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Low-mass and high-mass supermassive black holes in radio-loud AGNs are spun-up in different evolution paths

Jing Wang[1,2,3⋆], Min-Zhi Kong[4⋆], Shun-Fang Liu[2], Da-Wei Xu[2,3], Qiang Zhang[4] and Jian-Yan Wei[2,3]

[1] Guangxi Key Laboratory for Relativistic Astrophysics, School of Physical Science and Technology, Guangxi University, Nanning 530004, China; *wj@nao.cas.cn*

[2] Key Laboratory of Space Astronomy and Technology, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China

[3] School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, China

[4] Department of Physics, Hebei Normal University, Shijiazhuang 050024, China; *confucious_76@163.com*

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Abstract How supermassive black holes (SMBHs) are spun-up is a key issue in modern astrophysics. As an extension to the study in Wang et al., here we address the issue by comparing the host galaxy properties of nearby ($z < 0.05$) radio-selected Seyfert 2 galaxies. With the two-dimensional bulge+disk decompositions for the SDSS r-band images, we identify a dichotomy in various host galaxy properties for radio-loud SMBHs. By assuming that radio emission from the jet reflects a high SMBH spin, which stems from the well-known Blandford-Znajek mechanism of jet production, high-mass SMBHs (i.e., $M_{\rm BH} > 10^{7.9}\,M_\odot$) have a preference for being spun-up in classical bulges, and low-mass SMBHs (i.e., $M_{\rm BH} = 10^{6-7}\,M_\odot$) in pseudo-bulges. This dichotomy suggests and confirms that high-mass and low-mass SMBHs are spun-up in different ways, i.e., a major "dry" merger and a secular evolution respectively.

Key words: galaxies: bulges — galaxies: nuclei — galaxies: Seyfert

1 INTRODUCTION

Both merger and secular evolutionary scenarios have been proposed to understand the growth of supermassive black holes (SMBHs) located at the centers of host galaxies, which stem from the widely accepted conception of co-evolution of active galactic nuclei (AGNs) and their host galaxies (e.g., Heckman & Best 2014; Alexander & Hickox 2012; Sanders et al. 1988). Although a high fraction of mergers is found in luminous quasars and ultraluminous infrared galaxies (ULIRGs) (e.g., Liu et al. 2008; Mainieri et al. 2011; Treister et al. 2012; Veilleux et al. 2009; Hao et al. 2005), studies examining data from the Sloan Digital Sky Survey (SDSS) clearly suggest that the growth of local less-massive SMBHs mainly results from gas accretion occurring in small host galaxies (see a review in Heckman & Best 2014), which implies a prevalence of a disk-like bulge (i.e., a pseudo-bulge, e.g., Kormendy & Kennicutt 2004) for these host galaxies. In fact, observations with high spatial resolution reveal a pseudo-bulge in the galaxies of some narrow-line Seyfert 1 galaxies (NLS1s) which are believed to have less-massive SMBHs and high Eddington ratios (e.g., Zhou et al. 2006; Ryan et al. 2007; Mathur 2000; Orban de Xivry et al. 2011; Mathur et al. 2012).

Wang et al. (2016) recently claimed that for less-massive SMBHs powerful radio emission is favored to occur in pseudo-bulges, which implies that the less-massive SMBHs are spun up by gas accretion due to significant disk-like rotational dynamics of the host galaxy in the secular evolution scenario.

Are high-mass SMBHs spun up in the same way or not? Although there is accumulating observational evidence supporting that radio-loud quasars could be spun up by a black hole (BH)-BH merger (e.g., Laor 2000; Best et al. 2005; Chiaberge & Marconi 2011; Chiaberge et al. 2015), a comparison study between low-mass and high-mass SMBHs is still rare. The morphology of the host galaxies of quasars is in fact hard to investigate because the host galaxies are overwhelmed by luminous emission from the central SMBH accretion, even though previous studies indicated that the bulge morphology preserved evolutionary information well (e.g., Kormendy & Kennicutt

⋆ Corresponding author.

2004; Kormendy & Ho 2013). Barišić et al. (2019) recently reported a higher radio-loud fraction in elliptical galaxies with larger mass and higher stellar velocity dispersion than in disk galaxies with smaller mass and lower velocity dispersion, which implies that star formation in elliptical galaxies is suppressed by feedback energy deposited by the AGN's jet.

