Black Hole Masses and Radio Properties of AGNs

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Abstract Supermassive black hole (SMBH) is believed to be an essential part of AGN activities. Recently a lot of dynamical measurements have shown that many nearby galaxies host SMBHs. Reverberation mapping of about 40 AGNs also revealed that such SMBHs exist in AGNs. A tight relation between SMBH masses and central velocity dispersions has been found for both nearby and active galaxies. Using this correlation we can reliably estimate the SMBH masses of a lot of AGNs for which other mass measurement techniques can not apply. For a sample of Seyfert galaxies, we found that the radio power increase with SMBH masses, similar as that found for quasars and nearby galaxies. However, AGNs have 100 times more radio power than that of nearby galaxies at the given black hole mass. For radio-loud AGNs, the nuclear radio-loudness tends to increase with SMBH mass. But such a relation has not been found for radio-quiet AGNs. In addition, we estimated the SMBH masses and the Eddington ratios ($L/L_{\rm Edd}$) for a sample of AGNs with elliptical host galaxies and found that radio-loud AGNs may have lower Eddington ratios than radio-quiet AGNs. Some related physics on black hole accretion and jet formation mechanisms are discussed.

Key words pulsar-mode change-spectrum

1 Introduction

Supermassive black holes with masses in the range of 10^6 to $10^9 M_\odot$, have been suggested to exist in the center of quasars and active galactic nuclei (AGNs) in order to account for the huge power of these energetic objects (Lynden-Bell 1969; Rees 1984). Recently, the masses of central objects in 20 Seyfert galaxies and 17 nearby quasars have been measured with the reverberation mapping technique (Ho 1999; Wandel, Peterson & Malkan 1999; Kaspi et al. 2000), which confirmed the existence of SMBHs in these objects. On the other hand, a lot of observations using gas and stellar dynamics indicated that SMBHs also exist in the center of our Galaxy (Ghez et al. 1998; Genzel et al. 1997) and in the nuclei of many normal galaxies (Kormendy & Richstone 1995; Kormendy & Gebhardt 2001).

One interesting result found recently for nearby galaxies is the correlation of black hole masses with the properties of galactic bulges. Although with large scatters, the black hole masses seem to correlate with bulge luminosities (Kormendy & Richstone 1995; Magorrian et al. 1998). This also leads to the finding that the black hole mass, $M_{\rm BH}$, is possibly proportional to the bulge mass, $M_{\rm bulge}$, though the mass ratio found by different authors was different, in the range of 0.2% to 0.6% (Kormendy & Richstone 1995; Magorrian et al. 1998; Ho 1999). Recently, a significantly tight correlation of $M_{\rm BH}$ with the bulge velocity dispersion σ was also found for nearby galaxies (Gebhardt et al. 2000a; Ferrarese & Merritt 2000). More recent studies indicated that 11 Seyfert galaxies with $M_{\rm BH}$ measured by reverberation mapping follow the same $M_{\rm BH} - \sigma$ relation as for normal galaxies (Gebhardt et al. 2000b; Ferrarese et al. 2001), implying another possible universal relation for both normal and active galaxies. These correlations strongly suggest a tight connection between the formation and evolution of the SMBH and galactic bulge, though the nature of this connection is still in debate.

Nonthermal radio emissions of quasars and AGNs are believed to be probably produced by relativistic electrons that are powered by jets (Begelman, Blandford & Rees 1984; Blundel & Beasley 1998). Similar radio emissions have been detected in the nuclei of normal elliptical galaxies (Sadler, Jenkins & Kotanyi 1989) and also in some spiral galaxies (Sadler et al. 1995). Recently, some studies have indicated that the radio power may be directly correlated with the black hole mass. Franceschini, Vercellone & Fabian (1998) found a very tight relation between black hole mass and radio power in a small sample of nearby mostly non-active galaxies. McLure et al. (1999) estimated the black hole masses for a sample of AGNs using $M_{\rm BH}$-bulge mass relation found by Magorrian et al. (1998) and noted they follow the same correlation with radio power as found by Franceschini et al. (1998). However, Laor (2000) recently argued that the $M_{\rm BH}$ and radio power of a sample of 87 $z < 0.5$ Palomar-Green (PG) quasars do not follow the tight correlation suggested by Franceschini et al. (1998), because quasars usually have over 100 times larger radio power than normal galaxies at a given $M_{\rm BH}$. He also noted that the radio-loud quasars seem to host more massive black holes than radio-quiet quasars. Very recently, Ho & Peng (2001) studied the radio-loudness of bright Seyfert 1 galaxies using the nuclear radio and optical luminosities, and suggested that the majority of Seyfert 1 nuclei in their sample are essentially radio loud. Therefore, it is useful to check if these radio-loud Seyfert nuclei host more massive black holes than radio-quiet ones and if the Seyfert galaxies still follow the same correlation between the radio power and black hole masses of nearby galaxies and quasars (Wu & Han 2001).

