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The Relation between the Inclinations of Broad Line Regions and the Accretion Disk *

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Abstract According to the standard model, an active galactic nucleus (AGN) consists of an inner accretion disk with a jet around a central massive black hole, and a number of outer broad line regions (BLRs) and narrow line regions (NLRs). The geometrical relationship between the BLRs and the accretion disk is not well understood. Assuming the motion of the BLRs is virialized and its configuration is disk-like, we derived its inclination to the line of sight for a sample of AGNs from their bulge stellar velocity dispersion, their size of the BLRs and their Hβ linewidth. Compared with the inclination of the accretion disk obtained from the X-ray Fe Kα emission lines, we found that there is no positive correlation between the two. Our results showed that BLRs are not coplanar with the accretion disk and that we should be cautious of using the BLRs inclination as the disk inclination. The non-coplanar geometry of the outer BLRs and the inner accretion disk provides clues to the origin of BLRs and the properties of the accretion disk. Our preferable interpretation is that BLRs arise out of the outer part of a warped accretion disk.

Key words: galaxies: active — galaxies: nuclei — galaxies: Seyfert

1 INTRODUCTION

One basic component of the standard model of active galactic nuclei (AGNs) is an inner accretion disk around a supermassive black hole. Then there are broad-line regions (BLRs) and narrow-line regions (NLRs) outside the accretion disk, which are responsible for the emission lines appearing in the AGN spectra. The geometrical relation between the different components is pertinent to an understanding of the physics of the AGNs. Many lines of evidence show that there is little or no correlation between the position of the radio jets and the major axis of the disk of the host galaxy (Schmitt et al. 2001). However, for the inner region of AGNs the geometrical relation between the BLRs and the accretion disk still remains a mystery. The reason is that it is difficult to determine the inclinations of the BLRs and the disk.

Recently Wu & Han (2001) suggested a simple method to calculate the BLRs inclination in AGNs with the virial reverberation mass ($M_{\rm rm}$) and the stellar velocity dispersion of the

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bulge (σ). Up to now, there are just 37 AGNs with measured $M_{\rm rm}$ (Ho 1998; Wandel et al. 1999; Kaspi et al. 2000) and about a dozen AGNs with measured σ (Wu & Han 2001, and reference therein). Fortunately there exists an empirical size-luminosity relation (Kaspi et al. 2000) which can be used to calculate the virial mass. At the same time, we can estimate σ from the width of the [O III] line because there exists a strong correlation between σ and the [O III] linewidth (Nelson & Whittle 1996).

It is difficult to determine the inclination of the accretion disk of AGNs. Comparing the theoretical spectra from the standard accretion disk with the observed optical spectra, Laor (1990) found his derived accretion disk inclinations have large uncertainties. Using X-ray Fe Kα profiles, Nandra et al. (1997) derived the accretion disk inclinations for a sample of 18 Seyfert galaxies observed by ASCA.

In this paper we use the sample of Nandra et al. (1997) to investigate the relation between the inclinations of the BLRs and the accretion disk. In the next section we describe the data and the methods to derive the two inclinations. Our result and discussion are presented in Section 3. All of the cosmological calculations in this paper assume $H_0 = 75$ km s^{-1} Mpc^{-1}, $\Omega = 1.0$, $\Lambda = 0$.

2 DATA

2.1 Disk Inclinations

X-ray emission of many AGNs consists of a power law component, a soft X-ray excess at lower X-ray energies, a strong Fe emission line at about 6.4 keV, and the Compton-reflection hump in the energy range of 20–100 keV (Fabian 2000). The broad Fe Kα line at 6.4 keV is believed to arise from fluorescence of neutral iron in the inner regions of the accretion disk (Reynolds & Fabian 1997), which could give information about the disk's inclination. Nandra et al. (1997) presented a sample of 18 Seyfert galaxies and fitted the broad Fe Kα line observed by ASCA using the models proposed by Fabian et al. (1989) and Laor (1991). The inclinations of the accretion disks of these 18 AGNs (Nandra et al. 1997) are listed in Table 1. We adopted the inclinations from three models: Model A, the Schwarzschild model; Model B, the Schwarzschild model with $q = 2.5$, where q is a parameter characterising the line emissivity as a function of radius; Model C, the Kerr model (Nandra et al. 1997).