In this paper, by continuing our previous study in Wang et al. (2016), we attempt to explore the role of both merger and secular evolution scenarios on the spinning-up of an SMBH in a sample of nearby radio-selected Seyfert 2 galaxies with powerful radio emission, in which the bulge morphology of high-mass SMBHs is compared to that of low-mass SMBHs. Our study is based on the well-known Blandford-Znajek (BZ) model (Blandford & Znajek 1977) in which the observed powerful jet results from an extraction of rotational energy from the central SMBH. In fact, Martínez-Sansigre & Rawlings (2011) indicate that the efficiency with which the jet is produced is required to increase with the SMBH's spin to reproduce the observed quasar's "radio-loudness" range, although a direct correlation between radio power and measured spin has not been found in AGNs (see Reynolds 2019 for a recent review). The lack of correlation implies the strength and geometry of the magnetic field is important in the production of a jet.

This paper is organized as follows. Section 2 presents the sample selection and analysis. The results and discussions are given in Section 3. A conclusion is provided in Section 4. A ΛCDM cosmology with parameters $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_\mathrm{m} = 0.3$ and $\Omega_\Lambda = 0.7$ is adopted throughout the paper.

2 SAMPLE AND ANALYSIS

2.1 Sample Selection

A sample of nearby radio-selected Seyfert 2 galaxies is applied in the current study, which consists of two sub-samples with small and large M_BH. The sub-sample with small M_BH comes from our previous investigation, in which Wang et al. (2016) compiled a sample of radio-selected nearby ($z < 0.05$) "pure" Seyfert 2 galaxies with small M_BH ($10^6 - 10^7\,M_\odot$) by cross-matching the value-added SDSS Data Release 7 Max-Planck Institute for Astrophysics/Johns Hopkins University (MPA/JHU) catalog (see Heckman & Kauffmann 2006 for a review) with the FIRST survey catalog (Becker et al. 2003). Briefly speaking, not only is the three widely employed Baldwin-Phillips-Terlevich diagnostic diagram employed (e.g., Veilleux & Osterbrock 1987) but also the [OIII]λ5007/[OII]λ3727 line ratio corrected by local extinction (Heckman et al. 1981) is utilized to remove star-forming galaxies, composite galaxies and LINERs (e.g, Kewley et al. 2001, 2006). The M_BH of each galaxy is obtained from the measured velocity dispersion $\sigma_\star$ of the bulge through the well-calibrated $M_\mathrm{BH} - \sigma_\star$ relationship (Magorrian et al. 1998; McConnell & Ma 2013 and references therein) $\log(M_\mathrm{BH}/M_\odot) = (8.32 \pm 0.05) + (5.64 \pm 0.32)\log(\sigma_\star/200\,\mathrm{km\,s^{-1}})$ that is valid for M_BH in a range of $10^6 - 10^{10}\,M_\odot$. Although there is evidence that pseudo-bulges deviate from the $M_\mathrm{BH} - \sigma_\star$ relationship established in classical bulges (e.g., Kormendy & Ho 2013), we argue that the deviation is not a serious issue for the current study because the $M_\mathrm{BH} - \sigma_\star$ relationship is only used by us to select SMBHs at both high-mass and low-mass ends.

We selected a sub-sample with large M_BH by following the scheme adopted in Wang et al. (2016). The M_BH values that are obtained again from the $M_\mathrm{BH} - \sigma_\star$ relationship are required to be larger than $10^{7.9}\,M_\odot$. This lower limit on M_BH is adopted by taking into account a balance between threshold and sample size.

After the selection on M_BH, the sub-sample with large M_BH is further filtered out according to their nuclear accretion properties. By using the [OIII]λ5007 line luminosity as a proxy of the bolometric luminosity (e.g., Kauffmann et al. 2003), we finally focus on objects located within a bin of $\log L_\mathrm{[OIII]} = 40.5 - 41.5$, where the intrinsic extinction due to the host galaxy has been corrected by the standard method based on both the Balmer decrement in the standard case B recombination and the Galactic extinction curve with $R_V = 3.1$. The bin size that is applied is determined by a balance between the distribution of $\log L_\mathrm{[OIII]}$ and the size of our sample.