2 SMBH Masses of Seyfert Galaxies

Currently the SMBH masses of a few weak AGNs have been well measured by stellar dynamics, ionized gas dynamics and water maser dynamics (Kormendy & Gebhardt 2001). Using the reverberation mapping technique, the SMBH masses of 20 Seyfert galaxies and 17 bright quasars have been recently estimated (Ho 1999; Wandel et al. 1999; Kaspi et al. 2000). However, for most Seyfert galaxies, it is difficult to measure the SMBH mass using these methods because of either the large nuclear luminosity or the lack of long-term variability monitoring and precise measurements of characteristic velocity dispersions in the broad emission line region. Since the tight correlation between the SMBH mass and bulge velocity dispersion has been found for both normal and active galaxies (Gebhardt et al. 2000b; Ferrarese et al. 2001), it may be straightforward to estimate the SMBH mass from the measured bulge velocity dispersion. Here we adopt the $M_{\rm BH}$-σ relation found by Merritt & Ferrarese (2001), namely,

$$M_{\rm BH} = 1.3 \times 10^8 {\rm M}_\odot (\sigma/200\,{\rm km\,s^{-1}})^{4.72}\,, \tag{1}$$

to derive the SMBH masses for Seyfert galaxies with measured nuclear velocity dispersions. Using a slightly flatter relation found by Gebhardt et al. (2000) does not cause significant changes in our results.

We selected 37 Seyfert galaxies, including 22 Seyfert 1s and 15 Seyfert 2s from two well-studied Seyfert samples, namely the Palomar and CfA bright Seyfert samples (Ho et al. 1997a; Osterbrock & Martel 1993). These Seyfert galaxies have either the measured SMBH masses or the measured central velocity dispersions. Among them, three Seyfert 1s and two Seyfert 2s have dynamical SMBH masses (Ho 1999; Gebhardt et al. 2000a), and ten Seyfert 1s have SMBH masses measured by the reverberation mapping method (Wandel et al. 1999; Ho 1999). Another Nine Seyfert 1s and 13 Seyfert 2s have measured central velocity

