Was 49b: An Overmassive AGN in a Merging Dwarf Galaxy?

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Abstract

We present a combined morphological and X-ray analysis of Was 49, an isolated, dual-AGN system notable for the presence of a dominant AGN, Was 49b, in the disk of the primary galaxy, Was 49a, at a projected radial distance of 8 kpc from the nucleus. Using X-ray data from *Chandra*, the *Nuclear Spectroscopic Telescope Array*, and *Swift*, we find that this AGN has a bolometric luminosity of $L_{\text{bol}} \sim 10^{45} \text{ erg s}^{-1}$, with a black hole mass of $M_{\text{BH}} = 1.3_{-0.9}^{+2.9} \times 10^8 M_{\odot}$. Despite the large mass, our analysis of optical data from the *Discovery Channel Telescope* shows that the supermassive black hole (SMBH) is hosted by a stellar counterpart with a mass of only $5.6_{-2.6}^{+4.9} \times 10^9 M_{\odot}$, which makes the SMBH potentially larger than expected from SMBH–galaxy scaling relations, and the stellar counterpart exhibits a morphology that is consistent with dwarf elliptical galaxies. Our analysis of the system in the *r* and *K* bands indicates that Was 49 is a minor merger, with the mass ratio of Was 49b to Was 49a between $\sim 1:7$ and $\sim 1:15$. This is in contrast with findings that the most luminous merger-triggered AGNs are found in major mergers and that minor mergers predominantly enhance AGN activity in the primary galaxy.

Key words: galaxies: active – galaxies: bulges – galaxies: dwarf – galaxies: interactions – galaxies: nuclei – galaxies: Seyfert

1. Introduction

Galaxy mergers are generally understood to be major drivers of galaxy evolution, as gravitational torques effectively funnel gas into the central regions of the merging galaxies (e.g., Toomre & Toomre 1972; Barnes & Hernquist 1991; Di Matteo et al. 2005). This inflowing gas enhances star formation (e.g., Ellison et al. 2008, 2010) as well as AGN activity (Koss et al. 2010; Ellison et al. 2011, 2013; Satyapal et al. 2014). Along with AGN “feedback” (e.g., Silk & Rees 1998; Springel et al. 2005), these effects have led to a strong correlation between the mass of supermassive black holes (SMBHs) and the mass of their host galaxies’ stellar bulge (e.g., Magorrian et al. 1998; Gebhardt et al. 2000), suggesting a coevolution of SMBHs and their host galaxies throughout cosmic history (Richstone et al. 1998). Empirically, Ellison et al. (2011) find that while major mergers ($M_1/M_2 > 1/3$) enhance AGN activity in both galaxies, minor mergers ($M_1/M_2 < 1/3$) predominantly enhance AGN activity in the larger galaxy during the merger. Similarly, Koss et al. (2012) find that the most powerful AGNs in minor mergers are triggered in the more massive galaxy.

In this context, the dual-AGN system Was 49 (Bothun et al. 1989) is quite peculiar. The system is composed of a disk galaxy, Was 49a, hosting a low-luminosity Seyfert 2 nucleus, and a powerful Type 2 AGN, Was 49b, co-rotating within the disk (Moran et al. 1992) at a projected distance of ~ 8 kpc from the center of Was 49a. Nishiura & Taniguchi (1998), using the broad ($\sim 6000 \text{ km s}^{-1}$) polarized $H\beta$ emission seen in Was 49b, determine a black hole mass of $2.9 \times 10^8 M_{\odot}$. The optical continuum is almost featureless, and previous estimates led to an upper limit of $\lesssim 15\%$ on any stellar component in the optical continuum (Tran 1995a). Since these studies were published, the discovery of SMBH/galaxy scaling relations has provided

a new context for the unusual nature of Was 49b, with its large SMBH and apparent lack of a stellar counterpart.

In this paper, we quantify the peculiarities of Was 49b. We determine the intrinsic luminosity and accretion rate of the AGN through a detailed X-ray spectral analysis, and we combine the results of our X-ray analysis with an analysis of its optical spectrum to derive an independent measure of the black hole mass. We perform a morphological analysis of the Was 49 system to estimate the mass of the stellar counterpart to Was 49b, and we estimate the stellar mass ratio of the primary galaxy Was 49a to Was 49b. We adopt $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$. We use the redshift to the nucleus of the primary galaxy Was 49a ($z = 0.06328$) for distances.

2. Methodology

2.1. X-Ray Analysis

In order to constrain the X-ray spectral parameters of Was 49b as tightly as possible, we obtained all archival X-ray data suitable for spectral fitting. These data sets come from the *Chandra* X-ray Observatory, the *Nuclear Spectroscopic Telescope Array* (*NuSTAR*; Harrison et al. 2013), and the *Swift* Burst Alert Telescope (BAT; Krimm et al. 2013). There is also data from the *Advanced Satellite for Cosmology and Astrophysics* (Tanaka et al. 1994); however, an estimated 10% of this low spatial resolution data is contaminated by RX J1214.4 +2936, located 4.6 away (see Awaki et al. 2000), so we elected not to use it.

Swift: We downloaded the BAT spectrum and response file directly from the BAT 70 month Hard X-Ray Survey (Baumgartner et al. 2013) webpage.⁶ The BAT spectrum covers the period from 2004 December 16 to 2010 September

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⁶ <http://swift.gsfc.nasa.gov/results/bs70mon/>

Table 1
Chandra Information

Was 49	R.A.	Decl.	Counts 0.5–7 keV	Counts 2–7 keV
a	12 ^h 14 ^m 18 ^s .262	+29°31′46″.75	7 ^a	0
b	12 ^h 14 ^m 17 ^s .816	+29°31′43″.17	215	159

Note.

^a The 1σ statistical uncertainty on the source position for a 7-count source, estimated using *wavdetect*, is $\sim 0''.7$.

30 and has an effective exposure time of 13.1 Ms, yielding a total signal-to-noise (S/N) of 8.64.

