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INCLINATIONS AND BLACK HOLE MASSES OF SEYFERT 1 GALAXIES

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ABSTRACT

A tight correlation between black hole mass ($M_{\rm BH}$) and central velocity dispersion (σ) has been found recently for both active and quiescent galaxies. By applying this correlation, we develop a simple method to derive the inclination angles for a sample of 11 Seyfert 1 galaxies that have both measured central velocity dispersions and black hole masses estimated by reverberation mapping. These angles, with a mean value of 36° that agrees well with the result obtained by fitting the iron Kα lines of Seyfert 1 galaxies observed with *ASCA*, provide further support to the orientation-dependent unification scheme of active galactic nuclei (AGNs). A positive correlation of the inclinations with observed FWHMs of the Hβ line and a possible anticorrelation with the nuclear radio loudness have been found. We conclude that more accurate knowledge of inclinations and broad-line region dynamics is needed to improve the black hole mass determination of AGNs with the reverberation mapping technique.

Subject headings: black hole physics — galaxies: active — galaxies: nuclei — galaxies: Seyfert

1. INTRODUCTION

A supermassive black hole is believed to be an essential part of active galaxies and quasars (Lynden-Bell 1969; Rees 1984). Recently, a lot of evidence has also been found for the existence of supermassive black holes in nearby quiescent galaxies (Kormendy & Richstone 1995; Magorrian et al. 1998). A significantly tight correlation of black hole mass ($M_{\rm BH}$) with the bulge velocity dispersion (σ) was found for nearby galaxies (Gebhardt et al. 2000a; Ferrarese & Merritt 2000). More recent studies indicated that some Seyfert galaxies with $M_{\rm BH}$ measured by the reverberation mapping method follow the same $M_{\rm BH}$-σ relation as for normal galaxies (Gebhardt et al. 2000b; Ferrarese et al. 2001), which implies that this relation may be universal for galaxies. This relation strongly suggests a tight connection between the formation and evolution of the supermassive black hole and the galactic bulge, although the nature of this connection is still unclear.

The black hole masses of some active galactic nuclei (AGNs) have been recently estimated by the reverberation mapping technique (Wandel, Peterson, & Malkan 1999; Ho 1999; Kaspi et al. 2000). With this technique, the broad-line region (BLR) size can be measured using the lag between the variability of continuum and emission-line fluxes. The black hole mass can then be estimated from the BLR size and the characteristic velocity (determined by the FWHM of the emission line). However, it may not be so straightforward to estimate the characteristic velocity of BLRs according to the observed FWHMs of emission lines (Fromerth & Melia 2000). Many effects, especially the inclination and BLR geometry, can lead to larger uncertainties to the estimation of black hole mass using reverberation mapping (Krolik 2001).

Inclination is an important ingredient in the orientation-dependent unified scheme of AGNs (Urry & Padovani 1995), but it is not easily derived directly from observations. By fitting the observed iron Kα line profile with the accretion disk model, Nandra et al. (1997) estimated the inclinations, with a mean value of 30°, for 18 Seyfert 1 galaxies. Although with large uncertainties, their result suggested that the inclinations of Seyfert 1 galaxies are small, consistent with a Seyfert 1/2 unification scheme (Antonucci & Miller 1985). Moreover, numerous observations have shown evidence for the lack of edge-on Seyfert 1 galaxies (Keel 1980) and suggested that Seyfert 1 galaxies have the dusty torus with half-opening angles of 40°–60° (Osterbrock & Martel 1993; Ho, Filippenko, & Sargent 1997; Schmitt et al. 2001). Therefore, the inclinations of Seyfert 1 galaxies are generally expected to be small, although further evidence is obviously needed.

If the $M_{\rm BH}$-σ relation is valid for Seyfert galaxies, this provides an independent way to determine $M_{\rm BH}$ from the reverberation mapping. Using $M_{\rm BH}$ derived from the measured stellar velocity dispersion and assuming a simple BLR geometry, we develop a method to derive the inclinations for 11 Seyfert 1 galaxies with both measured central velocity dispersions and estimated black hole masses by reverberation mapping. Our results are supported by several correlation studies and are consistent with previous knowledge of inclination effects of AGNs.