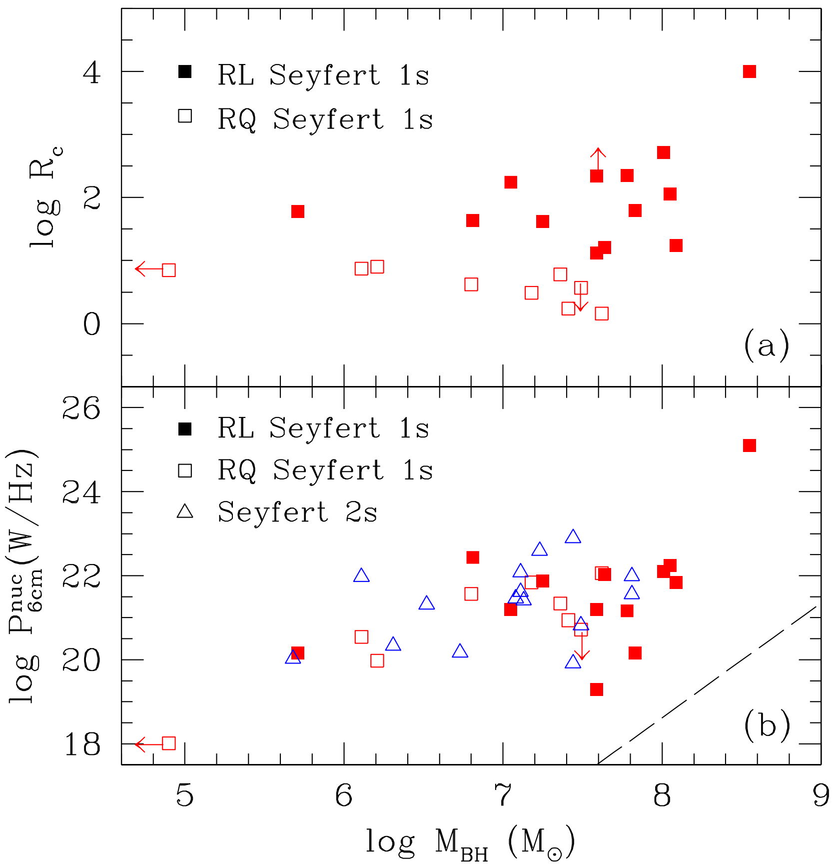

Fig. 1 The nuclear radio-loudness and the nuclear radio power against the black hole masses for Seyfert galaxies. The dashed line in the lower panel represents the tight correlation for nearby galaxies found by Franceschini et al. (1998).

dispersions but unknown SMBH masses (Nelson & Whittle 1995). The SMBH masses can be estimated by equation (1) using the measured central velocity dispersions. Therefore, our sample consists of 37 Seyfert galaxies with derived SMBH masses.

The radio properties of Seyfert galaxies have been investigated using the Very Large Array (VLA) at 3.6 cm by Kukula et al. (1995) for the CfA sample, and at 6 cm and 20 cm recently by Ho & Ulvestad (2001) for the Palomar sample. Here we adopt the radio data for Seyfert 1s from Ho & Peng (2001) and the data for Seyfert 2s from Ho & Ulvestad (2001) and Kukula et al. (1995). The 6 cm data for some sources in the CfA sample (Kukula et al. 1995) were extrapolated from the 3.6cm data assuming $f_\nu \propto \nu^{-0.5}$.

Seyfert galaxies have been considered usually as radio-quiet AGNs because most of them have lower radio-loudness, defined as the ratio of the radio to optical luminosities, $R = L_{6cm}/L_B$. However, recently Ho & Peng (2001) showed that though the nuclear radio power for Seyfert 1 galaxies on average accounts for about 75% of the total radio emission, the nuclear optical luminosity, measured by high-resolution optical images, accounts for merely 0.01% of the integrated light. If the radio-loudness is measured by the nuclear radio and optical luminosities, most Seyfert 1s are in the category of radio-loud AGNs (with radio-loudness larger than 10). Their nuclear radio-loudness, R_c, can be calculated by $R_c = L_{6cm}^{\rm nuc}/L_B^{\rm nuc}$. The Hubble constant $H_0 = 75{\rm kms^{-1}Mpc^{-1}}$ and the deceleration parameter of $q_0 = 0.5$ were adopted. For Seyfert 2s, the measurements of their nuclear optical magnitudes are not available in the literature.

Figure 1 shows the relation of SMBH masses with the nuclear radio-loudness of Seyfert 1s and the radio power of Seyfert galaxies. It is clear that the radio-loud Seyfert 1s with larger nuclear radio-loudness seem to host more massive black holes. The similar tendency has been found for nearby quasars by Laor (2000). From Figure 1(b) we see a trend that Seyfert galaxies having a larger radio power perhaps host a more massive black hole than those of less radio power. With the same black hole mass, Seyfert galaxies seem to have 100 to 1000 times greater radio power than normal galaxies. Laor (2000) has shown that nearby quasars also depart from such a correlation for nearby galaxies, with the radio luminosity of quasars being 10^4 larger at a given $M_{\rm BH}$. The difference of radio luminosities of quasars, Seyfert galaxies and nearby galaxies may be simply due to different levels of nuclear activity.

