Quenching of Supermassive Black Hole Growth around the Apparent Maximum Mass

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Abstract

Recent quasar surveys have revealed that supermassive black holes (SMBHs) rarely exceed a mass of \(M_{\text{BH}} \sim 10^{10} M_\odot\) during the entire cosmic history. It has been argued that quenching of the BH growth is caused by a transition of a nuclear accretion disk into an advection-dominated accretion flow, with which strong outflows and/or jets are likely to be associated. We investigate the relationship between the maximum mass of SMBHs and the radio-loudness of quasars with a well-defined sample of \(\sim 10^3\) quasars at a redshift range of \(0 < z < 2\), obtained from the Sloan Digital Sky Surveys DR7 catalog. We find that the number fraction of the radio-loud (RL) quasars increases above a threshold of \(M_{\text{BH}} \sim 2 \times 10^9 M_\odot\), independent of their redshifts. Moreover, the number fraction of RL quasars with lower Eddington ratios (out of all RL quasars), indicating lower accretion rates, increases above the critical BH mass. These observational trends can be natural consequences of the proposed scenario of suppressing BH growth around the apparent maximum mass of \(\sim 10^{10} M_\odot\). The ongoing VLA Sky Survey in radio will allow us to estimate of the exact number fraction of RL quasars more precisely, which gives further insight into the quenching processes for BH growth.

Key words: galaxies: active – galaxies: nuclei – quasars: general

1. Introduction

The question of whether or not supermassive black holes (SMBHs) in the universe have a maximum mass is a fundamental one. The recent and ongoing optical and near-infrared surveys of high-z quasars have revealed that SMBHs with masses of \(M_{\text{BH}} > 10^9 M_\odot\) already exist at \(z > 6\) (Mortlock et al. 2011; Wu et al. 2015; Jiang et al. 2016; Matsuoka et al. 2016). Since the \(\varepsilon\)-folding time for BH growth in mass is only \(\sim 40\) Myr, SMBHs are likely to exceed \(M_{\text{BH}} \sim 10^{11} M_\odot\) significantly by \(z \simeq 0\). However, such SMBHs have not yet been observed in the local universe (McConnell et al. 2011; Kormendy & Ho 2013). More intriguingly, the surveys have also revealed that there is a redshift-independent maximum mass limit at \(M_{\text{max}} \sim 10^9 M_\odot\) (Netzer 2003; McLure & Dunlop 2004; Ghisellini et al. 2010; Trakhtenbrot 2014; Jun et al. 2015).

The origin of the maximum mass of SMBHs has been argued by several authors (Natarajan & Treister 2009; Inayoshi & Haiman 2016; hereafter IH16; King 2016) with a simple analytical model. IH16 proposed that SMBHs exceeding \(M_{\text{max}}\) are prevented from growing by small-scale accretion physics, which is independent of the properties of their host galaxies or cosmology. A high gas-supplying rate from galactic scales into a nuclear region is required to form more massive SMBHs. However, most of the gas is consumed by star formation in a gravitationally unstable galactic disk at large radii (\(\gtrsim 100\) pc) beyond reaching the nuclear region at \(\lesssim 1\) pc (Thompson et al. 2005), where the gas accretion rate results in \(\lesssim 1\%\) of the Eddington accretion rate. In such a low accretion rate, the gas flow at the vicinity of the SMBH never forms a standard geometrically thin disk but instead transits into an advection-dominated accretion flow (ADAF; Ichimaru 1977; Narayan & Yi 1994, 1995). Since the Bernoulli parameter of the ADAF is positive, strong outflows and jets are likely to be launched from the accreting system and shut off the BH feeding effectively (Blandford & Begelman 1999; Igumenshchev & Abramowicz 1999; Stone & Pringle 2001; Hawley & Balbus 2002). Those outflows and jets interact with the ambient gas and form shock regions, from which radio emission can be produced by non-thermal electrons (see a review by Yuan & Narayan 2014). Thus, as a possible outcome of the quenching process, the largest SMBHs would be associated with radio emission due to jets.

