Hubble Space Telescope Imaging of the Active Dwarf Galaxy RGG 118

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Abstract

RGG 118 (SDSS 1523+1145) is a nearby (z = 0.0243), dwarf disk galaxy (M* ≃ 2 × 10^9 M_☉) that is found to host an active ∼50,000 solar mass black hole at its core. RGG 118 is one of a growing collective sample of dwarf galaxies known to contain active galactic nuclei (AGNs)—a group that, until recently, contained only a handful of objects. Here, we report on new Hubble Space Telescope Wide Field Camera 3 UVIS and IR imaging of RGG 118, with the main goal of analyzing its structure. Using 2D parametric modeling, we find that the morphology of RGG 118 is best described by an outer spiral disk, an inner component consistent with a pseudobulge, and a central point-spread function (PSF). The luminosity of the PSF is consistent with the central point source that is being dominated by the AGN. We measure the luminosity and the mass of the “pseudobulge” and confirm that the central black hole in RGG 118 is under-massive, with respect to the MBH−MBulge and MBH−Lbulge relations. This result is consistent with a picture in which black holes in disk-dominated galaxies grow primarily through secular processes.

Key words: galaxies: active – galaxies: dwarf – galaxies: individual (RGG 118) – galaxies: spiral – quasars: supermassive black holes

1. Introduction

While black holes (BHs) are ubiquitous in the cores of massive galaxies, the population of BHs in dwarf galaxies (M_* < 10^{9.5} M_☉) has been relatively elusive (Reines & Comastri 2016). The first dwarf galaxies identified to have active galactic nuclei (AGNs) were NGC 4395 (Filippenko 1989; Filippenko & Ho 2003) and Pox 52 (Kunth et al. 1987). The AGNs in these systems were serendipitous discoveries, and they were the only dwarf galaxies known to contain AGNs for almost two decades (Barth et al. 2004). In recent years, thanks to large-scale surveys such as the Sloan Digital Sky Survey (SDSS), we have started to identify an increasing number of such systems. Using optical spectroscopic diagnostics, Reines et al. (2013) identified 151 dwarf galaxies with signatures of AGN activity in the SDSS. This constituted an order of magnitude increase in the number of known dwarf galaxies with AGN. While optical spectroscopic diagnostics have identified the largest number of such systems (see also earlier works by Greene & Ho 2004, 2007; Barth et al. 2008; more recent studies by Moran et al. 2014; Sartori et al. 2015), searches that use radio and/or X-rays have also been successful at identifying dwarf galaxies with AGNs (Gallo et al. 2008; Reines et al. 2011, 2014; Lemons et al. 2015; Pardo et al. 2016; Chen et al. 2017). There have been efforts to use infrared (IR) diagnostics (Satyapal et al. 2014; Sartori et al. 2015), though extreme star-forming dwarf galaxies can have IR colors that mimic AGNs (Hainline et al. 2016). In all, there now exists a collective sample of roughly 200 dwarf galaxies with AGN signatures.

With the number of known dwarf galaxies that host AGNs growing, it is important to characterize the host galaxies in detail in order to understand what factors (if any) may influence the presence of an AGN. Additionally, studies of the host galaxies are necessary to determine if scaling relations between BH mass and host galaxy properties hold at the low-mass end (see Kormendi & Ho 2013 for a review of scaling relations). Where these low-mass systems fall with respect to scaling relations has important implications for the BH formation and growth scenarios (Volonteri et al. 2008; Greene 2012; Natarajan 2014). For example, semi-analytic models suggest the slope and the scatter of the low-mass end of the MBH−σ relation between the BH mass and the bulge stellar velocity dispersion depends on the mechanism by which the first BH seeds formed (Volonteri & Natarajan 2009; see also Volonteri 2010; Latif & Ferrara 2016 for reviews of BH formation scenarios).

