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 — galaxies: X-ray.

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 BLR inclinations in AGNs with the virial reverberation masses (\(M_{\text{rm}}\)) and the bulge stellar velocity dispersion (\(\sigma\)). Up to now, there are just 37 AGNs with measured \(M_{\text{rm}}\) (Ho 1998; Wandel et al. 1999; Kaspi et
al. 2000) and about a dozen AGNs with measured $\sigma$ (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 $\sigma$ from [O III] linewidth because there exists a strong correlation between $\sigma$ and [O III] linewidth (Nelson & Whittle 1996).

It is difficult to determine the accretion disk inclinations in 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 inclinations of the accretion disk 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 BLRs and the accretion disk. In the next section we describe the data and the methods to derive these 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 the fluorescence of the neutral iron in the inner regions of the accretion disk (Reynolds & Fabian 1997), which could give the information about disk inclinations. 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 disk for these 18 AGNs (Nandra et al. 1997) are listed in table 1. We adopted the inclinations from three models: Model A, the Schwarzschild mode; Model B, the Schwarzschild mode with $q=2.5$, where $q$ is a parameter about the line emissivity as a function of radius; Model C, the Kerr model (Nandra et al. 1997).

2.2 BLRs Inclination

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

$$V_{\text{FWHM}} = 2(V_r^2 + V_p^2 \sin^2 \theta)^{1/2},$$

where $\theta$ is the BLRs inclination, $V_p$ is the component in the plane of the disk, and $V_r$ 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). If we assume the BLRs motion around the central black hole is Keplerian, the central black hole mass is

$$M_{\text{bh}} = R_{\text{BLR}} V_p^2 G^{-1},$$

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

$$M_{\text{bh}} = 10^{8.13} \left( \frac{\sigma}{200 \text{ km s}^{-1}} \right)^{4.02} M_{\odot},$$

where $\sigma$ is the bulge stellar velocity dispersion.
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From above equations, we can calculate BLRs inclinations knowing $V_{\text{FWHM}}$, $\sigma$, and $R_{\text{BLR}}$.

$$\sin \theta = \sqrt{\frac{V_{1000}^2 R_{\text{day}}}{2768.2 \sigma^2_{200}},}$$

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

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

$$R_{\text{day}} = 32.9 \left( \frac{\lambda L_\lambda(5100 \text{ Å})}{10^{44} \text{ erg s}^{-1}} \right)^{0.7} \text{ lt} - d,$$

where $\lambda L_\lambda(5100\text{Å})$ 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 [O III] linewidth. The calculated inclinations of 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 BLRs. We use the least square linear regression to fit the data in figure 1, considering the errors of the inclinations of the accretion disk. The correlation coefficients and possibility that the correlation is caused by a random factor are listed in table 2. In Model A and C, there is very weak correlation between them. In Mode C, there is a median strong anti-correlation between them, namely, AGNs with a more face-on accretion disk tend to have larger inclination of BLRs.

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

We should note that for some objects the BLRs sizes are calculated from the B-band luminosity or the velocity dispersion is calculated from the width of [O III] line. The error of the calculated inclination of BLRs is mainly from the uncertainties of size of BLRs, FWHM of H$\beta$, and the velocity dispersion. From the error transform formula, \[ \delta \theta = \sqrt{\left(4 \frac{\delta V}{V}\right)^2 + \left(\frac{\delta R}{R}\right)^2 + \left(4.02 \frac{\delta \sigma}{\sigma}\right)^2 (2 \tan \theta)}, \]

the error of inclination of 30 (deg) is about 5.5 (deg) assuming 10% uncertainties of these three parameters (see Wu & Han 2001). The uncertainties of BLRs sizes and the H$\beta$ FWHM for NGC 3516 and NGC 4593 are unavailable in the literature 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 equation 5 were also assumed to be 10%. The uncertainties of the calculated inclinations of BLRs are listed in table 1.

A too large $V_{\text{FWHM}}$, a too large $R_{\text{BLR}}$, or a too smaller $\sigma$ may lead to the right of equation (4) larger than one, i.e., to the breakdown of the underlying method. MCG-2-58-22 is a case in point. Using equation (4) to derive the BLR 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 can’t not be omitted, $(\sin \theta)^2 \propto (V_{FWHM}^2 - 4V_r^2)R_{BLR}/\sigma^2$. The inclination derived from equation (4) is an upper limit when we omitted the random velocity $v_r$. The breakdown of equation (4) suggested that 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 large uncertainties on the inclinations even for the same model (see table 1.). Recent research showed that the Fe Kα may be some sort of composite feature from inner accretion disk and/or outer BLRs (Turner et al. 2002). It is necessary to obtain the Fe Kα

Fig. 1 The inclination of the accretion disk versus the inclination of BLRs.
Wilkes et al. (1999), the others are the directed measured from host spectra listed in Wu & Han (2001).