One key observational consequence of the above argument is that the number fraction of the radio-loud (RL) quasars (hereafter RL fraction) in the high-mass regime (\(M_{\text{BH}} > 10^9 M_\odot\)) would increase. Observationally, RL quasars have systematically higher BH masses than their radio-quiet (RQ) counterparts (e.g., Laor 2000; McLure & Jarvis 2004; Shen et al. 2008), whereas a clear correlation between the radio-loudness parameter \(R\) (defined later) and \(M_{\text{BH}}\) were not found (e.g., Ho 2002; Woo & Urry 2002) up to \(M_{\text{BH}} \sim 10^{10} M_\odot\). Best et al. (2005) first showed that the RL fraction increases with \(M_{\text{BH}}\) using the local \((z < 0.5)\) Sloan Digital Sky Survey (SDSS) DR2 type-2 active galactic nucleus sample for \(M_{\text{BH}} \lesssim 10^9 M_\odot\). This motivates us to extend the study to SMBHs with higher masses (\(M_{\text{BH}} \lesssim 10^{11} M_\odot\)), where the critical BH mass theoretically expected is covered.

In this Letter, in light of the large number samples of SDSS-selected quasars, we report the dependence of the RL fraction as a function of \(M_{\text{BH}}\) by expanding the BH mass range with \(10^8 < M_{\text{BH}} < 10^{11} M_\odot\) and in the redshift range of \(0 < z < 2\).

2. Sample

2.1. Quasar Catalog

The initial sample adopted in this Letter is drawn from the SDSS DR7 Quasar Catalog (Shen et al. 2011, hereafter S11), which contains 105783 quasars in the redshift range of \(0.05 < z < 5.5\). The sources in the sample are brighter than the \(K\)-corrected, \(i\)-band absolute magnitude \(M_i(z = 2) = -22\) which is normalized at \(z = 2\) (Richards et al. 2006), and have
In order to investigate the RL fraction of quasars as a function of BH mass, we here utilize $H_\beta$ and MgII lines for quasars at $z < 0.7$ (Vestergaard & Peterson 2006) and $0.7 < z < 2.0$ (Shen et al. 2011), respectively, as adopted in S11 as a fiducial choice of the BH estimates. At $z > 2.0$, CIV lines are commonly used to estimate BH masses. However, we do not use the measurements with CIV lines because their mass estimation would have almost ubiquitous ambiguities due to non-virial wind component (Shen et al. 2008; Trakhtenbrot & Netzer 2012; Mejía-Restrepo et al. 2016). This selection reduces the number of sources to 75872 in the redshift interval of $0.05 < z < 2.0$.

2.2. Radio-loudness Parameter and $M_{BH}$

Figure 1 shows the distribution of our quasar sample in the $M_{BH}$–$R$ plane. Quasars with the detection and the non-detection in the FIRST band are shown by orange and gray dots, respectively. For the latter sample, the radio-loudness parameters are estimated from the upper limits of the radio fluxes. Because of the shallow sensitivity of the FIRST survey with a threshold of $1\text{ mJy}$ (Becker et al. 1995), the radio-loudness parameters $R$ have been measured for 7219 sources ($\lesssim 9.5\%$) among all of the selected 75872 quasars. As shown in Figure 1, a significant fraction of the non-radio-detected quasars (gray dots) distribute evenly above the conventional RL/RQ quasar boundary of $R = 10$. Therefore, we here adopt a RL/RQ boundary of $R = 100$ instead of $R = 10$, in order to reduce the contamination from non-radio-detected quasars and to give a more conservative estimate of the RL fraction. We also note that if we adopt $R > 100$ as the RL/RQ boundary, only the sample size is reduced without improving the contamination level. In addition, we remove all of the sources with $M_{BH} < 10^8 M_\odot$ because more than half of the sources located at $M_{BH} < 10^8 M_\odot$ and $R > 100$ are non-radio-detected sources. This provides a significant level of contamination in those BH mass ranges, even if we adopt the conservative RL/RQ boundary of $R = 100$. Finally, our sample contains 72162 sources with a mass range of $8.0 < \log(M_{BH}/M_\odot) < 11.0$ and a redshift range of $0.05 < z < 2.0$. The number of quasars at each $M_{BH}$ range ($N_{all}$) is compiled at the second column in Table 1.

We calculate the RL fraction based on different criteria for non-radio-detected quasars: (1) those sources are always regarded as RQ quasars, and (2) if the upper limits of the radio-loudness parameters $R$ are higher than the RL/RQ boundary of $R = 100$, the sources are categorized as RL quasars. The former (latter) cases give the lower (upper) limits of the RL fraction. The lower and upper values of the RL fraction ($N_{RL}^{\text{min}}$) and ($N_{RL}^{\text{max}}$) are shown in Table 1.