In the continuing effort toward the detailed characterization of host galaxies, we present a Hubble Space Telescope (HST) imaging analysis of RGG 118 (SDSS 1523+1145), which is a nearby (z = 0.0243) dwarf, disk galaxy with an active ∼50,000 M_☉ BH (Baldassare et al. 2015). It was first identified in Reines et al. (2013) as having AGN signatures based on narrow emission line ratios, which place it in the composite region of the BPT diagram (Baldwin et al. 1981; Kauffmann et al. 2003; Kewley et al. 2006). A subsequent analysis of the high-resolution spectroscopy with the Magellan Echellette Spectrograph on the 6.5 m Clay telescope at Las Campanas Observatory clearly revealed a broad Hα L6563 emission feature, which is characteristic of dense gas orbiting a central massive black hole. Furthermore, the galaxy was found to have a hard X-ray point source coincident with the nucleus; this is a strong confirmation that RGG 118 hosts an AGN. The mass of the BH, based on single-epoch spectroscopic techniques using the broad Hα emission line (Greene & Ho 2005), was found to be just ∼50,000 solar masses, which is the smallest yet identified in a galaxy nucleus (Baldassare et al. 2015).
et al. 2015; Graham et al. 2016). Using 2D light profile modeling techniques, Baldassare et al. (2015) find that RGG 118 is composed of an extended disk, a central bulge-like component, and a central point source. A subsequent analysis of the SDSS imaging was done by Graham et al. (2016), who claim the presence of a stellar bar. In this paper, we analyze new HST imaging of RGG 118, with the aim of characterizing the morphology of the host galaxy and studying the galaxy’s stellar populations.

2. Data

We obtained HST Wide Field Camera 3 (WFC3) imaging of RGG 118. Images were taken over three orbits during 2016 July (Cycle 23, Proposal 14187, PI: Baldassare). We took observations in two Ultraviolet-Visible (UVIS) filters (F475W and F775W) and one IR filter (F160W). These filters correspond to the g, i, and H band, respectively. We also employ a traditional four-point dither pattern.

Data were reprocessed using the AstroDrizzle pipeline in the DrizzlePac software package. We used a square drizzling kernel and an inverse-variance map weighting, which are recommended for background-limited targets. The native pixel scales for WFC3 are 0′′04/pix for the UVIS channel and 0′′13/pix for the IR channel. However, the dithering of observations allows one to improve the pixel sampling of the final product. For the UVIS observations, our final drizzled product used a final pixel fraction (final_pixfrac parameter in AstroDrizzle) of 0.5 and a final pixel scale (final_scale) of 0′′03/pix. The IR observations have a final_pixfrac of 0.8 and final_scale of 0′′09/pix. Point-spread functions (PSFs) for each filter were constructed using the PSF fitting software Starfit.\footnote{https://www.ssacet.org/~thamilton/research/starfit.html} Figure 1 shows a three-color HST image of RGG 118, and Figure 2 shows the HST imaging in each band. We also construct a PSF using a bright star in order to determine how much the PSF used impacts the final fit parameters. Figure 3 shows a comparison of the Starfit-generated PSF with the profile of a bright star in the F160W image.

3. Results

3.1. Profile Fitting

We fit the 2D light profile of RGG 118 using GALFIT (Peng et al. 2002, 2010). The fitting is performed on the image taken in the F160W filter, which has the greatest sensitivity. The best-fit model is then applied to the optical filters in order to measure the total luminosity of each component. We also compare the results of the 2D fitting to the 1D surface-brightness profile. We extract 1D light profiles for each filter using the IRAF program ellipse, which fits elliptical isophotes to the imaging data. Using the results of ellipse, we plot 1D surface-brightness profiles for RGG 118 (i.e., surface brightness as a function of semimajor axis). We also obtain measurements of the ellipticity and position angle as a function of the semimajor axis from ellipse.

The main goal of this analysis is to decompose the 2D light profile of RGG 118 into its individual components. Each tested model is comprised of some combination of the following components: a Sérsic profile (Sérsic 1963), a disk (defined as a Sérsic profile with index \( n = 1 \)), a Ferrers profile (which is typically used to model galaxy bars; Peng et al. 2010), and a PSF. In some models, we also introduce a spiral structure in the outermost component. The components used for each tested model are listed in Table 1.

We start by testing a model with a single Sérsic component to describe the galaxy light output and find that a single Sérsic profile produces a poor fit. The addition of central PSF components improves the fit, but still results in large residuals. We next consider models with two main components: an “inner” component and an “outer” component. The outer component is always described by a Sérsic profile, the index of which is either free to vary or is restricted to the canonical disk value of \( n = 1 \). We also consider the spiral structure in the outer profile. The inner component is either modeled with a Sérsic or a modified Ferrers profile.