NuSTAR: An archival *NuSTAR* observation (ObsID = 60061335002) of Was 49b was taken on 2014 July 15 as part of the extragalactic survey (Harrison et al. 2016). We created Level 2 event files by running *nupipeline*, version 0.4.4, with the latest *NuSTAR* CALDB files. We created source and background region files in *ds9* by using two $30''$ radius circular apertures, one at the position of Was 49b and the other on the same detector between the source and the edge of the image. We created Level 3 data products for the FPMA and FPMB data, including source and background spectra, using *nuproducts*, and by setting the *rungrppha* flag to produce grouped output spectra. We required a minimum grouping of 30 counts for the χ^2 statistic, and we set the high and low bad data energy channel thresholds at 1909 and 35, which correspond to 3–78 keV. Because *NuSTAR* has two detectors, inter-instrumental sensitivity differences may affect our analysis. To address this, we fit the FPMA and FPMB data with a single absorbed power-law model between 3 and 78 keV, appending a constant to each detector group and holding the FPMA constant fixed at unity. We found the FPMB constant equal to $1.07^{+0.10}_{-0.90}$, consistent with a negligible instrumental sensitivity difference.

Chandra: A 5 ks ACIS-I data set (ObsID = 14042) exists for Was 49b, taken on 2012 March 25. We reprocessed the event and calibration files for this data set using CIAO, version 4.7, and CALDB 4.6.9. We limited our reprocessed event files to events between 0.5 and 7 keV, and we used *dmextract* with a $3''$ radius aperture and a nearby background region to extract counts. We give a summary of the *Chandra* data for the Was 49 system in Table 1, but we note that we found a 7-count (2.6σ) detection at the nucleus of the larger galaxy, Was 49a, which may be in line with earlier findings that this is a dual-AGN system. We show the *Chandra* image of the Was 49 system in Figure 1, right.

We masked all the sources in the event data using regions obtained with *wavdetect*, and we extracted the background light curve using *dmextract*. We found no significant ($>3\sigma$) flaring intervals during this 5 ks observation. Within the same $30''$ aperture that we used for the *NuSTAR* data is a third X-ray source—in addition to the nuclear source in Was 49a—without any obvious association with the Was 49 system and with 9 counts between 0.5 and 7 keV. Adding this to the Was 49a nuclear source, we found a contamination level of $(7^{+3}_{-2})\%$ within the *NuSTAR* aperture between 0.5 and 7 keV, where the uncertainty represents the 90% confidence interval calculated using Poisson statistics. However, extracting counts only in the harder 2–7 keV band reduced the contamination level to $(3 \pm 2)\%$. We therefore did not attempt to make any sort of contamination correction to our X-ray spectral analysis, which

Figure 1. Optical and X-ray images of the Was 49 system, with optical color representation following Lupton et al. (2004). At the redshift of Was 49 ($z = 0.06328$), [O III] and $H\beta$ fall within the *g* (blue) filter, the *r* (green) filter is predominantly continuum, and the *i* (red) filter contains $H\alpha + [N II]$. Note the extensive ionization region around Was 49b, which indicates that the optical light is dominated by line emission. Images oriented north up, east left.

was dominated by the hard X-ray data from *NuSTAR* and *Swift*. We extracted X-ray spectra using *specextract*, and we used the same $3''$ aperture we used to isolate emission from Was 49b, as we sought to minimize contamination at soft energies by other sources. Using GRPPHA, we grouped the spectra by a minimum of 20 counts for the χ^2 statistic.

We performed spectral analyses on the grouped spectra⁷ using XSPEC, version 12.9.0 (Arnaud 1996). We confined our X-ray spectral analysis to 0.5–7 keV, 3–78 keV, and 14–195 keV for the *Chandra*, *NuSTAR*, and *Swift* spectra, respectively. To derive fluxes and uncertainties for specific model components, we appended the *cflux* convolution model, holding the additive model component of interest normalization fixed. We modeled the Galactic hydrogen column density as a fixed photoelectric absorption multiplicative component (*phabs*) with a value of $N_H = 1.88 \times 10^{20} \text{ cm}^{-2}$, calculated using the *Swift* *nhtot* tool,⁸ which uses the prescription of Willingale et al. (2013). All X-ray spectral parameters, fluxes, and uncertainties given in this work are the values that minimize the χ^2 statistic, along with their 90% confidence intervals.

2.1.1. Inter-epoch Variability

Owing to the difference in epochs between the X-ray data, variability may hamper joint spectral fitting. This is especially a concern for the higher-energy *NuSTAR* and *Swift* data sets, since the highest-energy photons are produced in the innermost accretion regions of the AGN. To address this issue, we looked for variability in the *Chandra* and *Swift* data relative to the *NuSTAR* data, because *NuSTAR* shares its energy range with the other two. We first fit the *Chandra* and *NuSTAR* data with an absorbed power-law model, allowing the model normalizations to vary. We found the *Chandra* and *NuSTAR* normalizations ($\text{keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$) to be $6.2^{+3.4}_{-2.1} \times 10^{-4}$ and $7.6^{+3.5}_{-2.3} \times 10^{-4}$, respectively, which indicate no discernible variability between the two epochs.

We found normalizations of $8.4^{+7.2}_{-3.8} \times 10^{-4}$ and $8.5^{+4.5}_{-2.8} \times 10^{-4}$ for *Swift* and *NuSTAR*, respectively, which place any flux variability between the data sets below the threshold of detectability. We note that in the above analysis,

⁷ With the exception of the BAT spectrum, as it does not require grouping; see <http://swift.gsfc.nasa.gov/analysis/threads/batspectrumthread.html>.

⁸ <http://www.swift.ac.uk/analysis/nhtot/>

we implicitly assumed that the power-law spectral index Γ remained unchanged from epoch to epoch. Soldi et al. (2014) find, using data from the BAT 58 month survey, that the majority of AGNs in the survey do not exhibit significant spectral variability. Hernández-García et al. (2015) similarly find, using a sample of 25 Seyfert 2 galaxies with *Chandra*/*XMM-Newton* observations, that X-ray variability depends primarily on flux (e.g., the normalization of the power-law spectra) and not on spectral shape (e.g., Γ). Moreover, setting the normalizations of the power-law fit to the *Swift* and *NuSTAR* data equal and allowing the spectral indices Γ to vary, we found $\Gamma = 1.6 \pm 0.1$ and $\Gamma = 1.6_{-0.1}^{+0.2}$ for *Swift* and *NuSTAR*, respectively, consistent with insignificant spectral variability.