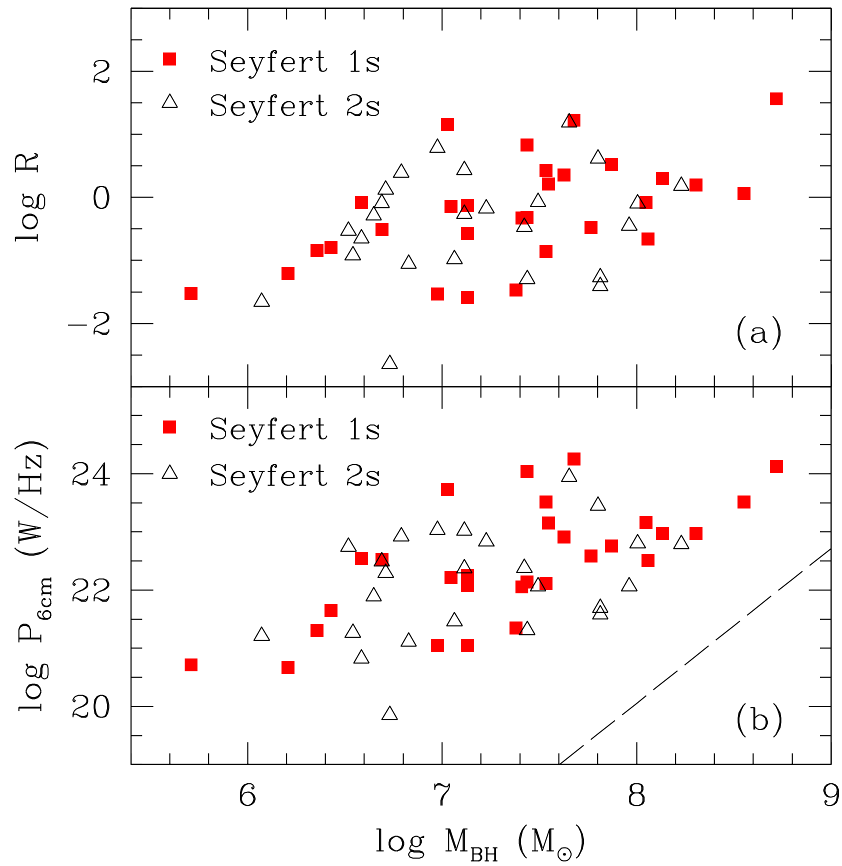

Fig. 2 The radio-loudness (a) and radio power (b) against the black hole masses for Seyfert galaxies in the sample of Nelson & Whittle (1995). The dashed line in (b) represents the tight correlation found by Franceschini et al. (1998) for nearby galaxies.

We can also investigate the relation between SMBH masses and radio properties using the Seyfert sample in Nelson & Whittle (1995), where the measurements of nuclear velocity dispersions of about 70 Seyfert galaxies were reported. After excluding several LINERs and normal galaxies, we got 33 Seyfert 1s and 32 Seyfert 2s. We estimated the SMBH masses of these Seyfert galaxies using the M_{BH}-σ relation (eq. (1)). The total radio power at 5 GHz of them was calculated from the 1.4 GHz data in Nelson & Whittle (1995) by assuming $f_\nu \propto \nu^{-0.5}$ and $H_0 = 80 \mathrm{kms^{-1}Mpc^{-1}}$. The radio-loudness was calculated by the 5 GHz radio luminosity and the B-band optical luminosity. The radio-loudness and total radio power against the SMBH masses for 29 Seyfert 1s and 25 Seyfert 2s with available radio data in the sample of Nelson & Whittle (1995) are plotted in Fig. 2. Now we see that most Seyfert galaxies seem to be radio quiet ($R < 10$) when we adopted the total radio and optical luminosities to calculate the radio-loudness. There is a weak tendency that Seyfert galaxies with larger radio-loudness have larger SMBH masses. A comparison with the result in Figure 1(a) indicates that the nuclear radio-loudness may be more fundamental and reflect the nature of central engine of Seyfert galaxies. From Figure 2(b) we see that there is a strong correlation between the total radio power and the SMBH mass, which confirms the previous result that AGNs with larger radio power may host more massive SMBHs (Franceschini et al. 1998; McLure et al. 1999). However, Seyfert galaxies depart significantly from the tight relation between the radio power and SMBH mass found for normal galaxies by Franceschini et al. (1998).