Each combination of inner and outer component is also tested with and without a central PSF component; in all cases, the inclusion of a central PSF improves the \( \chi^2 \) value by more than 40%. Table 1 lists each tested model and its corresponding \( \chi^2 \) value, which are computed by comparing the intensity as a function of semimajor axis for the model and the data. Ultimately, we find the best-fit model includes an outer disk \((n = 1)\) with a spiral structure, an inner Sérsic component with \( n = 0.8 \pm 0.01 \), and a central PSF (see Figure 4). The best-fit parameters (the Sérsic index, the effective radius, and the effective surface brightness) for this model are given in Table 2. Figure 5 shows the Sérsic+ Spiral Disk+PSF model applied to the F475W and F775W filters. When applying the model to the F475W and F775W bands, all components were held fixed, except the magnitude of each component. The position of the PSF was also allowed to vary, as the angular resolution differs between the IR and UVIS filters.

The magnitudes of each component in each filter for our best-fit model are reported in Table 3. As noted in the GALFIT documentation, the error bars returned by GALFIT rely on the assumptions that the residuals are due only to Poisson noise, and the noise has a Gaussian distribution. Similar to the procedure described in Shangguan et al. (2016), we estimate errors on the magnitude using the standard deviation of the sky.

\footnote{https://www.ssacet.org/~thamilton/research/starfit.html}
The resulting GALFIT trial. For all models except Sérsic components and corresponding chi-squared values for each note.

Figure 2. HST WFC3 images of RGG 118 in F475W (left), F775W (middle), and F160W (right) filters. These are full galaxy images smoothed with a Gaussian kernel of 3 pixels. The color distribution for all images is in log-scale, and the limits are chosen to encompass the distribution of pixel values.

![Figure 2](image-url)

Figure 3. Intensity vs. semimajor axis of the PSF generated by Starfit and a bright star in the image. They have been normalized to the same central intensity.

![Figure 3](image-url)

Table 1
GALFIT Fitting Results

| Components | $\chi^2$ | $M_{\text{F160W}}$ (PSF) |
|------------|---------|------------------------|
| Sérsic     | 347.77  | ...                    |
| Sérsic + PSF | 33.09  | 21.92 ± 0.02           |
| Sérsic + Sérsic | 353.31 | ...                    |
| Sérsic + Sérsic + PSF | 6.05 | 22.00 ± 0.03           |
| Sérsic + Disk | 281.56 | ...                    |
| Sérsic + Disk + PSF | 11.51 | 22.06 ± 0.03           |
| Ferrers + Sérsic | 83.37 | ...                    |
| Ferrers + Sérsic + PSF | 74.09 | 22.22 ± 0.03           |
| Ferrers + Disk | 82.88 | ...                    |
| Ferrers + Disk + PSF | 64.83 | 22.25 ± 0.03           |
| Sérsic + Spiral Sérsic + PSF | 11.46 | 22.05 ± 0.03           |
| Sérsic + Spiral Disk + PSF | 3.97 | 22.02 ± 0.03           |

Note. Model components and corresponding chi-squared values for each GALFIT trial. For all models except Sérsic + Spiral Disk + PSF (which are shown in Figure 4). The errors on the PSF are those reported by GALFIT.

background. The standard deviation is computed by measuring the median sky value in a series of 50 × 50 pixel boxes that are placed in the sky regions surrounding the galaxy. We estimate errors on the Sérsic index and the effective radii by fitting it with our alternate bright star PSF (see Section 2) and taking the error as the difference between the values of each parameter.

3.2. Colors and Stellar Masses

Using the $g$-, $i$-, and $H$-band magnitudes from GALFIT and extinction corrections based on the extinction map from Schlafly & Finkbeiner (2011), we find the $g - i$ color and $H$-band luminosity for the outer disk and the inner Sérsic components. For the inner component, we find $(g - i)_{\text{bulge}} = 1.18^{+0.48}_{-0.40}$. The disk is faint in the $g$ and $i$ bands, and the errors on the disk magnitudes returned from GALFIT are large (they give $(g - i)_{\text{disk}} = -0.01^{+1.13}_{-1.2}$). An alternate way to try to constrain the disk color is using the 1D light profiles output by ellipse. Using the total flux computed between a radius of 10 and 16′′, i.e., where the disk is dominant, we find $(g - i)_{\text{disk}} = 0.5 ± 0.3$.

