A Geometrical Relationship between Broad-Line Clouds and an Accretion Disk around Active Galactic Nuclei

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ABSTRACT

Recent hard X-ray spectroscopy of active galactic nuclei has strongly suggested that double-peaked, very broad Fe K emission arises from an accretion disk around the central engine. Model fitting of the observed Fe K emission line profile makes it possible to estimate a probable inclination angle of the accretion disk. In order to study the geometrical relationship between the accretion disk and broad emission-line regions (BLRs), we investigate the correlation between the inclination angle of the accretion disk and the velocity width of BLRs for 18 type-1 Seyfert galaxies. We found that there may be a negative correlation between them, i.e., Seyfert nuclei with a more face-on accretion disk tend to have larger BLR velocity widths, suggesting that the BLRs are not coplanar with respect to the accretion disk. The most probable interpretation may be that the BLRs arise from outer parts \( r \sim 0.01 \text{ pc} \) of a warped accretion disk illuminated by the central engine.

Key words: galaxies: active - galaxies: nuclei - galaxies: X ray

1. Introduction

Given the current paradigm of active galactic nuclei (AGNs), the observed huge luminosities of AGNs are powered by gravitational accretion onto a supermassive black hole (e.g., Rees 1984; Blandford 1990; Antonucci 1993; Peterson 1997). The central engines are considered to be surrounded by dusty tori whose typical inner radii are on the order of \( \sim 1 \text{ pc} \) (e.g., Antonucci, Miller 1985; Pier, Krolik 1992, 1993). Therefore, in order to understand AGNs, it is very important to investigate the spatial structures of the inner \( \sim 1 \text{ pc} \) regions in which a supermassive black hole, an accretion disk, warm absorbers, and broad emission-line regions (BLRs) reside.

The innermost constituent is the accretion disk; its typical radius is \( \sim (10^{-4} - 10^{-3}) M_8 \text{ pc} \) where \( R_S \) is the Schwarzschild radius of a black hole and \( M_8 \) is the black-hole mass in units of \( 10^8 M_\odot \). The existence of accretion disks in AGNs has been demonstrated by the recent X-ray spectroscopy, collected using ASCA (Tanaka et al. 1994). The ASCA X-ray spectra of type-1 AGNs show the presence of very broad Fe Kα emission, whose line profile can be fitted well by some accretion-disk models (Tanaka et al. 1995; Fabian et al. 1995; Mushotzky et al.
An ionized accretion disk has also been detected by the recent radio continuum mapping in the archetypical, nearby Seyfert galaxy NGC 1068 (Gallimore et al. 1997).

Another inner constituent is broad-line regions (BLRs), because their typical radii are of the order of 0.01 pc (e.g., Peterson 1993). One of the most important questions related to the BLRs is how emission-line clouds are distributed around AGNs. Although there is still no definite consensus concerning the dynamical and spatial structure of BLRs, there are three alternative models: 1) the disk model (Shields 1979; see also Osterbrock 1989), 2) the high-velocity streamer model (Zheng et al. 1991), and 3) a pair of conical regions in which photoionized clouds are orbiting randomly with Keplerian motion (Wanders et al. 1995; Wanders, Peterson 1996, 1997; Goad, Wanders 1996). In particular, a recent detailed analysis of the reverberation mapping has strongly suggested that the BLRs of the type-1 Seyfert galaxy NGC 5548 has the third type of geometry (Wanders et al. 1995). It is, however, still not known which model is the most popular one.

Since recent observations have shown that the BLRs are dominated by rotational motion, rather than the radial motion (e.g., Peterson 1993; Wanders et al. 1995), it is interesting to examine whether or not the rotational axis of the BLR is nearly the same as that of the accretion disk. If the disk model for BLRs would be correct, the BLRs may be coplanar with respect to the accretion disk. In fact, double-peaked BLRs have sometimes been considered to arise from accretion disks, themselves [e.g., Pérez et al. (1988); Livio, Xu (1997) and references therein; see also, however, Gaskell (1996)]. Motivated by this, we investigate the relationship between the inclination angle of the accretion disk and the width of BLR statistically using published data.