2. BLACK HOLE MASS DETERMINATIONS OF AGNs

According to the reverberation mapping technique, the black hole mass can be estimated by a virial form,

$$M_{\rm rev} = \frac{V^2 R}{G}, \tag{1}$$

provided that the BLR of the AGN is gravitationally bounded and has a Keplerian characteristic velocity (V). The BLR size (R) can be derived by the lag between the variability of continuum and broad emission line. Assuming an AGN having random inclinations, Wandel et al. (1999) and Kaspi et al. (2000) related the BLR characteristic velocity to the FWHM of the Hβ emission line by $V = (\sqrt{3}/2)V_{\rm FWHM}$. However, as pointed out recently by McLure & Dunlop (2001), the assumption of random inclinations seems unrealistic for quasars. Many observational studies also indicated that Seyfert 1 galaxies are probably not viewed at all inclinations (Osterbrock & Martel 1993; Ho et al. 1997; Nandra et al. 1997; Schmitt et al. 2001).

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TABLE 1
Data of Seyfert 1 Galaxies

Name	σ (km s^{-1})	Reference	$M_{\rm rev}$ ($\times 10^7\ M_\odot$)	$V_{\rm FWHM}$ (rms) (km s^{-1})	log $R_{\rm nuc}$	Inclination (deg)
3C 120	162 ± 20	1	$2.3^{+1.5}_{-1.1}$	2210 ± 120	…	$22.0^{+9.3}_{-7.7}$
Mrk 79	130 ± 9	2	$5.2^{+2.0}_{-2.8}$	6280 ± 850	…	$58.5^{+21.7}_{-27.9}$
Mrk 110	86 ± 5	2	$0.56^{+0.20}_{-0.21}$	1670 ± 120	…	$37.4^{+9.2}_{-9.5}$
Mrk 590	169 ± 28	1	$1.78^{+0.44}_{-0.33}$	2170 ± 120	1.62	$17.8^{+6.1}_{-5.9}$
Mrk 817	142 ± 6	2	$4.4^{+1.3}_{-1.1}$	4010 ± 180	1.21	$41.6^{+8.5}_{-7.5}$
NGC 3227	144 ± 22	1	$3.9^{+2.1}_{-3.9}$	5530 ± 490	1.12	$37.5^{+17.3}_{-25.4}$
NGC 3516	124 ± 5	3	$2.3^{+0.69}_{-0.69}$	4760 ± 240	0.78	38.3 ± 7.6
NGC 4051	80 ± 4	2	$0.13^{+0.13}_{-0.08}$	1230 ± 60	0.87	$19.6^{+10.4}_{-6.6}$
NGC 4151	93 ± 5	2	$1.53^{+1.06}_{-0.89}$	5230 ± 920	0.49	$60.0^{+30.0}_{-30.6}$
NGC 4593	124 ± 29	1	$0.81^{+0.24}_{-0.24}$	3720 ± 180	…	21.6 ± 10.5
NGC 5548	183 ± 10	2	$12.3^{+2.3}_{-1.8}$	5500 ± 400	1.24	$43.7^{+7.6}_{-6.9}$

References.—(1) Nelson & Whittle 1995; (2) Ferrarese et al. 2001; (3) Di Nella et al. 1995.

On the other hand, the BLR dynamics of AGNs have not been well understood yet. The simplest case may be described as circular orbits confined to the disk plane, but the real case is probably much more complicated. The same as assumed for quasars, the BLR velocity of Seyfert 1 galaxies may be better represented by a combination of a random isotropic component, with characteristic velocity V_r, and a component in the disk plane, with characteristic velocity V_p (Wills & Browne 1986). Therefore, the observed FWHM of the emission line will be given by

$$V_{\rm FWHM} = 2(V_r^2 + V_p^2 \sin^2 i)^{1/2}, \qquad (2)$$

where i is the inclination angle of the disk normal relative to the line of sight. Assuming that V_p is significantly larger than V_r and that i lies randomly between 0° and 46°, McLure & Dunlop (2001) have reproduced the distribution of observed Hβ FWHMs for a sample of AGNs using the above formula. If we relate the observed emission-line FWHM and BLR characteristic velocity with equation (2), the black hole mass of AGNs can be obtained by

$$M_{\rm BH} = \frac{1}{4(\sin^2 i + A^2)} \frac{V_{\rm FWHM}^2 R}{G}, \qquad (3)$$

where $A = V_r/V_p$. In most recent studies, the black hole mass ($M_{\rm rev}$) determined by reverberation mapping is based on the assumption of random inclinations and is expressed as $M_{\rm rev} = \frac{3}{4}(V_{\rm FWHM}^2 R/G)$ (Wandel et al. 1999; Kaspi et al. 2000). If the inclination effect is considered, using equation (3) we can derive the inclination angle by

$$i = \arcsin \sqrt{\frac{M_{\rm rev}}{3M_{\rm BH}} - A^2}. \qquad (4)$$

If $M_{\rm BH}$ of AGNs can be derived independently by other methods, we can use equation (4) to estimate the inclinations of AGNs. Fortunately, a tight relation between black hole mass and central velocity dispersion seems to exist for AGNs; therefore, $M_{\rm BH}$ can be directly derived from the measured central velocity dispersion. According to Gebhardt et al. (2000a), the $M_{\rm BH}$-σ relation is

$$M_{\rm BH} = 1.2 \times 10^8\ M_\odot(\sigma/200\ {\rm km\ s^{-1}})^{3.75}. \qquad (5)$$