We show the $g - i$ (F475W–F775W) color evolution of a single stellar population with an initial mass of $10^9$ solar masses using GALEV (Kotulla et al. 2009) and show the results in Figure 6 for a solar metallicity model and a sub-solar metallicity model. While treating the bulge and the disk as single stellar populations is a significant simplification, we can nevertheless get a rough idea of the relative ages of the bulge and the disk. A disk with $(g - i) ≈ 0.5$ would be dominated by young stellar populations with ages of hundreds of Myr to $\sim 1$ Gyr. The observed bulge color suggests a population that is older than $\sim 1$ Gyr. We also show the color evolution for an Sa-galaxy with a total mass of $5 \times 10^9 M_\odot$ in Figure 6.

We compute the stellar mass of each component using the color-based mass-to-light ratios derived by Bell et al. (2003). We measure the luminosity using our F160W observations (which are roughly equivalent of $H$ band), since the variation in $M/L$ is decreased at near-infrared (NIR) wavelengths. We use the $(g - i)$ color to compute the log($M/L_H$) ratio $\tau_H$. The resulting equation is $\tau_H = -0.186 + (0.179 \times (g - i))$. We compute a disk stellar mass of $M_{*, \text{disk}} = 10^{9.23(0.1, -0.09)} M_\odot$ and an inner component stellar mass of $M_{*, \text{bulge}} = 10^{8.59(0.11, -0.12)} M_\odot$. This gives a total stellar mass of $M_{*, \text{total}} = 10^{9.32(0.11, -0.11)} M_\odot$. This is in good agreement with the total stellar mass in the NASA-Sloan Atlas, which uses the k-correct code (Blanton & Roweis 2007) $M_{*, \text{total}} = 10^{9.35} M_\odot$. 
4. Discussion

4.1. Nature of the Central Point Source

In the following section, we discuss the nature of the observed point source. We first consider if the optical point source is consistent with an AGN given the X-ray luminosity and assuming a typical quasar spectral energy distribution (SED). Using the quasar SED from Richards et al. (2006), we use the observed X-ray luminosity (from Baldassare et al. 2015) to determine the expected luminosity at the central wavelength in the F475W filter. The Richards et al. (2006) SED is computed out to a maximum energy of 0.4 keV, beyond which it is assumed to have a constant \( L_n \). From our X-ray observations, \( \nu L_\nu(2 \text{ keV}) = 1.96 \times 10^{39} \text{ erg s}^{-1} \). Based on the Richards et al. (2006) SED, we expect \( \nu L_\nu(4659 \, \text{Å}) = 2.7 \times 10^{40} \text{ erg s}^{-1} \). The measured luminosity of the point source is \( \nu L_\nu(4659 \, \text{Å}) = 2.5 \times 10^{40} \text{ erg s}^{-1} \), which is based on the magnitude of the point source, as determined in GALFIT (22.56 mag). While we

| Inner Sérsic Component | Outer Disk |
|------------------------|------------|
| \( r_{\text{eff}} \) (kpc) | \( r_{\text{eff}} \) (kpc) | \( \mu_{\text{eff}} \) (mag/arcsec\(^2\)) | \( \mu_{\text{eff}} \) (mag/arcsec\(^2\)) | \( n \) | \( (b/a) \) | \( n \) | \( (b/a) \) |
| 1.57 ± 0.22 | 6.51 ± 1.72 | 22.5 | 24.1 | 0.80 ± 0.1 | 0.69 |

Note. Best-fit model parameters (the effective radius, the surface brightness at the effective radius, the Sérsic index, and the axis ratio) for the Sérsic + Spiral Disk + PSF model in the F160W filter.
note that there is a considerable scatter (∼0.5 dex) in the
Richards et al. (2006) mean quasar SED, the measured
luminosity is in excellent agreement with the predicted
luminosity, suggesting that the point source is indeed dominated
by the AGN.
We also consider the possibility of a nuclear star cluster
(NSC) for the point source. NSCs become increasingly
prevalent as one moves down the galaxy mass function, with
as many as 80% of galaxies with $M_\star < 10^{10} M_\odot$ hosting a
massive, compact NSC (see, e.g., Carollo et al. 1997; Carollo
et al. 1998; Böker et al. 2002; Côté et al. 2006, 2007). These
NSCs are typically a few to a few tens of parsecs in radius, with
masses from $\sim 10^5$ to $10^7 M_\odot$ (Böker et al. 2002, 2004; Walcher
et al. 2005). At the distance of RGG 118, $0''1$ corresponds to
50 pc, meaning that for our observations, an NSC would appear
as an unresolved point source.

