.96	46.87	-	-
WFI2033	B	3.74	45.72	44.29	46.12	8.54	-0.60
	C	3.66	45.51	44.13	46.02	8.47	-0.63
PSJ1606	A+B+C+D	8.00	46.12	44.34	46.53	8.86	-0.51
HE0435	B	5.18	46.07	44.28	46.44	8.74	-0.48
	D	3.42	46.31	44.59	46.85	8.72	-0.05
DESJ0405	A+B+C+D	93.30	42.27	43.49	45.04	7.02	-0.16
J1537	A	2.93	45.89	44.69	46.32	9.08	-0.93
	B	1.65	46.01	44.86	46.45	8.94	-0.66
	C	2.70	45.94	44.81	46.39	8.94	-0.73
	D	1.92	45.49	44.42	46.01	8.79	-0.96
J2017	B	5.4	45.53	-	45.66	7.94	-0.46
PG1115	A	2.49	44.85	44.72	46.57	9.20	-0.80
	B	3.31	45.55	44.60	46.62	9.27	-0.83
	C+D	22.63	44.95	44.44	46.58	9.25	-0.85
WISEJ0259	A+B+C+D	12.64	44.23	45.39	46.67	8.07	0.42
WFI2026	B	2.78	46.60	44.90	46.99	9.11	-0.30
J0608	A+B+C+D	24.60	45.52	44.59	46.54	8.51	-0.15
PSJ0147	B	9.36	46.69	44.66	47.31	9.52	-0.39
	C	16.44	46.96	44.70	47.40	9.52	-0.29
	D	9.76	47.23	44.87	47.61	9.60	-0.17
SDSSJ0248	A+B+C+D	27.60	-	44.02	46.46	8.50	-0.21
J1042	A+B+C+D	47.31	44.37	45.28	46.90	-	-

Notes. We have reported the magnification-corrected intrinsic 2500 Å, 2 keV, and bolometric luminosities, in $\log(L/\text{erg s}^{-1})$. We also present the black hole masses (M_{BH}) of our sources in units of $\log(M_{\text{BH}}/M_{\odot})$. Finally, we list the estimated value of the Eddington ratios (λ_{Edd} in log).

^(a) Gilman et al. 2025

^(b) Black hole mass estimate from Sluse et al. (2012)

Table B.1 continued.

Object	Image	Macro-Magnification ^a	$L_{2500\text{Å}}$	$L_{2\text{keV}}$	L_{bol}	M_{BH}	λ_{Edd}
H1413	A+B+C+D	31.54	45.84	44.35	46.77	9.48	−0.88
MG0414	A+B	29.91	-	44.97	46.85	-	-
	C	4.29	-	45.15	47.23	-	-
	D	1.82	-	45.11	47.23	-	-
2M1134	A	1.78	47.40	45.30	47.92	9.28	0.46
	B	0.57	47.35	45.39	47.79	9.22	0.40
	C	1.85	47.25	45.62	47.87	9.11	0.59
	D	1.01	48.04	46.04	48.26	9.01	1.08
J0803	A+B+C+D	23.00	-	44.75	46.77	-	-
J0659	A	4.84	45.97	45.13	46.72	9.15	−0.61
	B	2.94	46.12	45.76	47.01	9.26	−0.42
	C	3.59	45.90	45.46	46.87	9.22	−0.53
	D	10.17	46.16	45.47	47.01	9.28	−0.44