2.2. Estimating the Black Hole Mass

To obtain an independent measure of the mass of the black hole in Was 49b, we used the optical spectrum of Was 49b from the Baryon Oscillation Spectroscopic Survey (BOSS; Dawson et al. 2013) to determine the FWHM of the broad $H\alpha$ line, and we used the intrinsic X-ray luminosity (Section 3.1) to estimate the size of the broad line region (BLR) using the $L_{2-10\text{ keV}}-R_{\text{BLR}}$ relation from Kaspi et al. (2005). We used the intrinsic X-ray luminosity instead of the $\lambda L_{\lambda}(5100\text{ \AA})$ luminosity, commonly used to estimate the size of the BLR (e.g., Kaspi et al. 2000), because Was 49b is a known polarized BLR AGN (e.g., Tran et al. 1992; Tran 1995b), and so most if not all of the optical continuum is scattered to some degree, making it difficult to determine the intrinsic 5100 $\text{\AA}$ luminosity. Moreover, the relation we employ here has been shown to be in agreement with the maser-determined black hole mass for a sample of four polarized BLR AGNs, including NGC 1068 and Circinus (Kuo et al. 2011).

The optical continuum of Was 49b is almost entirely nonstellar, so we effectively subtracted the continuum by fitting a simple power-law model, after masking the emission lines. We treated the residuals after continuum subtraction as an additional source of uncertainty by adding the standard deviation of the residuals near the lines of interest to the square root of the spectral variance, in quadrature.

The emission lines of Was 49b exhibit a complex morphology, showing multiple broadened components in the forbidden lines. To prevent this complex morphology from affecting our measure of the FWHM of $H\alpha$, we first modeled the [S II] $\lambda\lambda 6713, 6731$ doublet, which provides an accurate parameterization of the non-BLR line emission (e.g., Filippenko & Sargent 1988; Ho et al. 1997), as a combination of several Gaussian components, with the wavelength of each member of the doublet separated by the laboratory difference and with each Gaussian component allowed to vary in redshift as well as in FWHM and flux. Once a suitable model of the [S II] doublet was found, we applied this model to the $H\alpha$ + [N II] complex, holding the [N II] $\lambda 6583/\lambda 6548$ flux ratio equal to the theoretical value of 2.96 and setting the wavelengths to the laboratory difference. We then added an additional broad line component to $H\alpha$, and we also included the He I $\lambda 6678$ line seen in the spectrum, as it overlaps with the extended broad $H\alpha$ emission. The free parameters we fit using this model are the $H\alpha$, [N II] $\lambda 6583$, and He I fluxes and the FWHM and redshift of the additional broad $H\alpha$ line. In both the fit to the [S II] doublet and the fit to the $H\alpha$ + [N II] complex, we used the SciPy nonlinear least-squares fitting routine

`curve_fit`, weighting by the uncertainty of the spectrum and correcting for the wavelength-dependent instrumental spectral resolution.

2.3. Morphological Analysis

We observed Was 49 on 2016 April 3 with the *Discovery Channel Telescope* (DCT) Large Monolithic Imager, in the Sloan $u' g' r' i' z'$ bands. Owing to exceptional seeing ($\sim 0''.5$) during the observing run, we were able to achieve a much sharper view of Was 49 than is available from SDSS archival images. We obtained 5×100 s images in each filter, dithering by $30''$ between images. For the u' band images, we took sky flats, and we took dome flats for the g' , r' , and i' bands. The fringing typically seen in the z' band has a strong dependence on illumination, so we used the z' band images themselves to make a flat field by taking their median. The airmass of the observations was between 1.01 and 1.06.

After reducing our data using the flat and bias frames, we removed cosmic rays using the Python implementation of L.A.Cosmic (van Dokkum 2001).⁹ We found that the sky background in our data is uniform, so we chose a number of source-free regions neighboring Was 49 to calculate the mean sky background, which we subtracted from our images. We aligned our images using the IRAF task `imalign`. We co-added the aligned images within each band to produce mean and variance images. Our final, co-added images have an angular resolution of $\sim 0''.5$ – $0''.6$.

We initially corrected the astrometric solution of our data with *Astrometry.net*, version 0.67 (Lang et al. 2010), using SExtractor, version 2.19.5 (Bertin & Arnouts 1996), and a custom index file we built directly from the SDSS DR12 PhotoObj table. We then refined our astrometric solution in the following manner: First, we cross-matched sources in the PhotoObj table with the SpecObj table to produce a list of extragalactic sources in our field. We then randomly sampled between 20 and 80 sources in the PhotoObj table in an iterative manner, at each iteration performing a least-squares fit to a linear six-parameter plate model and using the resultant WCS solution to cross-match the position of the extragalactic sources in our field to their SDSS positions. If the mean value of the astrometric residuals improved at a given iteration, we stored the new WCS solution. We were able to achieve a mean astrometric accuracy *relative* to SDSS of 24 mas with 68 reference sources.

We calculated photometric zero-points using SExtractor to obtain instrumental magnitudes and fluxes, which we fit to the SDSS PhotoObj catalog fluxes by using unresolved sources in our data and comparing their instrumental magnitudes to their point-spread function (PSF) magnitudes. We fit the instrumental magnitudes to their PSF magnitudes by selecting all sources with `psfMag` < 21 to minimize uncertainty due to low S/N. As expected, the instrumental and PSF magnitudes of these sources are closely correlated, with a residual scatter of 0.01–0.02 mag. We hereafter refer to the DCT Sloan magnitudes simply as *ugriz*. We show the flux-calibrated DCT *gri* image of Was 49 in Figure 1, left.

We fit the Was 49 system with GALFIT, version 3.0.5 (Peng et al. 2002, 2010), using the *r*-band image. This band was selected because it does not overlap with major emission lines ($H\beta$, [O III], $H\alpha$ +[N II]) at the redshift of the system, and a

⁹ http://obswww.unige.ch/~tewes/cosmics_dot_py/

Figure 2. Unfolded rest-frame X-ray spectrum of Was 49b with the best-fit model. The absorbed power-law component is shown as a dashed line, and the scattered component as a dotted line.

comparison with the BOSS optical spectrum of Was 49b indicates that the r band has a minimum of emission line contamination ($\sim 6\%$). The r variance image described above was used as weighting and for calculating the reduced chi-square of the fit, and our model of the system was convolved with an empirical PSF template constructed from stars within a few arcminutes of Was 49.