Using a slightly steeper slope found by Ferrarese & Merritt (2000) has no significant effect on our results.

3. INCLINATION ANGLES OF SEYFERT 1 GALAXIES

We collected 11 Seyfert 1 galaxies with both measured central velocity dispersion (σ) and estimated black hole masses ($M_{\rm rev}$) by reverberation mapping (Wandel et al. 1999; Ho 1999; Kaspi et al. 2000). Their σ- and $M_{\rm rev}$-values, together with the observed FWHMs of the Hβ line (Wandel et al. 1999; Ho 1999) and the nuclear radio loudness (Ho & Peng 2001), are summarized in Table 1. Seven sources have σ-values from high-quality measurements of Ferrarese et al. (2001) and Di Nella et al. (1995). The σ-values of another four sources were adopted from Nelson & Whittle (1995). The uncertainties of $M_{\rm rev}$ and $V_{\rm FWHM}$ for NGC 3516 and NGC 4593 are unavailable in the literature and were assumed to be 30% and 5%, respectively.

The inclinations of these 11 Seyfert 1 galaxies can be estimated using equations (4) and (5). For simplicity, we further assume $A \ll M_{\rm rev}/3M_{\rm BH}$ in equation (4), which is equivalent to the approximation that the BLR characteristic velocity is dominated by the component in the disk plane (McLure & Dunlop 2001). Under this assumption, we derived the inclinations for 11 Seyfert 1 galaxies (see Table 1 and Fig. 1). The errors of i were estimated from the uncertainties of both σ and $M_{\rm rev}$. The inclination angles we derived are in the range from 20° to 60°, with a mean value of 36°.2. This agrees with the result obtained by fitting the observed iron Kα line in the X-ray band with the accretion disk model (Nandra et al. 1997) and is consistent with the expectation of the unified scheme of AGNs (Antonucci & Miller 1985). In Figure 2, we can clearly observe an apparent positive correlation between inclinations and observed Hβ FWHMs. A minimum χ^2 fit considering the errors of both parameters gives $\sin i = (0.23 \pm 0.09) + (0.086 \pm 0.024)(V_{\rm FWHM}/1000\ {\rm km\ s^{-1}})$, with χ^2 of 7.13 and probability of 62%. The zero slope is less favored because it produces a larger χ^2 (22.78) with a probability of 1% only. A simple Spearman test gives the correlation coefficient $R = 0.78$, with a probability of $P = 4.47 \times 10^{-3}$ to occur by chance. We have also applied the bootstrap method to investigate the uncertainty of the correlation coefficient by considering the uncertainties of both parameters and obtained $\langle R \rangle = 0.58 \pm 0.18$, which indicates a moderately significant correlation. In Figure 3, we plotted the inclinations against the nuclear radio loudness, defined by the ratio between 5 GHz nuclear radio luminosity and B-band nuclear optical luminosity (Ho & Peng 2001). Because there are serious contaminations to the luminosity of the Seyfert nucleus from the host galaxy, using the nuclear