2. Data

Nandra et al. (1997) presented a systematic analysis of the ASCA X-ray spectra of 18 type-1 Seyfert galaxies. They fitted the Fe Kα emission profiles and derived the most probable inclination angles for the following three models: Model A, the Schwarzschild model with reflection; Model B, the Schwarzschild model with the emissivity law for \( q = 2.5 \) (see below); and Model C, the Kerr model with reflection, where the Schwarzschild and Kerr models refer to those proposed by Fabian et al. (1989) and Laor (1991), respectively. In their model-fitting procedures, there are five parameters: 1) the inner radius of the disk \( (R_i) \), the outer radius \( (R_o) \), the inclination of the axis of rotation with respect to the line of sight \( (i_{AD}) \), the rest energy of Fe Kα line \( (E_{Kα}) \), and the line normalization \( (I_{Kα}) \). They adopted \( R_i = 3R_S \), \( R_o = 500R_S \), and \( E_{Kα} = 6.4 \) keV for Models A and B, while \( R_i = 0.615R_S \) and \( R_o = 200R_S \) for Model C. In addition to the above parameters, the line emissivity is also another parameter, which is usually parameterized by a power law as a function of the radius; i.e., \( R^{-q} \). Model B is the case for \( q = 2.5 \), which is an averaged value for the case of free line emissivity [see table 4 and figure 6 in Nandra et al. (1997)]. The inclination angles for the three models are summarized in table 1. Note that some Seyfert nuclei were observed by
ASC A more than once (e.g., NGC 4151). In these cases, we tabulated the estimated inclination angles for all of the observations.

We have compiled the line widths of both H$\alpha$ and H$\beta$ emission, FWZI (full width at zero intensity), for the above 18 Seyfert galaxies based on the literature. Since it is known that the BLR emission generally shows time variations (e.g., Peterson 1993), it would be desirable to obtain the data of both BLR and Fe K$\alpha$ emission simultaneously. However, all of the BLR data were taken far before the X-ray observations. In order to minimize any possible effect of time variations, we compiled more than-one measurements for each galaxy as much as possible, and then used the averaged value in a later analysis. For some Seyferts, FWHMs (full width at half maxima) of the emission lines are only available in the literature. In these cases, we estimated FWZIs using a relation $\text{FWZI} = 2\sqrt{3} \text{FWHM}$ (Wandel, Yahil 1985). The compiled data are summarized in table 2.

3. Results

In figure. 1, we compare $\sin i_{AD}$ with FWZI(H$\alpha$)/$L_X^{1/4}$ (left column) and with FWZI(H$\beta$)/$L_X^{1/4}$ (right column) for the three accretion-disk models A, B, and C, where $L_X$ is the X-ray (2 — 10 keV) luminosity. In these comparisons, we used both FWZI(H$\alpha$)/$L_X^{1/4}$ and FWZI(H$\beta$)/$L_X^{1/4}$, instead of their raw FWZI values. The reason for this is that the velocity width of BLRs depends on the central mass, even if the inner radius of the BLRs would be the same among the Seyferts, while the inclination angle of an accretion disk has no dependence on the black-hole mass. If the Eddington ratios are not very different among the Seyferts (i.e., the mass-to-luminosity ratios are nearly the same among the Seyferts), we expect the relation $\text{FWZI} \propto L_X^{1/4}$, which is analogous to the so-called Faber-Jackson relation (Faber, Jackson 1976). We adopted the X-ray luminosities given by Nandra et al. (1997).

Figure 1 shows that all of the correlations are negative. As shown in table 3, the correlation coefficients suggest that the negative correlations are not significant statistically. Therefore, our modest conclusion may be that there is a slight correlation between $\sin i_{AD}$ with FWZI(H$\alpha$)/$L_X^{1/4}$, suggesting a random orientation between the BLRs and the accretion disks. However, it is quite unlikely that the large errors in the estimate of $i_{AD}$ cause any accidental negative correlations for all of the cases shown in figure 1. Therefore, we may conclude that there is a tendency of a negative correlation between $\sin i_{AD}$ With FWZI(H$\alpha$)/$L_X^{1/4}$. More interestingly, we mention that there is no hint of a positive correlation between them.