3. Results

3.1. X-Rays

We fit the X-ray spectrum of Was 49b with an absorbed power-law model. To account for the fraction of the intrinsic continuum that is scattered at large radii (e.g., Awaki et al. 2000), we appended an additional power-law component multiplied by a constant that is free to vary, which represents the scattered fraction. Explicitly, our model is `phabs*(zphabs*zpow+const*zpow)`, with the second power-law component's parameters tied to those of the first. We found a good fit, with $\chi^2/\text{dof} = 81.76/67$, $\Gamma = 1.6 \pm 0.1$, $N_{\text{H}} = 2.3^{+0.5}_{-0.4} \times 10^{23} \text{ cm}^{-2}$, and a scattering fraction of $3.8^{+1.6}_{-1.2}\%$ (see Figure 2). Our model yielded unabsorbed fluxes ($\text{erg cm}^{-2} \text{ s}^{-1}$) of $F_{0.5-195 \text{ keV}} = (2.4 \pm 0.2) \times 10^{-11}$, $F_{2-10 \text{ keV}} = 4.0^{+0.7}_{-0.6} \times 10^{-12}$, and $F_{14-195 \text{ keV}} = 1.7^{+0.3}_{-0.2} \times 10^{-11}$. The corresponding intrinsic X-ray luminosities (erg s^{-1}) are $L_{0.5-195 \text{ keV}} = (2.4 \pm 0.2) \times 10^{44}$, $L_{2-10 \text{ keV}} = 4.0^{+0.7}_{-0.6} \times 10^{43}$, and $L_{14-195 \text{ keV}} = 1.7^{+0.3}_{-0.2} \times 10^{44}$. We note the apparent absence of Fe K α 6.4 keV in the spectrum of Was 49b. We calculated an upper limit on the strength of this line by freezing the model parameters and adding a Gaussian model component at 6.4 keV with a width of $\sigma = 0.1 \text{ keV}$. We calculated a 90% upper limit of $\sim 0.08 \text{ keV}$ on the equivalent width (EW) of this line. To test for the effect of grouping on our data, we repeated this procedure for an ungrouped version of our data, using Cash statistics (Cash 1979), but we found nearly identical results, with a 90% upper limit of $\sim 0.07 \text{ eV}$ on the EW. This upper limit on the Fe K α EW, however, is not inconsistent with expectations for hydrogen column densities of $\sim 10^{23} \text{ cm}^{-2}$ (e.g., Murphy & Yaqoob 2009; Brightman & Nandra 2011). To estimate the bolometric luminosity and accretion rate of Was 49b, we used the relation between L_{bol} and $L_{14-195 \text{ keV}}$

Figure 3. BOSS spectrum of Was 49b. The model spectrum is in red, the residuals are in gray, and the zero-flux line is in green. We plot the additional broad H α component as a dashed black line.

from Winter et al. (2012), which yielded $L_{\text{bol}} \sim 1.3 \times 10^{45} \text{ erg s}^{-1}$. Given $L_{\text{bol}} = \eta \dot{M} c^2$ and assuming a typical accretion efficiency $\eta = 0.1$, $\dot{M} \sim 0.2 M_{\odot} \text{ yr}^{-1}$.

For Was 49a, the nondetection of X-ray counts above $>2 \text{ keV}$ (Table 1) implies that we should not assume a typical AGN power-law X-ray spectrum. Indeed, using the Bayesian Estimation of Hardness Ratios code (Park et al. 2006), we found that the 90% statistical upper limit on the hardness ratio, defined as $(\text{H-S})/(\text{H+S})$, is -0.9 , requiring a power-law index of $\gtrsim 4$, which suggests significant contamination by soft X-ray photons of non-AGN origin. A detailed discussion of the nature of the X-ray source in Was 49a is beyond the scope of this work, and we defer it to when deeper X-ray data become available.

3.2. Black Hole Mass

Using a model of three Gaussian components derived from the [S II] doublet, we achieved a good fit to the H α + [N II] complex after including the additional broad line component (Figure 3).¹⁰ The FWHM of this broad line component is $6440 \pm 60 \text{ km s}^{-1}$, where the uncertainty is 1σ and is derived from the fit covariance matrix. As a check on this uncertainty, we created a “null” spectrum without any additional broad H α component and using the best-fit parameters for the rest of the line components of H α , [N II], and He I. We then made 10^4 permutations of this spectrum, adding to each a broad line with an FWHM randomly chosen between 4000 and 7000 km s^{-1} and with a flux randomly chosen between 1/3 and 3 times the flux of the line measured in the original spectrum. We then added Gaussian noise to the spectrum with sigma taken from the spectral uncertainty described in Section 2.2. After fitting

¹⁰ Because of the weakness of the He I line, one of the three Gaussian components had a flux consistent with zero. We removed this component to better constrain our model.

Figure 4. Top left: Cutout of Figure 1 with the position of the 2'' BOSS spectrum aperture overlaid as a dashed white circle and the position of the *Chandra* X-ray source overlaid as a solid white circle. In the case of the latter, the radius denotes the $\sim 90\%$ confidence level on the source position. Top right: As the r band is mostly uncontaminated by strong line emission, while the g band is strongly contaminated by [O III] and $H\beta$ emission (56% of the light integrated over the filter pass), $r - g$ traces the observed strength of [O III] + $H\beta$. Bottom left: $r - i$ traces the observed strength of $H\alpha$ + [N II], given the strong contamination of $H\alpha$ and [N II] in the i band. Bottom right: The $i - g$ image shows the observed strength of [O III] relative to $H\alpha$ + [N II], suggesting that the hard AGN radiation field of Was 49b extends to several kpc from the SMBH. Interestingly, there is a minimum of $i - g$ at the position of the AGN itself (as indicated by the location of the *Chandra* source), indicating that the region may be dominated by a stellar population and has a smaller contribution from line emission.

each spectrum with our model, we found that the scatter between the input FWHM and the fit FWHM has a standard deviation of $\sim 100 \text{ km s}^{-1}$, which we take as a more realistic estimate of the uncertainty. We repeated this procedure on the SDSS spectrum of Was 49a, but we did not find evidence for an additional broad line component.

Additionally, we explored any possible effect of the use of Gaussian components to parameterize the [S II] doublet by repeating our line fitting procedure using Lorentzian components. We tested models with and without a broad line component and compared their χ^2 values. The addition of a Gaussian broad line to the Lorentzian model reduced χ^2 by a factor of ~ 7 , with FWHM = 6540 km s^{-1} , consistent with the Gaussian-based [S II] model within the uncertainties. However, the model using Gaussian components yielded a much better overall fit to the data, with a χ^2 that is 42% the χ^2 of the Lorentzian model, and a K-S test showed that the residuals of the Gaussian model are consistent with the spectral uncertainties ($p = 0.18$), while the residuals of the Lorentzian model are not ($p = 8.2 \times 10^{-5}$). We therefore used the FWHM of the broad line from the Gaussian-based model, not only because of the better fit but also because it is a more conservative estimate of the FWHM of the broad line.