HST surveys of nearby late-type galaxies have revealed
relations between the galaxy properties and those of their NSCs
(see Böker et al. 2002, 2004). In particular, Böker et al. (2004)
finds a relation between the $B$-band magnitude of the galaxy
and the $I$-band magnitude of the NSC. RGG 118 has an
absolute $B$-band magnitude of $M_B = -18.39 \pm 0.521$
(from the HyperLeda database; Makarov et al. 2014). Using the
relationship from Table 2 of Böker et al. (2004), we find that if
RGG 118 has an NSC, its predicted $I$-band magnitude is
$M_{I,NSC} = -11.74$. Using the synthetic photometry package
SYNPHOT, we compute the predicted WFC3 F475W and
F775W magnitudes. We assume a stellar population with an
age of 1 Gyr and star formation occurring in an instantaneous
burst, which is normalized to the predicted $I$-band magnitude.
With these assumptions, SYNPHOT predicts NSC apparent
magnitudes of $m_{F475W,NSC} = 24.4$ and $m_{F775W,NSC} = 23.7$;
these are one to two magnitudes fainter than the observed
point source in RGG 118.

Given the mass and the morphology of RGG 118, it is
possible that it does contain an NSC. Based on the scaling
relations between the galaxy stellar mass and the NSC properties
(Georgiev et al. 2016), the NSC would have an expected radius
of $\sim 2$–3 pc, and the combined BH+NSC mass would be
$\sim 8 \times 10^5 M_\odot$. However, although it may contain an NSC, the
point source luminosity in RGG 118 is consistent with being
dominated by the AGN. We note that our main results that relate
to the structure of RGG 118 are unaffected by the relative
contributions to the central PSF from an AGN versus an NSC.

### 4.2. Comparison to SDSS Imaging Analysis
Baldassare et al. (2015) first analyzed the SDSS imaging of
RGG 118. They also used GALFIT to decompose the SDSS

| Filter  | PSF (mag) | Inner Component (mag) | Disk (mag) |
|---------|-----------|-----------------------|------------|
| F475W   | 22.56±0.37 | 19.38±0.27 | 17.49±0.40 |
| F775W   | 22.37±0.38 | 18.29±0.12 | 17.48±0.24 |
| F160W   | 22.02±0.03 | 18.31±0.08 | 16.42±0.12 |

Note. AB magnitude of each component in the best-fitted model (Sérsic + Spiral Disk + PSF) for each filter. The modeling was performed on the F160W filter, and the best-fit model was applied to the two optical filters.

Figure 5. Best-fit model as determined from the F160W data applied to the F475W (top row) and F775W (bottom row) images. For each filter, the scale and colormap are consistent between the images.
image into individual components, finding a best-fit model that includes an exponential disk, an inner Sérsic component with $n = 1.13 \pm 0.26$, and a PSF. The masses of the disk and the inner component were found to be $10^{9.3} \pm 0.1 M_\odot$ and $10^{8.8 \pm 0.2} M_\odot$, which is consistent with the masses determined in this work. We do find a slightly lower Sérsic index for the inner component based on modeling of the $HST$ data than for the SDSS data ($n = 0.8 \pm 0.1$ in this work compared to $n = 1.13 \pm 0.26$).

The SDSS imaging was subsequently analyzed by Graham et al. (2016). They used 1D modeling techniques to model the profile of RGG 118. Graham et al. (2016) included the spheroid (bulge), the bar, and the disk components, and find that a central PSF is not required for their model. Their bar component is fit with a modified Ferrers profile, while their bulge is fit with a Sérsic component of $n = 0.41$. Our attempts to model the RGG 118 light profile with a bulge, a bar, and the disk did not converge on a solution in GALFIT.

One potential explanation for our differing preferred models is that their spheroid component has an effective radius of 0.63, which is less than the typical FWHM of the SDSS $r$-band PSF (1.73), making it difficult to distinguish their bulge from a point source. We are able to find best-fit solutions for models, including a point source, a bar, and the disk, though these have higher $\chi^2$ values than the models without a bar (Table 1). Graham et al. (2016) found the stellar masses of the disk, a bar, and a bulge to be $10^{9.36} M_\odot$, $10^{7.76} M_\odot$, and $10^{7.92} M_\odot$, respectively. Their total stellar mass is consistent with our findings, though the masses of the individual components are not.