3 SMBH Masses and Eddington Ratios of Radio Galaxies and Quasars

The tight M_{BH}-σ relation suggests an interesting possibility to estimate the central black hole masses for galaxies using the measured values of bulge velocity dispersions. This straightforward method is particularly important for AGNs because the dynamical method cannot be applied for the determination of the black hole mass for most of them. However, AGNs usually have very bright nuclear emission, which makes it very difficult to measure their stellar velocity dispersions with the spectroscopic method. For most AGNs, one has to look for other methods to determine the central velocity dispersions of their host galaxies.

Imaging studies on the host galaxies of AGNs with HST have clearly revealed that a lot of BL Lac objects, radio galaxies, radio-loud quasars, and some radio-quiet quasars have massive elliptical hosts (Urry et al. 2000; McLure et al. 1999; Dunlop et al. 2002). It is well known for ellipticals that three observables, the effective radius, the corresponding average surface brightness and the central velocity dispersion, follow a surprisingly tight linear relation (so-called fundamental plane, see Djorgovski & Davis 1987; Dressler et al. 1987; Faber et al. 1989). Some subsequent studies have shown that the elliptical hosts of radio galaxies follow the same fundamental plane as normal ellipticals (Bettoni et al. 2001). Because the fundamental plane is probably universal and exists also for elliptical hosts of AGNs, it is possible to estimate the central velocity dispersions from the morphology parameters of the host galaxies (McLure & Dunlop 2001). This provides another possible way to derive the SMBH masses of AGNs for which high quality images of their host galaxies have been obtained (Wu, Liu & Zhang 2002).

A deep HST imaging study of the host galaxies of a sample of 10 radio galaxies (RGs), 10 radio-loud quasars (RLQs) and 13 radio-quiet quasars (RQQs) has been performed recently (McLure et al. 1999; Dunlop et al. 2002). The hosts of both radio-loud AGNs and bright radio-quiet AGNs were found to be virtually all massive ellipticals. The basic properties of these host galaxies are indistinguishable from those of normal ellipticals. Therefore, using the fundamental plane relation, we can derive the central velocity dispersions and black hole masses for this sample of AGNs based on the morphology parameters of their host galaxies. The average SMBH masses of RGs, RLQs and RQQs were estimated to be $10^{8.13}\mathrm{M}_\odot$, $10^{8.22}\mathrm{M}_\odot$ and $10^{7.90}\mathrm{M}_\odot$ respectively. The mean SMBH mass of 9 RQQs is smaller by only a factor of two than that of 10 RLQs. Most of these AGNs have black hole masses in the range of $10^{7.5}\mathrm{M}_\odot$ to $10^{9}\mathrm{M}_\odot$.

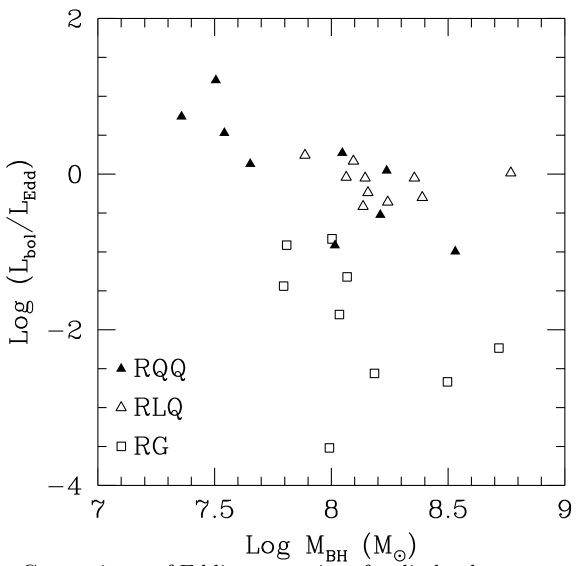

Fig. 3 Comparisons of Eddington ratios of radio-loud quasars, radio-quiet quasars and radio galaxies.