We note that the BOSS spectrum aperture overlaps somewhat with a knot of $H\alpha$ -heavy emission, seen in Figure 4, top and bottom left panels. While the method we employed to model the non-BLR emission is designed to avoid uncertainties with respect to the source of broad emission, it is nonetheless helpful to consider how significantly a knot of emission outside the AGN in Was 49b might be affecting our measure of the

FWHM of the BLR. The broadest component of our [S II] model is indeed consistent with highly broadened emission in the environment around the AGN, with an FWHM of $\sim 960 \text{ km s}^{-1}$, so a highly broadened non-BLR emission component was already factored into our fit of the $H\alpha$ + [N II] complex. However, we tested for the possibility that the [N II] and non-BLR $H\alpha$ line profiles might deviate significantly from [S II] by freeing their widths and velocities and refitting the spectrum. Freeing these parameters improved the fit, as expected, but the effect on the FWHM of the BLR component was not significant, increasing it to 6790 km s^{-1} , with about a factor of 2 increase in the uncertainty. To remain conservative, we retained our estimate of 6440 km s^{-1} for the FWHM of the BLR, and we adopted a factor of 2 increase of the uncertainty, equal to the uncertainty of 200 km s^{-1} assumed by Kuo et al. (2011).

We calculated the black hole mass as $M_{\text{BH}} = f R_{\text{BLR}} \sigma_{\text{H}\alpha}^2 / G$, where we adopt a virial coefficient of $\log(f) = 0.72$ (Woo et al. 2010), with an intrinsic scatter of 0.44 dex, and we calculated $R_{\text{BLR}} \sim 18 \text{ lt-day}$ with an uncertainty of 52% (Kaspi et al. 2005). Propagating these uncertainties and the uncertainty of the FWHM of the broad $H\alpha$, we derived $\log(M_{\text{BH}}/M_{\odot}) = 8.1 \pm 0.5$, where the uncertainty is 1σ , consistent with the mass estimate from Nishiura & Taniguchi (1998).

Finally, we note that while the $L_{2-10 \text{ keV}} - R_{\text{BLR}}$ relation from Kaspi et al. (2005) that we used has been shown to predict maser mass for several highly obscured AGNs similar to Was 49b with a high degree of accuracy (Kuo et al. 2011), there are some possible caveats. The objects studied in Kuo et al. (2011) had typical $L_{2-10 \text{ keV}}$ luminosities of about $10^{42} \text{ erg s}^{-1}$, over an order of magnitude less luminous than Was 49b. Of the objects studied in Kaspi et al. (2005) with $L_{2-10 \text{ keV}}$ luminosities similar to that of Was 49b, most also have BLR sizes of $\sim 20 \text{ lt-day}$, but there are some outliers. The most notable is IC 4392A, which has a BLR size of $\sim 2 \text{ lt-day}$, despite having $L_{2-10 \text{ keV}} = 4.5 \times 10^{43} \text{ erg s}^{-1}$. If Was 49b has a BLR of similar size, then its SMBH has a mass of $\log(M_{\text{BH}}/M_{\odot}) \sim 7.2$, and it is radiating very close to its Eddington limit. This is inconsistent with its X-ray spectral properties, as we discuss in Section 4, but moreover the BLR size uncertainty for IC 4392A is very large, and as such it is not included in other works on the radius–luminosity relationship (e.g., Bentz et al. 2009). Conversely, other objects with $L_{2-10 \text{ keV}}$ luminosities similar to that of Was 49b that have much smaller BLR size uncertainties have BLR sizes that are quite large, up to $\sim 100 \text{ lt-day}$. Given this, the SMBH in Was 49b has a mass of $\log(M_{\text{BH}}/M_{\odot}) \sim 8.9$. Neither of these extremes is inconsistent with the 0.5 dex uncertainty that we have derived for our SMBH mass, and the SMBH may in fact be somewhat larger given the uncertainty associated with IC 4392A. With these considerations, we use the value of $\log(M_{\text{BH}}/M_{\odot}) = 8.1 \pm 0.5$ originally calculated, noting the caveats detailed above.

3.3. Morphology

The best-fit morphological model has seven components, presented in Table 2. Was 49a was fit with four components, and Was 49b was fit with three. Both Was 49a and Was 49b have an unresolved nuclear source, although the source in Was 49a is considerably fainter. The unresolved nuclear source in Was 49b is coincident with the *Chandra* X-ray source and is

Figure 5. GALFIT model of the Was 49 system. The model and residual images are on the same scale and (arcsinh) stretch as their respective input images.

Table 2
GALFIT Morphological Parameters

Was 49	R.A.	Decl.	M_r^a mag	$\log L_r^b$ [$L_\odot$]	R_{eff} "	R_{eff} kpc	Sérsic n	b/a	PA deg
a: nucleus	12 ^h 14 ^m 18 ^s .256	+29°31'46"66	−16.7	8.54	...	...	...	...	...
a: bulge	12 ^h 14 ^m 18 ^s .256	+29°31'46"66	−20.0	9.86	0.96	1.19	1.43	0.80	82.9
a: disk	12 ^h 14 ^m 18 ^s .281	+29°31'47"12	−20.8	10.2	5.26	6.49	0.42	0.41	77.2
a: tidal	12 ^h 14 ^m 18 ^s .303	+29°31'44"86	−21.0	10.3	8.02	9.90	0.36	0.73	27.1
b: nucleus	12 ^h 14 ^m 17 ^s .819	+29°31'43"11	−17.8	8.99	...	...	...	...	...
b: bulge	12 ^h 14 ^m 17 ^s .816	+29°31'43"17	−19.1	9.50	1.31	1.62	1.07	0.68	344.0
b: ionization	12 ^h 14 ^m 17 ^s .789	+29°31'43"79	−18.2	9.14	0.52	0.64	0.41	0.63	340.1

Notes. The labeling of components with “a” or “b” is based on their spatial association.

^a Calculated using a distance modulus = 37.3 and without a K-correction, which is 0.04 for a color of $g - r = 0.5$ at the redshift of the Was 49 system, using the K-correction calculator at <http://kcor.sai.msu.ru/>.