2.2 BLRs Inclinations

Here we use the method proposed by Wu & Han (2001) to obtain the inclination of the BLRs. If the BLRs are disk-like, the FWHM of Hβ ($V_{\rm FWHM}$) is given by (Wills & Browne 1986)

$$V_{\rm FWHM} = 2(V_{\rm r}^2 + V_{\rm p}^2 \sin^2\theta)^{1/2}\,, \tag{1}$$

where θ is the BLR inclination, $V_{\rm p}$ is the component in the plane of the disk, and $V_{\rm r}$ is the random isotropic component. Because V_r is usually believed to be smaller than V_p, we ignored V_r in our calculation (Zhang & Wu 2002). Assuming the BLR motion around the central black hole to be Keplerian, the central black hole mass is

$$M_{\rm bh} = R_{\rm BLR} V_{\rm p}^2 G^{-1}\,, \tag{2}$$

where G is the gravitational constant and $R_{\rm BLR}$ is the size of the BLRs. The black hole mass can also be derived from the velocity dispersion (Tremaine et al. 2002),

$$M_{\rm bh} = 10^{8.13}\Big(\frac{\sigma}{200\ {\rm km\ s^{-1}}}\Big)^{4.02}\,{\rm M}_\odot, \tag{3}$$

where σ is the bulge stellar velocity dispersion.

From the above equations, we can calculate the BLR inclination knowing $V_{\rm FWHM}$, σ, and $R_{\rm BLR}$,

$$\sin\theta = \sqrt{\frac{V_{1000}^2 R_{\rm day}}{2768.2\sigma_{200}^{4.02}}}\ , \tag{4}$$

where $V_{1000} = V_{\rm FWHM}/(1000\ {\rm km\ s^{-1}})$, $R_{\rm day}$ is the BLRs size in units of light day, and σ_{200} is the stellar velocity dispersion in units of 200 km s^{-1}.

The BLRs size can be calculated from the reverberation mapping method or from the size-luminosity empirical formula (Kaspi et al. 2000),

$$R_{\rm day} = 32.9\Big(\frac{\lambda L_\lambda(5100\ \text{Å})}{10^{44}{\rm erg\ s^{-1}}}\Big)^{0.7}\quad {\rm lt-d}, \tag{5}$$

where λL_λ(5100Å) can be estimated from the B magnitude (Veron-Cetty & Veron 2001b) by adopting an average optical spectral index of -0.5 and accounting for the galactic redding and k-correction (Wang & Lu 2001; Bian & Zhao 2003a, 2003b, 2004). The stellar velocity dispersions are adopted from Wu & Han (2001) and the references therein. If the stellar velocity dispersion is not available in the literature, we derived it from the [O III] linewidth. The calculated inclinations of the BLRs for the sample of Nandra et al. (1997) are listed in Table 1.

3 RESULT AND DISCUSSION

We plot the inclination of the accretion disk versus the inclination of the BLRs. We use least squares linear regression to fit the data in Fig. 1, considering the errors in the inclinations of the accretion disk. The correlation coefficients and random probabilities (the probability that the calculated correlation is caused by random factors) are listed in Table 2. In Models A and C, there is a very weak correlation between the two inclinations. In Model C, there is a medium strong anti-correlation between them, that is, AGNs with a more face-on accretion disk tend to have a larger BLRs inclination.

Nishiura et al. (1998) used the ratio of the Hβ (or Hα) FWHM to the hard X-ray luminosity to trace the BLRs inclination and found a negative correlation between the two inclinations. Here we use the BLR size from the reverberation mapping method, the bulge velocity dispersion, and the Hβ FWHM to calculate the inclinations of disk-like BLRs assuming virialized motion of the BLRs (Peterson & Wandel 2000). With the more accurate estimation of the BLRs inclination, we also find this negative correlation in Model B, consistent with the results of Nishiura et al. (1998). However, there is now a very weak correlation in Models A and C.

We should note that for some objects the BLRs size is calculated from the B-band luminosity or the velocity dispersion is calculated from the width of the [O III] line. The error of the calculated BLRs inclination is mainly from the uncertainties in the BLRs size, the Hβ FWHM, and the velocity dispersion. From the formula for compounding errors,

$$\delta\theta = \sqrt{4(\delta V/V)^2 + (\delta R/R)^2 + (4.02\delta\sigma/\sigma)^2}(2\tan\theta)\,,$$

the error in the inclination (at inclination 30°) is found to be about 5.5°, assuming 10% uncertainties in each of these three parameters (see Wu & Han 2001). The uncertainties in the BLRs size and Hβ FWHM for NGC 3516 and NGC 4593 are unavailable and were assumed to be 10%. The uncertainties of the velocity dispersion derived from the [O III] width were assumed to be 10%. The uncertainties of BLRs sizes derived from Eq. (5) were also assumed to be 10%. The uncertainties of the calculated BLRs inclinations are listed in Table 1.