Finally, there are 31 objects in the sub-sample with a small M_BH and 26 in the sub-sample with a large M_BH.

2.2 Two-dimensional Bulge+Disk Decomposition

As in Wang et al. (2016), we model the surface brightness profile of each galaxy by a linear combination of an exponential radial profile for the disk component and a Sérsic profile with an index of n_B for the bulge component. The two-dimensional bulge+disk decomposition is performed for the r-band images of each of the objects listed in the large M_BH sub-sample by using the publicly available SExtractor and GIM2D packages (Bertin & Arnouts 1996; Simard et al. 2002), except for four cases. The decomposition is ignored for SDSS J081937.87+210651.4 and SDSS J111349.74+093510.7 because of their heavy obscuration. The other two objects (i.e., SDSS J080446.40+104635.8 and SDSS J130125.26+291849.4) are ignored in our decomposition since their host galaxies are strongly disturbed due to an ongoing merger of two galaxies. The SDSS r-band images are displayed in Figure 1 for the two objects with an ongoing merger. The seeing effect has been taken

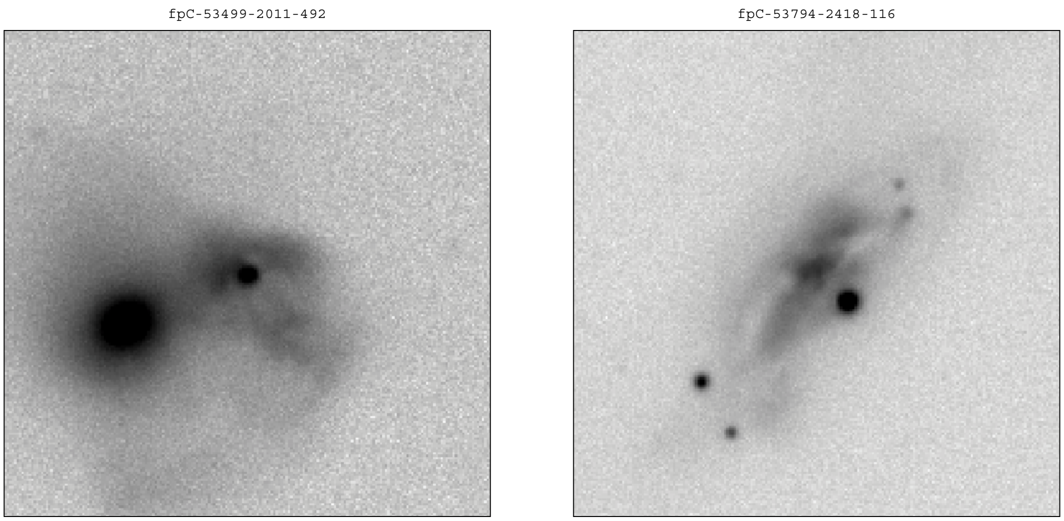

Fig. 1 The two SDSS r-band images for SDSS J130125.26+291849 (*left panel*) and SDSS J080446.40+104635.8 (*right panel*), both exhibiting a strongly disturbed profile.