Table 1 Inclinations of BLRs and the accretion disk

| Name       | \(i_{\phi}(A)\) | \(i_{\phi}(B)\) | \(i_{\phi}(C)\) | \(R_{\text{BLR}}\) | FWHM | \(\sigma\) | \(i_{\text{BLR}}\) |
|------------|-----------------|-----------------|-----------------|-----------------|------|---------|-----------|
| Mrk335     | 20+6     | 24+13    | 23+8     | 16.4 | 1620 | 119\(a\) | 21.26   |
| F0         | 46+14    | 32+8     | 80+19    | 16.3 | 5780 | 181\(a\) | 33.12   |
| 3C120      | 60+10    | 59+10    | 88+2    | 42   | 1910 | 162     | 21.29   |
| NGC3227    | 26+15    | 23+6     | 27+1     | 10.9 | 4920 | 144     | 37+18   |
| NGC3516    | 27+5     | 26+4     | 26+3    | 7    | 4760 | 124     | 39+10   |
| NGC3783(1) | 35+18    | 21+6     | 26+7    | 4.5  | 3790 | 98\(a\) | 40+26   |
| NGC3783(2) | 33+15    | 9+9      | 40+12   | 4.5  | 3790 | 98\(a\) | 40+26   |
| NGC4051    | 34+15    | 27+7     | 25+12   | 6.5  | 1170 | 80      | 21+11   |
| NGC4151(2) | 17+13    | 20+5     | 9+18    | 3    | 5910 | 93      | 65+44   |
| NGC4151(4) | 33+21    | 21+5     | 24+7    | 3    | 5910 | 93      | 65+44   |
| IC4329A    | 14+14    | 26+7     | 10+13   | 1.4  | 5050 | 234\(a\) | 5+15    |
| NGC5548    | 0+9      | 39+1     | 10+10   | 2.12 | 6300 | 183     | 41+17   |
| Mrk841(1)  | 71+26    | 27+6     | 26+5    | 33.4 | 5470 | 178\(d\) | 1.4+0.2 |
| Mrk841(2)  | 35+18    | 30+1    | 90+6    | 33.4 | 5470 | 178\(d\) | 1.4+0.2 |
| Mrk509     | 27+13    | 40+3     | 89+3    | 76.7 | 2270 | 221\(a\) | 18+4    |
| NGC7469(2) | 0+9      | 45+11    | 20+7    | 4.9  | 3000 | 153\(e\) | 12+7    |
| MCG-2-58-22| 46+14    | 41+10    | 26+6    | 57.8 | 6360 | 155\(e\) | -       |

Col.1: name, Col.2-4: inclinations of the accretion disk for Model A, B, and C, respectively, Col.5: the BLRs sizes in units of light days, Col.6: FWHM of H\(\beta\) in units of \(\text{kms}^{-1}\), Col.7: the stellar velocity dispersion in units of \(\text{kms}^{-1}\), Col.8: inclination of BLRs.

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

The velocity dispersions via [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 host spectra listed in Wu & Han (2001).

Table 2 The correlation coefficients and possibility

| Model | coefficient | possibility | 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 |

profile with higher spectral resolution and have a better model on the origin of Fe K\(\alpha\) to derive the inclination of the accretion disk.

In figure 1, we can’t find any positive correlation between the inclination of BLRs and that of the accretion disk, which shows that BLRs are not coplanar with respect to the accretion disk. The non-coplanar geometry of outer BLRs and the inner accretion disk in AGNs provides clues to the property of the accretion disk and the origin of BLRs (Nicasato 2000; Collin & Hure 2001; Bian & Zhao 2002; Bian & Zhao 2003c; Laor 2003). There are some ideas to interpret this non-coplanar geometry in AGNs. 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 accretion disk can be driven by the radiation pressure. Recent Nicastro (2000) suggested that the sizes of BLRs are determined by the transition radius between the radiation pressure and gas pressure dominated region of the disk. Our calculated inclinations of BLRs are derived from the disk-like BLRs. If the BLRs are not disk-like, there is another suggestion about the non-coplanar geometry that the gravitational instability of the standard accretion disk leads to the BLRs (Collin & Hure 2001; Bian & Zhao 2002), which can lead to a sphere-like BLRs considering the radiation pressure.

Since there is possibly no positive correlation between inclinations of BLRs and the accretion disk, namely they are not coplanar, it is a risk to use the inclination of the accretion disk as the inclination of BLRs. Rokaki & Boisson (1999) presented accretion disk fit to the UV continuum and Hγ emission line in a sample of AGNs. They found the inclination dependence on the central black hole is opposite fitting the UV continuum and Hγ emission line. They assumed inclinations of BLRs and that of the accretion disk are the same and then determined the inclination, black hole mass, and the accretion rates. We notice that the black hole masses are all larger than the value of the recent reverberation mapping masses for the common AGNs (Kaspi et al. 2000). The accretion rates they derived are also smaller compared to the results of the recent 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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