### Table 1

| $M_{BH}$ range | Full Sample | 0 < $z$ < 1 Sample | 1 < $z$ < 2 Sample |
|----------------|-------------|------------------|------------------|
|                | $N_{all}$  | $N_{RL}^{\text{min}}$ | $N_{RL}^{\text{max}}$ | $N_{all}$  | $N_{RL}^{\text{min}}$ | $N_{RL}^{\text{max}}$ |
| 8–8.5          | 11330      | 400              | 661              | 8087      | 255              | 378              | 3241      | 145              | 283              |
| 8.5–8.75       | 11651      | 445              | 607              | 5440      | 200              | 265              | 6209      | 245              | 342              |
| 8.75–9         | 16028      | 691              | 796              | 4582      | 255              | 292              | 11444     | 436              | 504              |
| 9–9.25         | 16283      | 781              | 838              | 2721      | 227              | 253              | 13562     | 554              | 585              |
| 9.25–9.5       | 10767      | 680              | 699              | 1155      | 169              | 183              | 9862      | 511              | 516              |
| 9.5–9.75       | 4440       | 376              | 381              | 347       | 62               | 67               | 4093      | 314              | 314              |
| 9.75–10        | 1290       | 125              | 126              | 78        | 18               | 18               | 1212      | 107              | 108              |
| 10–11          | 373        | 54               | 59               | 40        | 17               | 20               | 333       | 37               | 39               |

Note. Number of quasars and RL quasars at each $M_{BH}$ bin for the full sample (Column 2–4), the $0 < z < 1$ sample (Column 5–7), and the $1 < z < 2$ sample (Column 8–10). $N_{all}$ represents the number of quasars. $N_{RL}^{\text{min}}$ and $N_{RL}^{\text{max}}$ are the number of RL quasars defined by the criterion (1) and (2) in Section 2.2, respectively.

![Figure 1](image-url)
assuming that all of the upper-limit sources are RQ quasars. The dashed curve represents the cubic spline-function of which are tabulated in the SDSS quasar sample (e.g., Kellermann et al. 1989) since we apply the conservative criterion of the RL/RQ boundary (R = 100). Above the critical mass of \( M_{\text{BH}} \sim 2 \times 10^9 \, M_\odot \) (=\( M_{\text{crit}} \)), where the RL fraction becomes larger than the maximum values of \( f_{\text{RL}} \) at lower BH masses within the statistical errors, the RL fraction begins to increase toward higher masses and exceeds 15% at \( M_{\text{BH}} / M_\odot > 10^{10} \), which is three times higher than the constant fraction for lower masses. The overall behavior of the RL fraction agrees with that expected from the theoretical model by IH16. Note that the enhancement of the RL fraction occurs slightly before the BH mass reaches \( M_{\text{max}} \). We also confirm that the overall trend of the RL fraction above \( M_{\text{crit}} \) still holds as long as the RL/RQ boundary is set to \( 30 < \beta < 300 \).

The left panel of Figure 2 shows the RL fraction as a function of \( M_{\text{BH}} \) for the full sample (0 < \( z < 2 \)). The RL fraction is almost a constant value of 5% at \( 10^8 \lesssim M_{\text{BH}} / M_\odot \lesssim 2 \times 10^9 \). This value is slightly smaller than the conventionally well-known value of 10% (e.g., Kellermann et al. 1989) since we apply the conservative criterion of the RL/RQ boundary (R = 100). Above the critical mass of \( \sim 2 \times 10^9 \, M_\odot \) (=\( M_{\text{crit}} \)), where the RL fraction becomes larger than the maximum values of \( f_{\text{RL}} \) at lower BH masses within the statistical errors, the RL fraction begins to increase toward higher masses and exceeds 15% at \( M_{\text{BH}} / M_\odot > 10^{10} \), which is three times higher than the constant fraction for lower masses. The overall behavior of the RL fraction agrees with that expected from the theoretical model by IH16. Note that the enhancement of the RL fraction occurs slightly before the BH mass reaches \( M_{\text{max}} \). We also confirm that the overall trend of the RL fraction above \( M_{\text{crit}} \) still holds as long as the RL/RQ boundary is set to \( 30 < \beta < 300 \).