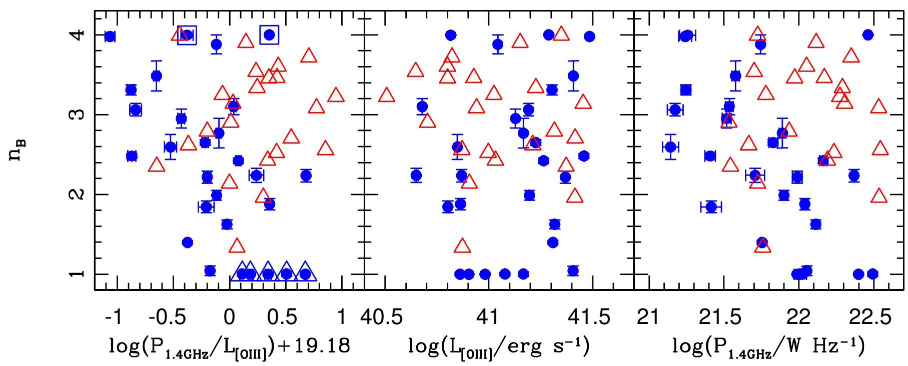

Fig. 2 The modeled Sérsic index $n_{\rm B}$ plotted against radio loudness R' defined in Eq. (1) (*left panel*), rest-frame [OIII]λ5007 line luminosity (*middle panel*) and rest-frame radio power at 1.4 GHz (*right panel*). The objects corresponding to the low-mass sub-sample are signified by *solid blue circles*, and the objects from the high-mass sub-sample by *open triangles*. The objects with a fixed value of $n_{\rm B}$ are marked by *triangles* for $n_{\rm B}=1$ and by *squares* for $n_{\rm B}=4$ (*Color version is online*).

into account by convolving the model with a simple point-spread function described by a Gaussian profile that is determined from field stars. The resulting reduced χ^2 is very close to unity for all the remaining 22 host galaxies.

3 RESULTS AND IMPLICATIONS

3.1 A Dichotomy of Pseudo-bulges and Classical Bulges for Radio-loud Low-mass and High-mass SMBHs

With the bulge+disk decomposition of the surface brightness, Figure 2 reproduces figure 2 in Wang et al. (2016) by complementing the objects listed in the large $M_{\rm BH}$ sub-sample, in which the modeled Sérsic index $n_{\rm B}$ of the surface brightness profile of the bulge in the host galaxies is plotted against the radio loudness R' (the left panel), the rest-frame [OIII] line luminosity $L_{\rm [OIII]}$ (the middle panel) and the rest-frame radio power $P_{\rm 1.4\,GHz}$ at 1.4 GHz (the right panel). A k-correction is performed in the calculation of $P_{\rm 1.4\,GHz}$ by adopting a universal spectral slope $\alpha=-0.8$ ($f_\nu\propto\nu^\alpha$, Ker et al. 2012): $P_{\rm 1.4\,GHz}=4\pi d_L^2 f_\nu(1+z)^{-1-\alpha}$, where d_L is the luminosity distance, z the redshift and f_ν the observed integrated flux density.

By combining the two traditionally applied bolometric corrections: $L_{\rm bol}\approx 3500L_{\rm [OIII]}$ and $L_{\rm bol}=9\lambda L_\lambda(5100\,\text{Å})$ (Kaspi et al. 2000; Heckman & Best 2014), the radio loudness R' based on the [OIII] line luminosity is defined as

$$\log R'=\log\left(\frac{P_{\rm 1.4\,GHz}/{\rm W\,Hz^{-1}}}{L_{\rm [OIII]}/{\rm erg\,s^{-1}}}\right)+19.18\,. \quad (1)$$

A comparison between small-$M_{\rm BH}$ and large-$M_{\rm BH}$ sub-samples for the occupation in the diagrams indicates that: 1) almost all the objects with large $M_{\rm BH}$ are associated with a classical bulge with $n_{\rm B}>2.0$ (e.g., Kormendy & Kennicutt 2004; Fisher & Drory 2008); 2) the radio-loud

Table 1 Statistical results of two-sample Gehan's generalized Wilcoxon tests for radio-loud SMBHs ($\log R' > 0$ or $\log P_{1.4\,\mathrm{GHz}} > 21.5$).

Parameter (1)	P (2)	Z-value (3)	Mean (4)
n_{B}	1.2×10^{-3}	3.242	1.90 ± 0.29
			2.99 ± 0.16
$\log(h_d/R_e)$	1.959×10^{-1}	1.293	0.17 ± 0.13
			0.42 ± 0.09
$D_n(4000)$	5×10^{-4}	3.474	1.39 ± 0.03
			1.59 ± 0.04

(i.e., $\log R' > 0$ or $\log P_{1.4\,\mathrm{GHz}} > 21.5$) low-mass SMBHs tend to be associated with a pseudo-bulge with $n_{\mathrm{B}} < 2.0$, even though the approximation to identify pseudo-bulges by the threshold of n_{B} was proposed by Gadotti (2009). To reveal the dichotomy in pseudo-bulges and classical bulges, we perform a two-sample Gehan's generalized Wilcoxon test on the distributions of n_{B} for the radio-loud objects with either $\log R' > 0$ or $\log P_{1.4\,\mathrm{GHz}} > 21.5$. The statistical results are tabulated in Table 1. Columns (2) and (3) display the probability that the two samples are drawn from the same parent population and the corresponding Z-value, respectively. The average value and the corresponding standard deviation are listed in the first row in Column (4) for the small-M_{BH} sub-sample, and in the second row for the large-M_{BH} sub-sample.