Appendix C: Additional material

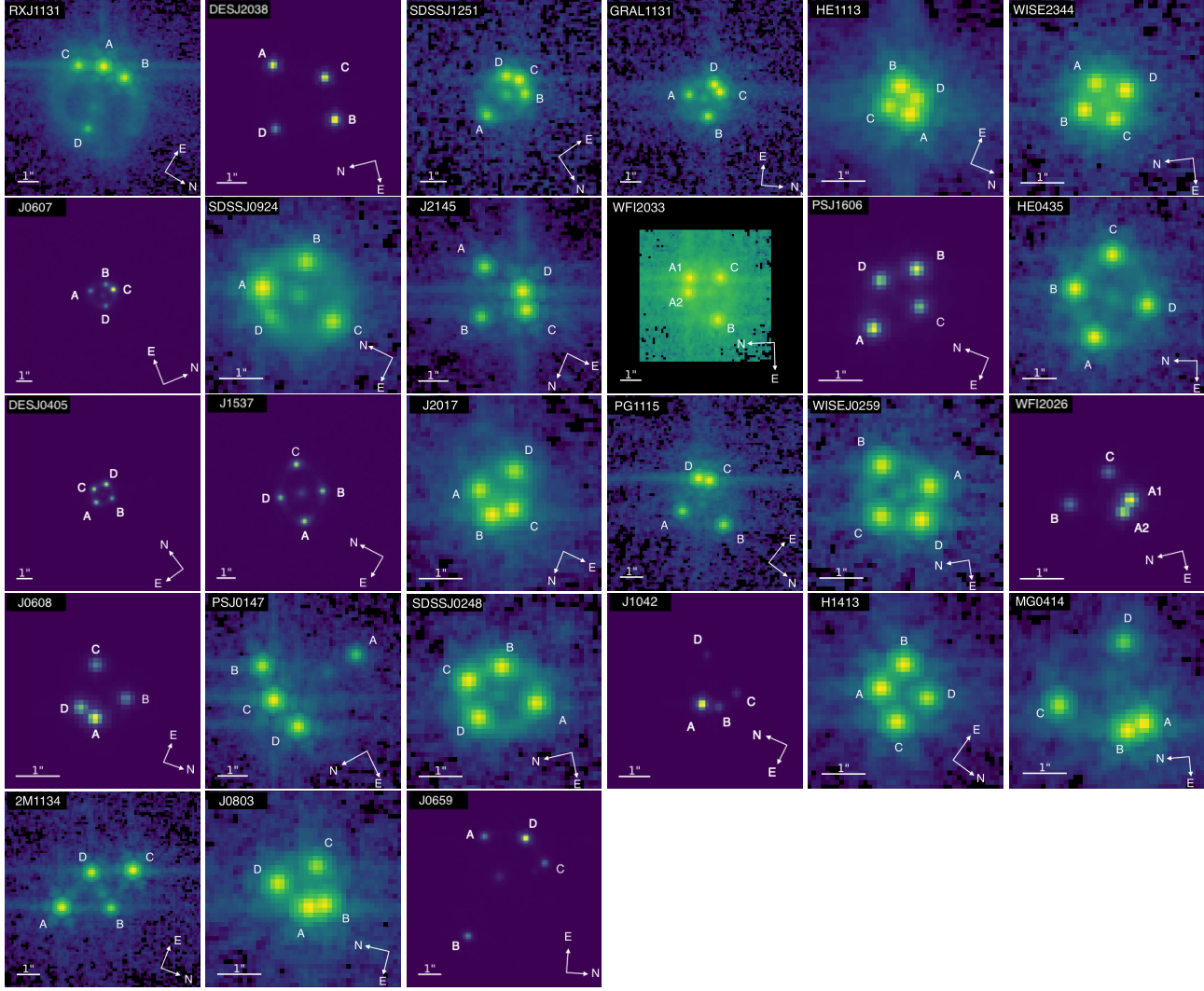


Fig. C.1: Image labeling of the four lensed images in our lensed quasar systems. All images correspond to observations in the F560W band of JWST/MIRI (Nierenberg et al. 2024; Keeley et al. 2024, 2025).

Table C.1: Optical/UV photometry from HST images

Object	Image	F475X	F814W
WISE2344	A	22.88 ± 0.19	21.69 ± 0.24
	B	21.71 ± 0.18	21.17 ± 0.19
	C	21.12 ± 0.15	20.82 ± 0.29
	D	21.64 ± 0.16	21.05 ± 0.22
WISEJ0259	A	21.01 ± 0.23	19.74 ± 0.19
	B	20.96 ± 0.20	19.45 ± 0.16
	C	20.50 ± 0.20	19.10 ± 0.17
	D	20.27 ± 0.17	18.79 ± 0.16
J1042	A	21.21 ± 0.17	20.36 ± 0.24
	B	22.22 ± 0.14	22.05 ± 0.15
	C	22.70 ± 0.19	22.47 ± 0.31
	D	23.25 ± 0.24	22.94 ± 0.39
J0659	A	20.17 ± 0.06	19.78 ± 0.12
	B	20.09 ± 0.06	19.46 ± 0.10
	C	20.30 ± 0.06	19.78 ± 0.13
	D	18.75 ± 0.10	18.21 ± 0.09