Table 1 Inclinations of the BLRs and the Accretion Disk

Name (1)	$i_{\rm Fe}$(A) (2)	$i_{\rm Fe}$(B) (3)	$i_{\rm Fe}$(C) (4)	$R_{\rm BLR}$ (5)	FWHM (6)	σ (7)	$i_{\rm BLR}$ (8)
Mrk 335	22^{+68}_{-22}	24^{+13}_{-24}	22^{+68}_{-22}	16.4	1620	119^a	21^{+6}_{-5}
F9	46^{+44}_{-27}	32^{+12}_{-8}	89^{+1}_{-49}	16.3	5780	181^a	33^{+9}_{-12}
3C 120	60^{+30}_{-13}	59^{+10}_{-13}	88^{+2}_{-1}	42	1910	162	21^{+9}_{-8}
NGC 3227	20^{+8}_{-14}	23^{+8}_{-6}	21^{+7}_{-21}	10.9	4920	144	37^{+18}_{-24}
NGC 3516	27^{+6}_{-7}	26^{+4}_{-4}	26^{+3}_{-4}	7	4760	124	39^{+10}_{-10}
NGC 3783(1)	35^{+2}_{-18}	21^{+5}_{-5}	26^{+5}_{-7}	4.5	3790	98^a	40^{+26}_{-24}
NGC 3783(2)	32^{+3}_{-15}	9^{+11}_{-9}	40^{+12}_{-40}	4.5	3790	98^a	40^{+26}_{-24}
NGC 4051	34^{+3}_{-14}	27^{+7}_{-11}	25^{+12}_{-4}	6.5	1170	80	21^{+11}_{-7}
NGC 4151(2)	17^{+12}_{-17}	20^{+5}_{-5}	9^{+18}_{-9}	3	5910	93	65^{+44}_{-37}
NGC 4151(4)	33^{+2}_{-18}	21^{+5}_{-6}	24^{+5}_{-7}	3	5910	93	65^{+44}_{-37}
NGC 4151(5)	17^{+5}_{-3}	15^{+4}_{-5}	21^{+5}_{-11}	3	5910	93	65^{+44}_{-37}
Mrk 766	34^{+3}_{-3}	35^{+5}_{-5}	36^{+8}_{-7}	14.8†	1630	94^b	33^{+9}_{-9}
NGC 4593	0^{+79}_{-0}	45^{+12}_{-11}	0^{+56}_{-0}	4	3720	124	22^{+3}_{-3}
MCG-6-30-15(1)	33^{+3}_{-5}	34^{+5}_{-5}	34^{+5}_{-6}	3.6†	1700	-	-
MCG-6-30-15(2)	34^{+3}_{-6}	33^{+8}_{-25}	34^{+16}_{-9}	3.6†	1700	-	-
IC 4329A	17^{+14}_{-17}	26^{+7}_{-8}	10^{+13}_{-10}	1.4	5050	234^a	5^{+6}_{-3}
NGC 5548	0^{+76}_{-0}	39^{+10}_{-11}	10^{+80}_{-10}	21.2	6300	183	41^{+7}_{-6}
Mrk 841(1)	27^{+7}_{-9}	27^{+6}_{-6}	26^{+8}_{-5}	33.4†	5470	178^d	$1.4^{+0.2}_{-0.2}$
Mrk 841(2)	38^{+2}_{-16}	30^{+9}_{-15}	90^{+0}_{-90}	33.4†	5470	178^d	$1.4^{+0.2}_{-0.2}$
Mrk 509	27^{+63}_{-27}	40^{+48}_{-24}	89^{+1}_{-89}	76.7	2270	221^a	18^{+4}_{-4}
NGC 7469(2)	0^{+89}_{-0}	45^{+11}_{-29}	20^{+70}_{-20}	4.9	3000	153^a	12^{+7}_{-7}
MCG-2-58-22	46^{+44}_{-46}	41^{+10}_{-15}	26^{+64}_{-26}	57.8†	6360	155^c	-

Col. 1: name; Cols. 2–4; inclination of the accretion disk for Model A, B, and C, respectively; Col. 5: the BLRs size in units of light days; Col. 6: FWHM of Hβ in units of km s^{-1}; Col. 7: the stellar velocity dispersion in units of km s^{-1}; Col. 8: the BLRs inclination.

†: BLRs sizes are calculated from Eq. (5), the others are from Kaspi et al. (2000).

The velocity dispersions via the [O III] linewidth labelled with ^{a} are from Nelson (2001), labelled with ^{b} are from Veron-Cetty et al. (2001a), labelled with ^{c} are from Whittle (1992), labelled with ^{d} are from Wilkes et al. (1999), the others are the directed measured from the host spectra listed in Wu & Han (2001).