In addition to the revealed dichotomy in the Sérsic index n_{B}, the discrepancy between the small-M_{BH} and large-M_{BH} subsamples can be further verified in Figure 3 for radio-loud SMBHs. The figure plots radio loudness R' as a function of stellar population age (the upper panel) as assessed by the Lick 4000 Å break index defined as $D_n(4000) = \int_{4000}^{4100} f_\lambda d\lambda / \int_{3850}^{3950} f_\lambda d\lambda$ (e.g., Bruzual & Charlot 2003; Coelho et al. 2007 and references therein) and the scalelength ratio h_d/R_e between disks and bulges (the lower panel). As revealed in Wang et al. (2016), the radio-loud low-mass SMBHs (i.e., $\log R' > 0$ and $n_{\mathrm{B}} < 2$) are associated with young stellar populations with $D_n(4000) < 1.6$, while their high-mass counterparts (i.e., $\log R' > 0$ and $n_{\mathrm{B}} > 2$) are found to be associated with both young and old stellar populations in the current study. Compared to the radio-loud high-mass SMBHs, the low-mass counterparts tend to have smaller h_d/R_e ratio. In fact, by performing a two-dimensional bulge+disk decomposition for a large sample of 1000 galaxies from SDSS, Gadotti (2009) reported that compared to the classical bulges, the pseudo-bulges tend to have younger stellar population and higher R_e/h_d ratio at the same B/T ratio, even though the author instead separates pseudo-bulges and classical bulges in terms of the $\langle\mu_e\rangle - R_e$ relation, which is a firmly established trend for elliptical galaxies (i.e., the Kormendy relation, Kormendy 1977). The statistical results based on the same two-sample test are again listed in Table 1.

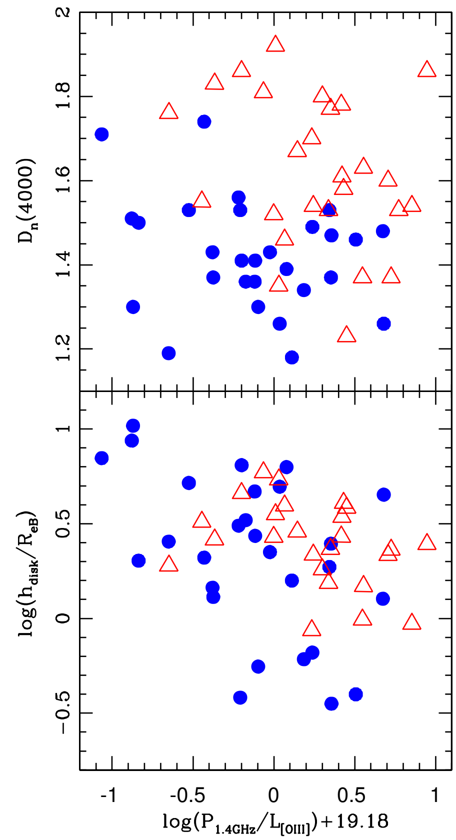

Fig. 3 *Upper panel*: the measured stellar population ages as assessed by the $D_n(4000)$ index are plotted as a function of radio loudness R'. The symbols are the same as in Fig. 2. *Lower panel*: the same as the upper panel but for the scalelength ratio between disks and bulges h_d/R_e (*Color version is online*).