^b r -band luminosity L_r calculated using $M_{r,\odot} = 4.67$ as per Bell et al. (2003).

buried within a region of extensive ionization (Figure 4, top left panel).¹¹ The surrounding ionized region extends $\sim 1''.5$ (1.9 kpc) to the northwest and the southeast of the stellar concentration and appears to be stratified into knots and filamentary structures of [O III] and H α + [N II] emission (Figure 4, remaining panels).

Both Was 49a and Was 49b also have bulge-like components with Sérsic indices of 1.43 and 1.07, respectively. These Sérsic indices suggest that these components may be pseudobulges; however, further investigation is needed in order to confirm this classification. An extended structure oriented roughly from north to south is also associated with Was 49a, which we modeled with a Sérsic profile with index = 0.36 and which we interpret as a tidal feature. We also used a component to model a knot of emission associated with the extensive ionization to the northwest of Was 49b, which is likely to be residual emission line contamination in the r band. The fact that our morphological analysis does not find a disk component associated with Was 49b suggests that Was 49b should be classified as a dwarf elliptical (dE) galaxy (e.g., Ryden et al. 1999). The results of our GALFIT morphological fitting are shown in Figure 5.

In order to calculate the stellar bulge mass of Was 49b, we used the close relationship between $g - r$ and the mass-to-light ratio from Bell et al. (2003), which has a scatter of 20%–50%. Because the g -band image is heavily contaminated by line emission, we did not attempt to model the g -band image with GALFIT and estimate $g - r$ directly. Instead, we utilized the fact

that $g - r$ is correlated with the galaxy morphology, as quantified by the Sérsic index n (e.g., Blanton & Moustakas 2009). For galaxies with a Sérsic index of ~ 1 , the typical $g - r$ color is about 0.4–0.5. We estimated that the scatter on this relationship is ~ 0.2 using galaxies from the bulge+disk decomposition catalog of Simard et al. (2011) with Sérsic indices between 0.5 and 1.5. Propagating this scatter and conservatively assuming an uncertainty of 50% for the corresponding mass-to-light ratio $\log(M/L_g) = 0.26$, we found that the stellar mass of the bulge of Was 49b is $\log(M_*/M_\odot) = 9.75 \pm 0.27$.

We also attempted to constrain the velocity dispersion of Was 49b, using a high-S/N SDSS spectrum of a K-type star as a template for a faint Ca II K line seen in the BOSS spectrum. We subtracted a second-order polynomial from the continuum on either side of the Ca II K line and normalized the line to the corresponding feature in the rest-frame spectrum of Was 49b. We iteratively stepped through a range of velocity dispersions σ_* between 70 and 500 km s^{−1}, in increments of 10 km s^{−1}, convolving the star’s Ca II K line with the corresponding Gaussian kernel and measuring χ^2 versus σ_* . At each step, we also added Gaussian noise to the original spectrum of Was 49b, taken from the variance of the spectrum, in order to estimate the significance of our results. We found that the faintness of the Ca II K line precluded us from constraining the velocity dispersion of Was 49b to any useful range.

The unresolved nuclear component in Was 49b may be stellar in nature. While its $g - r$ color of ~ -0.1 indicates considerable emission line contamination in the g band, it has an $i - g$ color of ~ -0.7 , much lower than that of the surrounding ionized region, which has an $i - g$ of -0.4 to -0.1 . Furthermore, we do not expect the optical counterpart of

¹¹ By registering background sources in the *Chandra* data with their optical counterparts in the DCT images, we estimate that the 90% confidence radius of the X-ray source position is $\sim 0''.4$.

Was 49b to be composed significantly of direct emission from the AGN, owing to a high level of line-of-sight obscuration (Section 3.1). Using the empirical relationship between E_{B-V} and N_H for AGNs (Maiolino et al. 2001), $N_H = 2.3 \times 10^{23} \text{ cm}^{-2}$ corresponds to an A_V of ~ 12 , given $R_V = 3.1$. If the nuclear component is stellar, then it may be a nuclear star cluster (NSC). NSCs are massive, dense clusters of stars that are often present in late-type and bulgeless galaxies in the absence of a classical bulge and are unique in that they are characterized by recurrent star formation and younger stellar populations (Walcher et al. 2006). If we suppose that this possible NSC has a mass-to-light ratio similar to that of the surrounding bulge, then it has a stellar mass of $\sim 2 \times 10^9 M_\odot$, consistent with expectations for NSCs, which are generally one to ten times the mass of their SMBHs (Seth et al. 2008). However, we emphasize that this is a highly tentative estimate, as the mass-to-light ratio is not known and the contribution to the r band from residual line contamination and the scattered AGN continuum has not been calculated.

To estimate the stellar mass ratio of Was 49b to Was 49a, we calculated their r -band light ratio. Without their nuclear components, the r -band light ratio of Was 49b to Was 49a is 1:7. With the addition of the nuclear components, the r -band light ratio is 1:6; however, we again urge caution that the unresolved nuclear component in Was 49b may be considerably contaminated by nonstellar emission. We have not included the tidal feature associated with Was 49a and modeled in our GALFIT analysis. This tidal feature may be some unknown mixture of material from Was 49a and Was 49b, and so we cannot quantify its contribution to either. If, however, this feature is material entirely from Was 49a, the r -band light ratio is 1:13, in line with the K -band light ratio calculated below. Conversely, if this feature is material entirely from Was 49b, the light ratio is 1:1, implying that the Was 49 system is a major merger. There are strong reasons why we do not consider this to be the case, as we discuss in Section 4.

We note that the residuals in Figure 5, right, can be interpreted as a mixture of tidal streams and regions of star formation in the disk of Was 49a, as can be seen in the gri image presented in Figure 1, left. It is plausible that at least some of the tidal streams seen in the residual image originate in the progenitor galaxy of Was 49b, perhaps in a disk that was tidally stripped earlier in the merger. In order to get a sense of the maximum possible mass that we might be missing, we summed the entire residual image. We found an absolute r -band magnitude of the residuals of -18.1 , corresponding to $2.3 \times 10^9 M_\odot$, assuming a similar mass-to-light ratio. The maximum *total* galaxy mass of Was 49b would therefore be $\sim 8 \times 10^9 M_\odot$.