Overall, we find models, including Ferrers (bar) components, produce poorer fits to the $HST$ data.

The presence of a bar can also be assessed using the ellipticity and the position angle profiles of RGG 118 (Figure 7). Menéndez-Delmestre et al. (2007) describe several signatures produced by a bar. Within the bar, there is typically a continuous increase in ellipticity with a fixed position angle. At the end of the bar, there is an abrupt drop off in ellipticity and a sharp change in position angle, as the profile moves from being bar-dominated to being dominated by the disk. We do not find evidence for a bar in either the ellipticity or the position angle profile of RGG 118.

4.3. Comparison to Other Systems

Studying the morphologies of the population of dwarf/low-mass galaxies with AGNs may help illuminate what factors are important for influencing the presence of an AGN in these systems. Here, we compare RGG 118 to other low-mass galaxies with AGNs, as well as to the general population of spiral galaxies. Jiang et al. (2011b) study the structures of 147 host galaxies of low-mass AGNs ($M_{\text{HI}} \lesssim 10^9 M_\odot$), in which the vast majority have extended disks. They find that for galaxies with detected disks, the mean ratio of the bulge-to-total luminosity ($B/T$) is 0.23 (with a median of 0.16). We find that the $B/T$ ratio for RGG 118 is 0.15 $\pm$ 0.03.

We can also compare RGG 118 to disk-dominated galaxies studied by MacArthur et al. (2003), who presented bulge-to-disk decompositions of 121 late-type spiral galaxies. They found that the bulge Sérsic indices ranged from 0.2--2.0, with a mean of $\sim$1.0. They also found a relation between the bulge and the disk radii, such that the mean ratio $\langle r_e/r_h \rangle = 0.22 \pm 0.09$. RGG 118 is consistent with these disk-dominated galaxies, with a bulge Sérsic index of $n = 0.8$ and a bulge-to-disk scale length ratio of 0.24.

There are also examples of low-mass galaxies with AGNs that have very different morphologies from RGG 118. For example, NGC 4395 has a disk and NSC, but is bulgeless Filippenko & Ho (2003). POX 52 on the other hand has no detected disk component and has a Sérsic index of $n = 4.0$ (Thornton et al. 2008). Accreting BHs have been found in the...
compact irregular dwarf galaxy Henize 2-10 (Reines et al. 2011; Reines & Deller 2012; Reines et al. 2016), and in a member of the the interacting dwarf galaxy pair Mrk 709 (Reines et al. 2014). Further demographic studies will be necessary to determine if the morphology of dwarf galaxies with AGNs is distinct from those without AGNs.

4.4. Scaling Relations

There are well-known scaling relations between the BH mass and the bulge properties, such as the stellar velocity dispersion (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Gültekin et al. 2009; McConnell & Ma 2013), the stellar mass (Marconi & Hunt 2003; Häring & Rix 2004), and the NIR luminosity (Marconi & Hunt 2003). These relations imply that the BH and the galaxy co-evolve despite the small gravitational sphere of influence of the BH relative to the galaxy. In this section, we discuss the importance of constraining the low-mass end of the scaling relations and revisit the position of RGG 118 relative to these relations.

Cosmological simulations suggest that the BH occupation fraction in low-mass galaxies, as well as the slope and the scatter of the low-mass end of the BH-galaxy scaling relations are related to the primary mechanism by which BH seeds form in the early universe (Volonteri & Natarajan 2009). BH seed formation models tend to fall into two categories: light seeds ($M_{BH,seed} \approx 100 \, M_\odot$) and heavy seeds ($M_{BH,seed} \approx 10^{4-5} \, M_\odot$). In light seed models, BH seeds form from the deaths of Population III stars (Madau & Rees 2001; Alvarez et al. 2009; Madau et al. 2014). These models predict a plume of objects that scatter below the present-day $M$-$\sigma$ relation at low galaxy/BH masses. On the other hand, heavy seed models (Begelman et al. 2006; Lodato & Natarajan 2006) produce BH seeds via the direct collapse of gas clouds and predict that objects at the low-mass end of $M$-$\sigma$ should scatter above the relation.