4. Discussion

The most important result in this study is that there is no obvious positive correlation between $\sin i_{AD}$ with FWZI(H$\alpha$)/$L_X^{1/4}$. This suggests that the BLRs are not coplanar with respect
Some Seyfert nuclei in our sample show double-peaked BLRs (DBLRs). It has sometimes been considered that such DBLRs may arise from an accretion disk, itself (e.g., Pérez et al. 1988). The DBLR emission profiles of the four Seyfert nuclei in our sample (NGC 3227, NGC 3783, NGC 5548, and 3C 120) were studied by Rokaki et al. (1992) using a standard geometrically-thin accretion-disk model; also, the inclination angles of the DBLRs (i_{BLR}) were derived. We compare these inclination angles with those of the accretion disks in figure 2. This comparison also suggests a negative correlation between i_{AD} and i_{BLR}, being consistent with our result. This strengthens our suggestion that the BLRs are not coplanar with respect to the accretion disks in the Seyfert nuclei studied here.

Let us consider what kind of geometrical configuration can explain the non-coplanar property. The negative correlation means that the normalized velocity width increases with decreasing inclination angle; i.e., Seyfert nuclei with a more face-on accretion disk tend to have larger BLR velocity widths. There may be three alternative ideas to explain this property. One is the bipolar streamer model (e.g., Zheng et al. 1990). If we observe the accretion disk from a face-on view, the velocity width would be widest because the bipolar wind flows along our line of sight. However, this model has an intrinsic difficulty, as claimed by Livio and Xu (1996), because the emitting region on the receding flow (jet) is obscured from view by the accretion disk; the standard, optically thick accretion disk is opaque up to \( \sim 1 \) pc, and, thus, the BLR component behind the disk cannot be seen, because the typical radial distance of BLRs from the central engine is on the order of 0.01 pc (e.g., Peterson 1993). The second idea is that BLRs are located in nearly the same plane as that of an accretion disk, but are orbiting with polaro orbits. If a two-sided jet is ejected with a highly inclined angle with respect to the global accretion disk, we can explain the negative correlation. Such a jet model is briefly described by Norman and Miley (1984). This idea is consistent with the recent reverberation mapping result for the BLRs of NGC 5548 because the most likely geometry of the BLRs of this galaxy is a pair of conical regions in which photoionized clouds are orbiting randomly with Keplerian motion (Wanders et al. 1995; Wanders, Peterson 1996, 1997; see also Goad, Wanders 1996). This model may also have the same obscuration problem as that for the above streamer model. However, if the BLR clouds are moving at randomly oriented orbits (Wanders et al. 1995), there may be no obscuration problem. The third idea is that BLRs arise from outer parts of a warped accretion disk. The disk model for BLR is the standard idea (Shields 1977; see also for a review Osterbrock 1989). It has been recently shown that accreting gas clouds probed by water-vapor maser emission at 22 GHz show evidence of significant warping (Miyoshi et al. 1995; Begelman, Bland-Hawthorn 1997). The warping of accretion disks can be driven by the effect of the radiation-pressure force (Pringle 1996, 1997). For typical AGN, the warping may occur at \( r > 0.01 \) pc (Pringle 1997), which is at a similar distance as BLRs. Therefore, the warped-disk model can explain the observed negative correlation reasonably well. This model is schematically shown in figure 3. Since the degree of warping and the viewing angle are different from AGN to AGN, the negative correlation between
\(i_{AD}\) and \(i_{BLR}\) may be blurred as obtained in our analysis, although the poor correlation may be also due to the large errors in the estimate of \(i_{AD}\).

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Table 1: The X-ray data of type 1 Seyfert galaxies.