The right panel of Figure 2 shows the RL fraction for quasars at 0 < \( z < 1 \) (blue), 1 < \( z < 2 \) (red), and 0 < \( z < 2 \) (black). For all of the cases, the RL fraction is almost constant at \( M_{\text{BH}} \lesssim M_{\text{crit}} \) and begins to increase toward higher masses, as shown in Figure 2. Therefore, the trend for the RL fraction does not depend on their redshifts, at least in the range of 0 < \( z < 2 \). We note that a slight enhancement of the RL fraction at \( 1 < z < 2 \) seen in a mass bin of \( 10^8 \lesssim M_{\text{BH}} / M_\odot \lesssim 10^{10} \) is due to the non-negligible level of contamination (138 out of 283 sources; see also Table 1) of the non-radio-detected sources.

4. Discussions

4.1. Suggestion of ADAF Scenario

One scenario to explain the enhancement of the RL fraction at high BH masses is based on the transition of an accretion disk to an ADAF (IH16). In order to test this theoretical model from another perspective, we investigate the Eddington ratios (\( \lambda_{\text{Edd}} = L_{\text{bol}} / L_{\text{Edd}} \)) of those RL quasars, the bolometric luminosities \( L_{\text{bol}} \) of which are tabulated in the SDSS quasar survey (Shen et al. 2011), and \( L_{\text{Edd}} \) are the Eddington luminosities. This is because the model also suggests that high-mass RL quasars should be fed with gas at low accretion rates, resulting in low Eddington ratios. Figure 3 shows the number fraction of RL quasars with lower \( \lambda_{\text{Edd}} \) (i.e., lower accretion rates) also increases with BH masses, notably above \( M_{\text{BH}} \sim M_{\text{crit}} \) as expected from the theoretical model.

We note that several authors have discussed possible mechanisms leading to an upper limit on the BH masses. Natarajan & Treister (2009) originally pointed out that the limit would be due to the self-regulation of BH growth, related to the coevolution with the host galaxies. Since gas clouds in halos with significantly higher masses than \( \sim 10^{12} \, M_\odot \) hardly cool, star formation in the halos would be reduced and thus the stellar masses would be at most \( M_\star \sim 10^{11} \sim 10^{12} \, M_\odot \), almost independently of redshifts (0 < \( z < 5 \); Rees & Ostriker 1977). Assuming that the mass ratios between SMBHs and their host galaxies at \( z \sim 0 \), \( M_{\text{BH}} / M_\star \sim 10^{3} \sim 10^{-2} \) (e.g., Kormendy & Ho 2013), the maximum BH mass would be estimated as \( \sim 10^{10} \, M_\odot \), which is consistent with the apparent maximum mass of SMBHs. However, since the BH/galaxy mass relation at \( z \sim 0 \) does not necessarily hold at high-redshifts (Trakhtenbrot et al. 2015; Inayoshi et al. 2016; Pacucci et al. 2017), the above mass limit may have a redshift-dependence (the apparent BH mass seems independent of redshifts). In order to test the scenario proposed by IH16 of suppressing BH feeding and distinguish from other scenarios, we need to investigate if the dependence of the RL fraction on the BH masses shown in Figure 2 holds at higher redshifts.

As an alternative scenario, King (2016) recently proposed that fragmentation of an AGN accretion disk due to gravitational instability would suppress the BH growth at \( M_{\text{BH}} \gtrsim 5 \times 10^{10} \, M_\odot \). This was because a gravitational...
stable disk could not exist in the whole region outside of the inner-most stable circular orbit (ISCO). However, since radiation pressure dominates near the ISCO and stabilizes the disk against its self-gravity, the critical mass due to fragmentation is boosted to \( M_{\text{BH}} \gtrsim 10^{13} M_\odot \). Since this mass is higher than the observed maximum mass of SMBHs by orders of magnitude (IH16, Shadmehri et al. 2017), this suppression process of BH feeding could not explain the increase of the RL fraction around \( \lambda_{\text{Edd}} \).