There has been considerable discussion surrounding the question of whether galaxies without classical bulges follow scaling relations. Kormendy & Ho (2013) find that the properties of galaxies with pseudobulges (i.e., flatter, rotationally supported components with Sérsic indices $n < 2.0$; Kormendy & Kennicutt 2004) do not correlate with the BH mass. Though there is a considerable intrinsic scatter in these scaling relations, it seems that galaxies with pseudobulges tend to fall below the $M_{BH}$-$M_{bulge}$ relation, such that their BHs are under-massive with respect to the mass of the (pseudo)bulge (Greene et al. 2010). With a Sérsic index of $n = 0.8$, the central component of RGG 118 is more consistent with a pseudobulge than with a classical bulge. Baldassare et al. (2015) find that RGG 118 does sit below the $M_{BH}$-$M_{bulge}$ relation that was defined by early-type galaxies; our results, which are based on HST imaging, are consistent with this. For the bulge mass of RGG 118 ($10^{8.59} \, M_\odot$), the relation given by Kormendy & Ho (2013) predicts a BH mass of $\sim 8 \times 10^5 \, M_\odot$, or 0.2% of the bulge mass. The BH in RGG 118 is, in actuality, roughly an order of magnitude smaller. We also find that RGG 118 sits below the relation between the BH mass and the IR-bulge luminosity.

In Figure 8, we show the position of RGG 118 relative to the $M_{BH}$-$M_{bulge}$ and $M_{BH}$-$L_{bulge}$ relations, as defined by Kormendy & Ho (2013) and Läsker et al. (2016). While the Kormendy & Ho (2013) relation is defined by elliptical/S0 galaxies with classical bulges, the Läsker et al. (2016) relation includes late-type galaxies as well. The spiral galaxies from Läsker et al. (2016) have BH masses ranging from $10^6 - 10^8 \, M_\odot$. It is important to mention that the Läsker et al. (2016) sample is comprised of galaxies with BH masses that are measured dynamically (i.e., through megamasers). There are a few low-mass galaxies for which comparisons between dynamical BH mass measurements and broad-line-based measurements can be made. However, for NGC 4395, the broad-line mass from Reines et al. (2013) is consistent with both the reverberation
mapping mass (Peterson et al. 2005) and the recent gas dynamical measurement from den Brok et al. (2015). Additionally, the relationship between $R_{\text{BLR}}$ and the 5100 Å luminosity, on which the broad-line mass measurements depend, has been shown to extend down to BHs of least $\sim 7 \times 10^5 M_\odot$ (Bentz et al. 2016).

Our result is consistent with those of Greene et al. (2008; followed by Jiang et al. 2011a, 2011b) suggesting a breakdown in the scaling relations for low-mass ($M_\text{BH} < 10^9 M_\odot$) BHs. Recent work by Reines & Volonteri (2015) showed that nearby AGNs (including dwarf AGNs) fall systematically about an order of magnitude below quiescent galaxies on the relation between the total galaxy stellar mass and the BH mass. This is potentially driven by a difference in the host galaxy properties; they find a significant fraction of the AGN-host galaxies are in spiral/disk galaxies.

There are several possible explanations for why bulgeless/disk-dominated galaxies or those with pseudobulges do not correlate with BH masses in the same way as galaxies with classical bulges. Kormendy & Ho (2013; see also Greene et al. 2008; Jiang et al. 2011a) suggest that there are two different modes of BH growth: one in which a merger drives copious amounts of gas toward the center, growing the BH rapidly; and a second where BH growth is a local, stochastic process. The first mechanism would be relevant for BHs in bulge-dominated/elliptical galaxies, while BHs in disk-dominated galaxies would grow via the second mode. This is consistent with a picture in which the BHs in disk-dominated and/or pseudobulge galaxies are under-massive with respect to the scaling relations defined by relatively massive, classical bulge-dominated systems.

In summary, we find that the light profile of RGG 118 is well described by an outer spiral disk, an inner Sérsic component with a stellar population older than $\sim 1$ Gyr, properties that are consistent with a pseudobulge, and a central point source. The properties of the central point source are consistent with originating from an AGN. We confirm that RGG 118 sits well below scaling relations between the BH mass and the bulge mass/luminosity, which is similar to other low-mass, disk-dominated systems.

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