Table 2 The Correlation Coefficients and Random Probabilities

Model	correlation coefficient	random probability	slope
A	–0.25	0.276	–0.13±0.4
B	–0.53	0.01	–0.27±0.1
C	–0.25	0.28	–0.24±0.22

A too large $V_{\rm FWHM}$, a too large $R_{\rm BLR}$, and/or a too small σ may lead to the right side of Eq. (4) greater than one, i.e., to the breakdown of the underlying method. MCG-2-58-22 is a case in point. Using Eq. (4) to derive the BLRs inclination, we assumed that the BLRs are virialized and the random isotropic component v_r can be omitted. However, it is possible that BLRs are not virialized and the random isotropic movements cannot be omitted, $(\sin\theta)^2 \propto (V_{\rm FWHM}^2 - 4V_{\rm r}^2)R_{\rm BLR}/\sigma^{4.02}$. The inclination derived from Eq. (4) is an upper limit when we omit the random velocity v_r. The breakdown of Eq. (4) suggested that the BLRs are not virialized. The effects of random velocity on the BLR inclination estimates have been discussed by Zhang & Wu (2002).

In this paper we adopted the inclinations of the accretion disk from the fitting of the Fe Kα profile with different models for a sample of 18 Seyfert galaxies observed by ASCA (Nandra et al. 1997). There is a large scatter in the inclinations even for the same model (see Table 1). Recent research showed that Fe Kα may be some sort of composite feature from the inner accretion disk and/or the outer BLRs (Turner et al. 2002). It is necessary to obtain the Fe Kα profile with higher spectral resolution and to have a better model of the origin of Fe Kα to derive the inclination of the accretion disk.

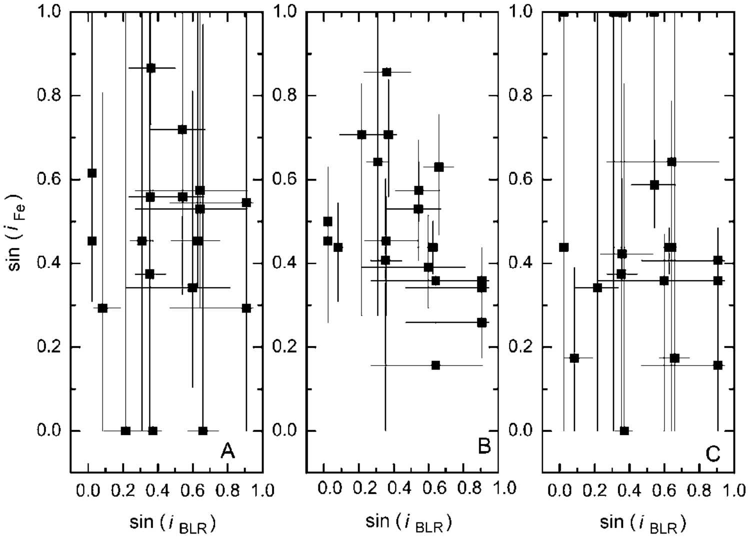

Fig. 1 Inclination of the accretion disk versus the inclination of the BLRs.

In Figure 1, we cannot find any positive correlation between the inclination of BLRs and that of the accretion disk, which shows that the BLRs are not coplanar with respect to the accretion disk. The non-coplanar geometry of the outer BLRs and the inner accretion disk in AGNs provides clues to the property of the accretion disk and the origin of the BLRs (Nicastro 2000; Collin & Hure 2001; Bian & Zhao 2002; Bian & Zhao 2003c; Laor 2003). There have been some views on the interpretation of this non-coplanar geometry. Nishiura et al. (1998) suggested that the BLRs arise from the outer parts of a warped accretion disk illuminated by the central engine. The warping of the accretion disk can be driven by the radiation pressure or gravitational warping effect (Nayakshin 2004). Recent Nicastro (2000) suggested that the sizes of the BLRs are determined by the transition radius between the radiation pressure and gas pressure dominated region of the disk. Our calculated BLR inclinations were derived for disk-like BLRs. However, if the BLRs are not disk-like, there would be some other interpretation of the non-coplanar geometry: gravitational instability of the standard accretion disk leads to the formation of the BLRs (Collin & Hure 2001; Bian & Zhao 2002) into a sphere-like system, considering the radiation pressure.

Since there is probably no positive correlation between the inclinations of the BLRs and the accretion disk, that is, since they are not coplanar, it is risky to use the inclination of the accretion disk as the inclination of the BLRs. For a sample of AGNs Rokaki & Boisson

(1999) fitted accretion disks to the UV continuum and to the Hβ emission line. They found the dependence on the central black hole mass of the inclination from the UV continuum is opposite to that from the Hβ emission line. They assumed the BLRs and the accretion disk have the same inclination, and determined the inclination, the black hole mass, and the accretion rate. We note that, for the common AGNs, their black hole masses are all larger than the recent reverberation mapping masses (Kaspi et al. 2000). The accretion rates they derived are also smaller compared to the recent results of accretion disk fit to the optical continuum (Collin et al. 2002) and the B band luminosity (Bian & Zhao 2002). It is necessary to fit the UV continuum using the reverberation mapping mass as a known parameter to constrain other parameters of the accretion disk.

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