### 4.2. Effects of the BH Spin on the RL Fraction

BH spin potentially increases the radio luminosity from the AGN because the rotational energy of the central SMBH is converted into the jet power (Blandford & Znajek 1977). Previous observations have proposed that the most massive SMBHs have relatively higher positive spin (Trakhtenbrot 2014). Assuming the Blandford–Znajek process, the jet luminosity is estimated as \( L_{\text{jet}} \sim \eta_{\text{jet}} M c^2 \), where \( \eta_{\text{jet}} \sim 1.3 a^2 \) (Tchekhovskoy 2015) and \( a \) is the spin parameter. On the other hand, the AGN bolometric luminosity is governed by \( L_{\text{bol}} = \eta_{\text{rad}} M c^2 \), where \( \eta_{\text{rad}} \) is the radiation efficiency. The typical value is estimated as \( \eta_{\text{rad}} \approx 0.1 \) (Soltan 1982), which corresponds to mildly rotating BHs with \( a \approx 0.6 \) and the highest value is \( \eta_{\text{rad}} \approx 0.42 \) for an extreme Kerr BH with \( a = 1 \). Therefore, the radio-loudness parameter can be estimated as \( R \sim \eta_{\text{jet}}/\eta_{\text{rad}} \approx 4.7 (3.1) \) for \( a \approx 0.6 (1.0) \). Since the radio-loudness parameter \( R \) hardly depends on the BH spin, the BH spin does not affect our conclusion.

We note that there is another caveat: the S11 quasar catalog used as the parent sample in this study would miss retrograde-spin (\( a < 0 \)) quasars in the high-mass end with \( >10^{10} M_\odot \). This is because those quasars produce relatively weaker UV excess, and therefore the color selections by SDSS could miss those weak UV excess quasars (Bertemes et al. 2016). Therefore, we need to explore quasar samples with different color selections from those for SDSS quasars. If we included those quasars in our sample, the RL fraction at the high-mass end would increase because quasars with retrograde spins (\( a \sim -1 \)) potentially provide higher radio-loudness parameters (\( R \propto \eta_{\text{jet}}/\eta_{\text{rad}} \sim 30 \)).

### 4.3. Gradual Increase of the RL Fraction Above \( M_{\text{crit}} \)

One might argue that if the BH growth is “turned off” at certain critical mass, the RL fraction increases drastically, up to almost 100%. However, the RL fraction shown in Figure 2 increases gradually above the critical mass of \( M_{\text{crit}} \approx 2 \times 10^9 M_\odot \). This fact suggests that the quenching process of BH growth would not occur instantaneously, but would instead take a certain amount of time and occur episodically until the disk state transitions to an ADAF state with the jet emission. The observed RL fraction for a BH mass bin can be interpreted as the ratio of the jet illuminating time \( t_{\text{jet}} \) (i.e., the disk is in an ADAF) to the time when BHs exist in the mass bin. Thus, the RL fraction is written as \( f_{\text{RL}} \approx t_{\text{jet}}/(t_{\text{acc}} + t_{\text{jet}}) \), where \( t_{\text{acc}} \) is the mass-doubling time (i.e., the disk in a standard disk). Figure 4 shows the possible range of \( t_{\text{acc}} \approx t_{\text{acc,RL}}/(1 - f_{\text{RL}}) \) as a function of \( M_{\text{BH}} \), where the mass-doubling time is estimated as \( t_{\text{acc}} \sim 4.5 \times 10^8 \) (\( M_{\text{BH}}/10^9 M_\odot \)) yr (Thompson et al. 2005) and \( f_{\text{RL}} \) is estimated from the dashed curve in Figure 2. Since our study uses the criterion of \( R \geq 100 \) for selecting RL quasars, the derived value of \( t_{\text{acc}}(R \geq 100) \) gives the lower limit of \( t_{\text{acc}} \) as shown in the dotted curve. We also over-plot the value of \( t_{\text{acc}} \) with \( R \geq 30 \) for choosing RL quasars, which gives the relatively larger value than that of \( t_{\text{acc}}(R \geq 100) \). Figure 4 also shows that \( t_{\text{acc}}(R \geq 30) \) becomes larger than \( t_{\text{acc}} \) at \( M_{\text{BH}} \gtrsim 10^{10.5} M_\odot \); that is, more than 50% of nuclear disks are in ADAF states, in which the SMBHs would be prevented from significantly increasing their own mass.

### 4.4. Exact Value of the RL Fraction

The exact value of the RL fraction at each BH mass is still unknown due to the shallower radio band sensitivity (see also Figure 1). This will be improved after the completion of the ongoing VLA Sky Survey (VLASS; https://science.nrao.edu/science/surveys/vlass/vlass), which covers the SDSS survey area with a sensitivity down to 0.12 mJy at S-band (2–4 GHz), giving us photometry that is almost one order of magnitude deeper compared to the current FIRST sensitivity of 1 mJy at 1.4 GHz. While the frequency coverage is slightly different, this survey allows us to discuss this argument with...
the conventional RL/RQ boundary of \( R = 10 \), instead of our conservative criterion of \( R = 100 \).

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