We also note that we do not have reason to think that we may be underestimating the stellar mass of Was 49b due to dust obscuration. We examined this possibility by measuring the K -band light ratio of Was 49b to Was 49a using an image from the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007), taken on 2010 February 27. At $2.2 \mu\text{m}$ the AGN is manifest as a dominant, unresolved source in Was 49b (Figure 6, left). Because of the dominance of the AGN and the shallowness of the UKIDSS image, it was difficult to model any extended emission in Was 49b using GALFIT, as was done for the DCT images. We instead subtracted the AGN and measured the remaining emission by determining the expected K -band AGN luminosity given its intrinsic luminosity found in

Section 3.1. Using five bright stars within a few arcminutes of Was 49, we made an empirical template of the PSF. We found that we could accurately model the stars in the image with a PSF with three Gaussian components. With our PSF template, we fit the unresolved source in Was 49b, allowing only the amplitude and position to vary (Figure 6, middle). We found a PSF K -band magnitude of 13.52, which corresponds to $L_{K,\text{observed}} = 3.34 \times 10^{43} \text{ erg s}^{-1}$. Before subtracting this unresolved source from the K -band image, we performed a check to ensure that it is consistent with the expected AGN emission. Using the value of $A_V \sim 12$ for the direct AGN continuum calculated above and the extinction curve of Cardelli et al. (1989), we found $A_K \sim 1.3$, which implies an intrinsic AGN luminosity of $L_K \sim 10^{44} \text{ erg s}^{-1}$. If we assume that the intrinsic spectral energy distribution is approximately flat in the near-IR to the mid-IR for luminous AGNs, then we can use $L_K \sim L_{6\mu\text{m}} \sim L_{2-10\text{keV}}$ (e.g., Mateos et al. 2015) to calculate $L_{K,\text{expected}} \sim 4 \times 10^{43} \text{ erg s}^{-1}$, consistent with the intrinsic value, given the scatter on E_{B-V}/N_H and $L_{6\mu\text{m}}/L_{2-10\text{keV}}$. As the observed unresolved source in Was 49b is consistent with expectations for the AGN, we subtracted it from the background-subtracted K -band image and photometered the remaining emission in Was 49b for comparison with Was 49a. We did not attempt to model any contribution to the K -band emission from the AGN in Was 49a, as the faint, soft X-ray source in Was 49a (Section 3.1) suggests that the 2–10 keV luminosity and therefore the expected K -band luminosity are negligible. We used the position and inclination angle for the disk of Was 49a (Table 2) to build an elliptical isophotal profile of Was 49a, which we interpolated across the position of Was 49b using a low-order polynomial and by taking the median isophotal value. Subtracting this profile and estimating the variance from a source-free region in the UKIDSS image, we found that the K -band light ratio is consistent with the Was 49 system being a $\sim 1:15_{-3}^{+17}$ merger, where the confidence intervals are $\sim 90\%$. We emphasize that these confidence intervals assume that the AGN has been accurately subtracted from Was 49b. This may not be the case, as there is scatter in the relationship between the intrinsic X-ray luminosity and intrinsic IR luminosity of AGNs. If our model of the AGN overestimated the observed K -band luminosity of the AGN, then the K -band light ratio would be somewhat lower. It is less likely, however, that our model underestimated the observed K -band luminosity of the AGN, as increasing the modeled luminosity would quickly lead to negative flux values when subtracting it from the K -band data. With these considerations, we consider Was 49 to be a minor merger, with a mass ratio between $\sim 1:7$ and $\sim 1:15$.

4. Discussion

Our results show that the AGN in Was 49b is radiating at a very high luminosity ($\sim 10^{45} \text{ erg s}^{-1}$) and is hosted by a possible dE galaxy in the disk of Was 49a. Without a stellar host, Was 49b may be a candidate for a recoiling black hole, as SMBH coalescence is thought to be the final stage in galaxy mergers and some SMBHs may be kicked out by gravitational-wave recoils at thousands of km s^{-1} , manifesting as an offset quasar for up to tens of megayears (e.g., Blecha & Loeb 2008; Blecha et al. 2011). However, Was 49a would also be left with no black hole, which is not the case, and the apparent co-rotation of Was 49b with the disk of Was 49a (Moran et al. 1992) would be difficult to explain. Compared to other known

Figure 6. Result of our model of the AGN in Was 49b as an unresolved source in the *K*-band UKIDSS image, displayed with an arcsinh scale.

dual AGNs, the Was 49 system is highly unusual in that it is a minor merger with the more luminous AGN hosted in the secondary galaxy. In all but one of the dual AGNs with BAT detections studied by Koss et al. (2012), the BAT AGN is hosted in the more massive galaxy, and the sole exception (NGC 3758) is a major merger (stellar mass ratio of 1:2).

We may gain some insight by comparing Was 49 to results from a numerical simulation of a gas-rich minor merger (Callegari et al. 2011; Van Wassenhove et al. 2012). This simulation of a coplanar, minor (1:10) merger bears some resemblance to the Was 49 system, given the apparent co-rotation of Was 49b within the disk of Was 49a and the fact that the AGN in the primary galaxy is largely quiescent throughout the merger. However, the secondary AGN only rarely reaches high luminosities ($L_{\text{bol}} > 10^{43} \text{ erg s}^{-1}$). Capelo et al. (2015) also simulate a coplanar, 1:10 merger and find similar results. However, these simulations assume that the central black holes were initially on the $M_{\text{BH}}-M_{\text{bulge}}$ relation: the Häring & Rix (2004) relation in the case of the former, and the Marconi & Hunt (2003) relationship in the case of the latter. Consequently, their secondary black holes start at a mass of 6×10^4 and $3.5 \times 10^5 M_{\odot}$, respectively, much smaller than the mass of $1.3 \times 10^8 M_{\odot}$ we found for Was 49b. Assuming a similar Eddington ratio and scaling up the bolometric luminosity of the secondary black hole in the Capelo et al. (2015) simulation by the ratio of the black hole masses, their simulation implies that Was 49b should have a bolometric luminosity of a few 10^{44} – $10^{45} \text{ erg s}^{-1}$, in line with the bolometric luminosity we calculated in Section 3.1. However, it is not clear how meaningful this scaling is, as the bulge mass of Was 49b is about 30 times as large as in these simulations. Moreover, while the black hole mass in these simulations is $\sim 0.03\%$ – 0.2% the mass of the host bulge, as expected from scaling relations, the black hole in Was 49b is apparently overmassive, at about 2.3% . It is therefore not certain how well these numerical studies can inform our picture of the Was 49 system.