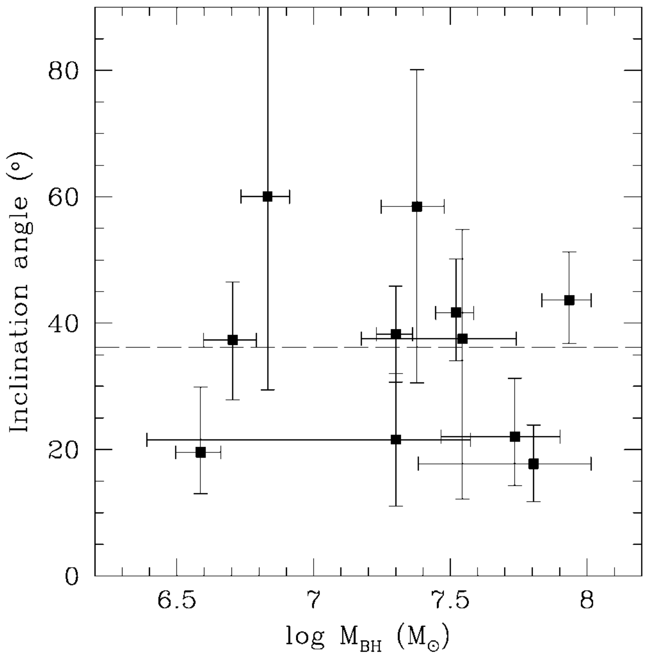

FIG. 1.—Derived inclination angles of 11 Seyfert 1 galaxies against the black hole masses determined by the M_{BH}-σ relation. The dashed line represents the mean value $\langle i \rangle = 36.^\circ2$.

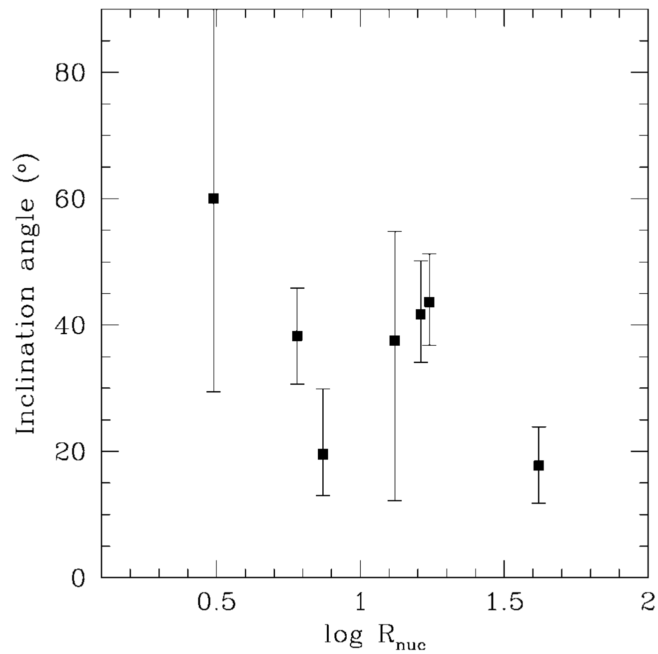

FIG. 3.—Inclination angles against the nuclear radio loudness

radio loudness can maximally diminish such contaminations and better describe the nature of Seyfert nuclei. Although with only seven sources with available data for nuclear radio loudness, Figure 3 still displays the trend that Seyfert 1 galaxies with larger nuclear radio loudness may have smaller inclinations. These results seem to be consistent with our knowledge on the inclination effects of quasars and AGNs (Wills & Browne 1986; Wills & Brotherton 1995).

If the characteristic velocity of the BLR is dominated by the component in the disk plane, the *intrinsic* FWHM of the Hβ emission line can be approximated by the observed FWHM divided by $\sin i$. In Figure 4, we show the distributions of intrinsic FWHMs of Hβ line and M_{BH}. Two narrow-line Seyfert 1 galaxies (NLS1's), NGC 4051 and Mrk 110, appear in the lower left corner of Figure 4, although their inclination angles, estimated to be $19.^\circ6$ and $37.^\circ4$, are not significantly smaller than those of other broad-line Seyfert 1 galaxies. This indicates that the narrowness of emission lines of NLS1's may not be simply due to the inclination effects but is probably more related to their smaller black hole masses. These NLS1's may have accretion rates close to the Eddington limit (Boller, Brandt,

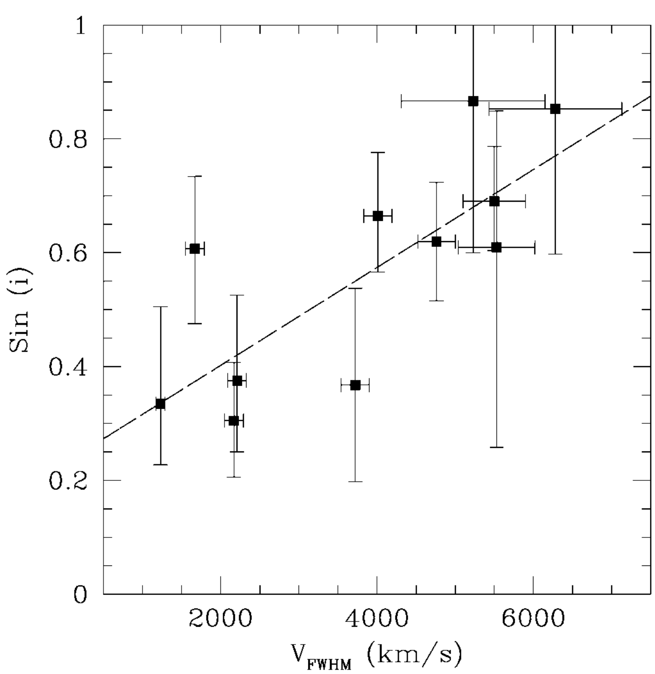

FIG. 2.—Inclination angles against the observed FWHMs of the Hβ line. The dashed line shows the minimum χ^2 fit with errors of both parameters considered.