3.2 Merger versus Secular Evolutions: A Dichotomy of Spinning-up Mechanisms

It is widely accepted that powerful radio emission from an SMBH is likely generated by energy extraction from the BH's spin through the BZ mechanism[1] (e.g., Blandford & Znajek 1977; Chiaberge & Marconi 2011; Ghisellini et al. 2014). In this model, the power of the jet L_{jet} is predicted to be $L_{\mathrm{jet}} \propto j^2 B_p^2$, where j is the dimensionless BH spin and B_p is the poloidal magnetic field strength at the horizon of the SMBH (e.g., Meier 2001; Koide et al. 2002; Daly 2009, 2016). Validation of the BZ mechanism for the jet production is supported by some numerical simulations and observations (e.g., Hawley & Krolik 2006; Sądowski & Narayan 2015; Martínez-Sansigre & Rawlings 2011). By assuming the BZ mechanism is present, the clearly re-

[1] An alternative is the Blandford-Payne mechanism in which the observed powerful radio emission results from an energy extraction from a disk wind (e.g., Blandford & Payne 1982; Wang et al. 2003; Cao 2016).

vealed dichotomy in the bulge morphology therefore predicates a profound dichotomy in the spinning-up mechanisms of low-mass and high-mass SMBHs. We argue that the dichotomy in spinning-up mechanisms is related with the two types of evolutionary scenarios, which are described as follows.

On the one hand, a low-mass SMBH is more likely spun-up within a pseudo-bulge with significant disk-like rotational dynamics. The pseudo-bulge can be produced in the secular evolution of a disk galaxy possibly through either a second hump instability or a vertical dynamical resonance (e.g., Kormendy & Kennicutt 2004; Fisher & Drory 2011; Silverman et al. 2011; Kormendy & Ho 2013; Sellwood 2014). On theoretical grounds, a less-massive SMBH can be spun-up efficiently by accreted gas through the frame-dragging effect that realigns the BH-disk system through interaction between the Lense-Thirring torque and strong disk viscous stress (e.g., King et al. 2005, 2008; Volonteri et al. 2005; Perego et al. 2009; Li et al. 2015), once the mass of the gas accreted onto the SMBH exceeds the alignment mass limit $m_{\mathrm{align}} \propto a^{11/16}(L/L_{\mathrm{Edd}})^{1/8}M_{\mathrm{BH}}^{15/16}$ (King et al. 2005), where $a = cJ/GM_{\mathrm{BH}}$ is the dimensionless angular momentum and L_{Edd} is the Eddington luminosity.

On the other hand, a classical bulge that is widely believed to result from a major "dry" merger of two galaxies (Toomre 1977) is responsible for the spinning-up of a high-mass SMBH. A "dry" merger of two galaxies is argued to be the origination of a ''core" galaxy since the deficit of starlight can result from an ejection of stars away from the central region during the merger (e.g., Faber et al. 1997; Kormendy et al. 2009). A spinning SMBH can be produced by the subsequent BH-BH merger if the masses of the two involved SMBH are comparable (e.g., Hughes & Blandford 2003; Baker et al. 2006). After the coalescences of the two SMBHs, formation and maintenance of a powerful jet results in a spinning-down due to an extraction of its rotational energy. By examining *Hubble Space Telescope* images with high spatial resolution, Capetti & Balmaverde (2006, 2007) pointed out that radio-loud AGNs tend to be associated with "core" galaxies that have a small logarithmic slope in their nuclear surface brightness profile (see also de Ruiter et al. 2015).In addition to the implication discussed above, the merger scenario is further supported by the current two cases with an ongoing merger (see Fig. 1). In fact, Chiaberge et al. (2015) pointed out that $\sim 90\%$ of radio-loud AGNs at $z > 1$ are associated with either recent or ongoing merger systems. Finally, the merger scenario is further validated by the fact that there is accumulating evidence supporting that radio-loud AGNs have richer environments than radio-quiet AGNs (e.g., Shen et al. 2009; Best et al. 2007).

4 CONCLUSIONS

By comparing the host galaxies of a sample of nearby ($z < 0.05$) radio-selected Seyfert 2 galaxies, we identify a dichotomy in the host galaxy properties for radio-loud SMBHs, in which high-mass SMBHs ($> 10^{7.9}\,M_{\odot}$) favor spinning-up in classical bulges, and low-mass SMBHs ($10^{6-7}\,M_{\odot}$) in pseudo-bulges, based on the assumption that a high spin of SMBH can be reflected by its powerful jet. We argue that high-mass and low-mass SMBHs are likely spun-up and grow in different ways, i.e., a major "dry" merger and secular evolution, respectively.

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