While the uncertainty on our SMBH mass of 0.5 dex means that it is possible that the SMBH is not as overmassive as the data suggests, we note that if Was 49b did follow the above black hole–galaxy scaling relations, then the AGN would be radiating very near its Eddington limit. However, the hard X-ray spectral index of $\Gamma = 1.6$ implies that the AGN is radiating at a small fraction of its Eddington limit (e.g., Brightman et al. 2016 and references therein). For example, the relation between the Eddington ratio λ_{Edd} and Γ from Brightman et al. (2013) implies that the AGN in Was 49b is radiating at only $\sim 1\%$ of its Eddington limit, and other relations between λ_{Edd} and Γ from the literature consistently imply that the Eddington ratio is only a few percent. Given the

bolometric luminosity calculated in Section 3.1, the Eddington ratio for a $1.3 \times 10^8 M_{\odot}$ black hole is 0.08, meaning that our mass estimate is generally consistent with the X-ray spectral index.

Conversely, for an SMBH of $M_{\text{BH}} = 1.3 \times 10^8 M_{\odot}$, the host spheroid should have a mass of $\sim 10^{11} M_{\odot}$, based on the same scaling relations of Callegari et al. (2011) and Capelo et al. (2015), making the Was 49 system a major merger, which is not the case, owing to two considerations. First, in a major merger between two disk galaxies, both disks are severely disrupted, while in minor mergers the disk of the primary galaxy is left relatively unperturbed (e.g., Cox et al. 2008; Hopkins et al. 2009), and there is no known mechanism by which only one member of an equal-mass system can be stripped. Second, while a stellar disk can reform following a major merger (e.g., Robertson et al. 2006; Governato et al. 2009), the Was 49 merger is still ongoing, as Was 49b is at a projected separation of ~ 8 kpc from Was 49a. This implies that the disk of Was 49a is the original. Moreover, Was 49a has a typical disk galaxy rotation curve (Moran et al. 1992), which strongly disfavors significant perturbation by Was 49b.

Empirically, Was 49 is not the only minor merger in which the smaller galaxy hosts the more luminous AGN. For example, NGC 3341 is a minor merger composed of two dwarf galaxies merging with a giant disk galaxy. One of the dwarf galaxies, 1/25 the size of the primary galaxy, hosts an AGN with an X-ray luminosity of $4.6 \times 10^{41} \text{ erg s}^{-1}$, while the primary galaxy is likely quiescent (Bianchi et al. 2013). Was 49b is 100 times as luminous, which makes it a unique system that may provide insight into the nature of minor-merger-driven AGN fueling.

As noted in Section 3.3, Was 49a is consistent with being a pseudobulge galaxy, a morphology with a distinctly different and largely merger-free origin, suggesting that it has not gone through any major mergers in the recent past. Indeed, the Was 49 system is isolated: a manual inspection of SDSS images/spectra shows that there are no other major galaxies ($M_r \lesssim -20$) within $\pm 1000 \text{ km s}^{-1}$ with a projected distance closer than about 1 Mpc. As it is consistent with a dE galaxy in terms of mass and light profile, Was 49b may have once been a late-type disk galaxy that was transformed into an elliptical morphology via galaxy “harassment” (e.g., Moore et al. 1996), or it may have been a primordial tidal dwarf galaxy (Dabringhausen & Kroupa 2013). The isolation of the system, however, implies that whatever morphological changes Was 49b underwent happened during the beginning of its encounter with Was 49a, and so it has not been severely tidally stripped (unlike, for example, the SMBH-hosting ultracompact

dwarf galaxy M60-UCD1; Seth et al. 2014), suggesting that the SMBH was intrinsically overmassive or that perhaps the black hole’s growth during the early phase of the merger happened well before the buildup of its host galaxy (e.g., Medling et al. 2015; see also the Discussion in van Loon & Sansom 2015). If Was 49b was originally a late-type/dwarf galaxy, its SMBH is a factor of 10^2 – 10^4 as massive as other black holes found in this galaxy type, which are typically between 10^4 and $10^6 M_\odot$ (e.g., Filippenko & Ho 2003; Barth et al. 2004; Izotov & Thuan 2008; Shields et al. 2008; Reines et al. 2011, 2013; Dong et al. 2012; Secrest et al. 2012, 2013, 2015; Maksym et al. 2014; Moran et al. 2014; Baldassare et al. 2015, 2016; Mezcuca et al. 2016; Satyapal et al. 2016), potentially giving new insight into how SMBHs form and grow in isolated systems. For example, recent work has suggested that black hole mass growth at higher redshifts precedes bulge growth (e.g., Zhang et al. 2012), while other work has found no such effect (e.g., Schulze & Wisotzki 2014). Numerical simulations suggest an evolution in black hole/galaxy scaling relations with redshift (e.g., Sijacki et al. 2015; Volonteri et al. 2016)—although it is not a dramatic effect—and predict increasing scatter in black hole/bulge scaling relations with decreasing bulge mass (e.g., Jahnke & Macciò 2011). Nonetheless, if early black hole growth is indeed common, it may help explain systems like Was 49b. A detailed discussion of this topic is, however, beyond the scope of this work.

5. Conclusions

We have performed a morphological decomposition of the Was 49 system using GALFIT and high-resolution optical images from the DCT as well as a comprehensive X-ray analysis of Was 49b between 0.5 and 195 keV using data from *Chandra*, *NuSTAR*, and *Swift*. Our main results can be summarized as follows.

1. Was 49, an isolated, dual-AGN system, is a pseudobulge disk galaxy (Was 49a) in a minor merger ($\sim 1:7$ to $\sim 1:15$) with a potential dE galaxy (Was 49b) of stellar mass $5.6^{+4.9}_{-2.6} \times 10^9 M_\odot$. The black hole mass of Was 49b is $1.3^{+2.9}_{-0.9} \times 10^8 M_\odot$, $\sim 2.3\%$ as large as the mass of the galaxy it resides in and larger than black hole scaling relations predict.
2. The AGN in Was 49b is extremely luminous, with an intrinsic 0.5–195 keV luminosity of $L_{0.5-195 \text{ keV}} = (2.4 \pm 0.2) \times 10^{44} \text{ erg s}^{-1}$ and a bolometric luminosity of $L_{\text{bol}} \sim 10^{45} \text{ erg s}^{-1}$. This is highly unusual for an AGN in the smaller galaxy of a minor-merger system and makes Was 49 a unique system that can potentially yield insights into how AGNs are triggered in minor mergers.

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