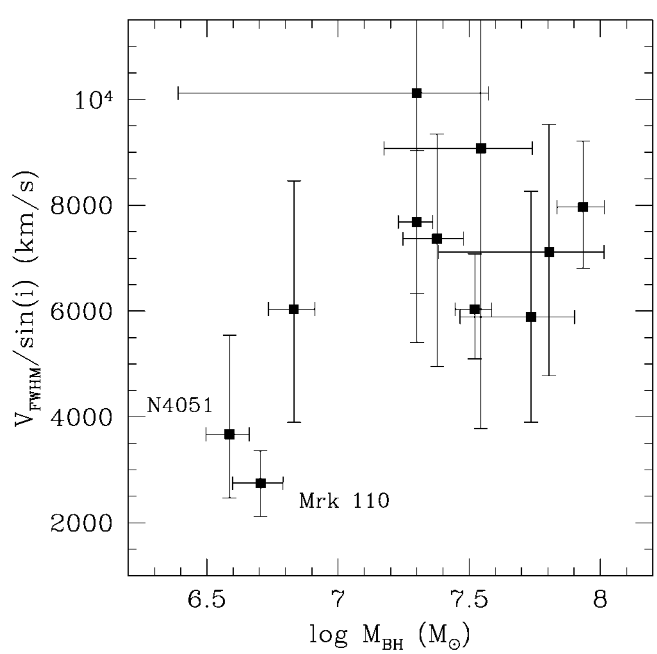

FIG. 4.—Intrinsic FWHMs of the Hβ line against black hole masses determined by the M_{BH}-σ relation.

& Fink 1996). For most broad-line Seyfert 1 galaxies, the Eddington ratios (L/L_{Edd}) are in the range of 0.1–0.01 (Wandel et al. 1999), which are significantly lower than those of NLS1's.

4. DISCUSSION

Assuming a Keplerian rotation of BLRs and Seyfert 1 galaxies following the same M_{BH}-σ relation as normal galaxies, we develop a method to derive the inclinations of 11 well-studied Seyfert 1 galaxies. The values of these inclinations derived by us seem to be supported by a positive correlation with the observed Hβ FWHMs and a possible anticorrelation with the nuclear radio loudness. Our results agree well with previous knowledge of inclinations of Seyfert 1 galaxies and are consistent with the expectation of the unification scheme of AGNs.

It is worth noting that the BLR dynamics may not be as simple as we assumed, although the Keplerian rotation of BLRs has been confirmed by some recent studies (Peterson & Wandel 1999, 2000). The inclinations we derived for 11 Seyfert 1 galaxies may be regarded as upper limits because we assumed the characteristic velocity in the disk plane is the dominant component in BLRs. Considering the isotropic component will reduce the values of inclinations (see eq. [4]). VLBI studies of the radio-loud Seyfert 1 galaxy 3C 120 derived a lower inclination angle (about 10°) based on the synchrotron self-Compton jet model (Ghisellini et al. 1993), which is smaller than but still marginally consistent with the value obtained by us.

We noticed that ratio between the black hole mass determined by reverberation mapping (M_{rev}) and the "true" black hole mass (M_{BH}) can be approximated by $3\sin^2 i$ (see eq. [4]). With the mean value of i (36.°2) derived by us, we obtained $M_{rev}/M_{BH} = 1.05$ for Seyfert 1 galaxies. It means that the black hole mass estimated by the standard method of reverberation mapping can still represent the "true" black hole mass well if the inclination of the Seyfert galaxy is not substantially different from 36.°2. This may be the reason why Seyfert galaxies also follow the M_{BH}-σ relation even if the values of M_{BH} measured by reverberation mapping were adopted (Gebhardt et al. 2000b; Ferrarese et al. 2001). However, the M_{rev}/M_{BH}-value changes from 0.35 to 2.25 if the inclination increases from 20° to 60°. Therefore, more accurate information about inclinations and the BLR dynamics of AGNs will be undoubtedly helpful to the improvement of central black hole mass estimations with the reverberation mapping technique.

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