Using the derived SMBH masses, we can estimate the Eddington ratio (defined as the ratio of bolometric luminosity and Eddington luminosity) of the source in our sample of RGs, RLQs and RQQs. We adopted the assumptions of $L_{\rm bol} \simeq 10\lambda L_{5100\mathring{A}}$ (Kaspi et al. 2000) and $f_\nu \propto \nu^{-0.2}$ (Dunlop et al. 2002) to convert the R-band luminosity to the bolometric luminosity for the nuclear component of AGNs. Figure 3 shows the distributions of Eddington ratios of 9 RGs, 10 RLQs and 9 RQQs. It is clear that the Eddington ratios of RGs are systematically smaller than those of RLQs and RQQs by two orders, while there is less significant difference in Eddington ratios for RLQs and RQQs. Our result is qualitatively consistent with that obtained by Ho (2002) who recently suggested that the strongly active AGNs have larger Eddington ratios. Figure 3 shows that both RLQs and RQQs have a bolometric luminosity comparable to the Eddington luminosity. A t-test also shows a significance of 56% that the Eddington ratios of RLQs and RQQs are from the same population. Therefore, our results indicate that the SMBH masses of RLQs may be slightly larger than those of RQQs; their Eddington ratios may not be significantly different. However, we must noted that these results were obtained with a small sample of radio-loud and radio-quiet quasars. More definitive conclusions can be reached only with larger and more complete samples.

4 Discussions

With a larger sample of Seyfert galaxies, we show that AGNs with a larger nuclear radio-loudness seem to have more massive black holes. This conclusion was obtained recently by Laor (2000) for nearby quasars and was supported by our study for Seyfert galaxies. Our results also strengthen the argument made by Ho & Peng (2001) that the majority of Seyfert

1s are essentially radio-loud AGNs. The total radio power of Seyfert galaxies increases with the black hole mass. At a given $M_{\rm BH}$, quasars and Seyfert galaxies seem to have greater radio power than that of nearby galaxies. These difference may simply be due to the different level of nuclear activity. A recent study using the quasars from the FIRST Bright Quasar Survey found evidence for the dependence of radio-luminosity on accretion rate and SMBH mass (Lacy et al. 2001). This may help us to understand the origin of scatters in the relation between the radio power and SMBH mass. If we describe the nuclear activity of galaxies using the accretion rate $\dot{M}$, the difference of radio power at a given $M_{\rm BH}$ may show that quasars and Seyfert galaxies have larger $\dot{M}$ than nearby galaxies. This seems also consistent with the idea that the accretion process in these systems may be different (Fabian & Rees 1995; Di Matteo & Fabian 1996). Most likely ADAFs with very low accretion rate exist in the nuclei of nearby galaxies, while quasars and most AGNs probably host standard geometrically thin accretion disks with higher accretion rate. However, the radio emissions from radio-quiet AGNs and nearby galaxies are not well understood at present. Whether they are from ADAFs (Narayan et al. 1998) or from weak jets (Falcke & Biermann 1996, 1999) still remains uncertain. For radio-loud AGNs, the radio emissions are thought to be mainly from the jet and are probably related to the magnetic fields or black hole spin (Blandford & Payne 1982; Blandford & Znajek 1977). If the radio emissions correlate with the black hole mass and accretion rate, we need to explain the possible relations of these parameters with magnetic fields and black hole spin. However, no satisfactory theory can provide clear physics about these relations at present.

In addition, our study on the Eddington ratios for quasars and radio galaxies implies that the importance of accretion rates in the evolutionary sequences of AGNs. The different observational appearances among radio-loud AGNs cannot be dominated by the different SMBH masses. Theoretical investigations have pointed out that accretion near the Eddington limit may produce optically thick accretion disks extending all the way to the innermost stable orbit, while accretion at very lower accretion rate may lead to advection dominated accretion mode (Narayan et al. 1998). Recently Ghisellini & Celotti (2001) also proposed that the separation of FR I and FR II radio galaxies may be closely related to the critical accretion rates. In addition, the state transition of Galactic black hole X-ray transients has been explained according to the different accretion modes at the different accretion rates (Esin et al. 1998). From all these points we suspect that the main reason for the evolutionary sequence of radio-loud AGNs may be accretion rate rather than the SMBH mass. In addition, our results show that there may still be a difference in SMBH masses of radio-loud and radio-quiet quasars, but such a difference is not significant as previously claimed. The Eddington ratios of these two sub-classes of quasars seem to be from the same population. These points are very important for our understanding of the physics of quasars and obviously need to be confirmed with larger samples.

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