| Object               | \( \log L_X \) (2—10 keV) (erg s\(^{-1}\)) | Model A | Model B | Model C |
|----------------------|-------------------------------------------|---------|---------|---------|
| Mrk 335              | 43.42                                      | 22\(^{+68}_{-22}\) | 24\(^{+13}_{-24}\) | 22\(^{+88}_{-22}\) |
| Fairall 9            | 44.26                                      | 46\(^{+41}_{-27}\)  | 32\(^{+12}_{-8}\)  | 89\(^{+1}_{-49}\)  |
| 3C 120               | 44.34                                      | 60\(^{+30}_{-13}\)  | 59\(^{+10}_{-13}\)  | 88\(^{+2}_{-1}\)   |
| NGC 3227             | 42.01                                      | 20\(^{+8}_{-14}\)   | 23\(^{+8}_{-6}\)    | 21\(^{+7}_{-21}\)  |
| NGC 3516             | 43.43                                      | 27\(^{-6}_{-7}\)    | 26\(^{-4}_{-4}\)    | 26\(^{-3}_{-4}\)   |
| NGC 3783(1)          | 43.25                                      | 35\(^{+2}_{-18}\)   | 21\(^{+5}_{-5}\)    | 26\(^{-5}_{-7}\)   |
| NGC 3783(2)          | 43.25                                      | 32\(^{+3}_{-15}\)   | 9\(^{+11}_{-9}\)    | 40\(^{+12}_{-40}\) |
| NGC 4051             | 41.56                                      | 34\(^{+3}_{-14}\)   | 27\(^{+7}_{-7}\)    | 25\(^{+12}_{-4}\)  |
| NGC 4151(2)          | 42.97                                      | 17\(^{+12}_{-17}\)  | 20\(^{+5}_{-5}\)    | 9\(^{+18}_{-9}\)   |
| NGC 4151(4)          | 42.97                                      | 33\(^{+2}_{-18}\)   | 21\(^{+5}_{-6}\)    | 24\(^{+5}_{-7}\)   |
| NGC 4151(5)          | 42.97                                      | 17\(^{+5}_{-5}\)    | 15\(^{+4}_{-4}\)    | 21\(^{+5}_{-11}\)  |
| Mrk 766              | 43.08                                      | 34\(^{+3}_{-3}\)    | 35\(^{-5}_{-5}\)    | 36\(^{+8}_{-7}\)   |
| NGC 4593             | 43.06                                      | 0\(^{-79}_{-0}\)    | 45\(^{-12}_{-11}\)  | 0\(^{+50}_{-0}\)   |
| MCG –6–30–15(1)      | 43.07                                      | 33\(^{+3}_{-5}\)    | 34\(^{+5}_{-5}\)    | 34\(^{+5}_{-6}\)   |
| MCG –6–30–15(2)      | 43.07                                      | 34\(^{+3}_{-6}\)    | 33\(^{+25}_{-25}\)  | 34\(^{+9}_{-9}\)   |
| IC 4329A             | 43.94                                      | 17\(^{+14}_{-17}\)  | 26\(^{+7}_{-7}\)    | 10\(^{+13}_{-10}\) |
| NGC 5548             | 43.76                                      | 0\(^{+76}_{-0}\)    | 39\(^{+10}_{-11}\)  | 10\(^{+80}_{-10}\) |
| Mrk 841(1)           | 43.82                                      | 27\(^{+7}_{-9}\)    | 27\(^{+6}_{-6}\)    | 26\(^{+8}_{-5}\)   |
| Mrk 841(2)           | 43.82                                      | 38\(^{+2}_{-16}\)   | 30\(^{+9}_{-15}\)   | 90\(^{+0}_{-90}\)  |
| Mrk 509              | 44.38                                      | 27\(^{+2}_{-16}\)   | 27\(^{+6}_{-4}\)    | 89\(^{+89}_{-89}\) |
| NGC 7469(2)          | 43.60                                      | 0\(^{-89}_{-0}\)    | 45\(^{+11}_{-11}\)  | 20\(^{+70}_{-20}\) |
| MCG –2–5–22          | 44.14                                      | 46\(^{+44}_{-46}\)  | 41\(^{+10}_{-15}\)  | 26\(^{+64}_{-26}\) |
Table 2: The optical data of type 1 Seyfert galaxies.

| Object       | Type | $i_{\text{BLR}}$ (degree) | FWZI(H$\alpha$) (km s$^{-1}$) | Ref. | adopt$^\dagger$ | FWZI(H$\beta$) (km s$^{-1}$) | Ref. | adopt$^\dagger$ |
|--------------|------|---------------------------|-------------------------------|------|----------------|-------------------------------|------|---------------|
| Mrk 335      | 1.0  | 1.0                       | 9500                          | 1    | 13620          | 10500                         | 1    | 11967         |
|              |      |                           | 9560                          | 2    | 12800          |                               | 3    |               |
|              |      |                           | 21800                         | 4    | 12600          |                               | 5    |               |
| Fairall 9    | 1.0  | 1.0                       | 16000                         | 6    | 14450          | 10650                         | 7    | 11025         |
|              |      |                           | 12900                         | 8    | 11400          |                               | 8    |               |
| 3C 120       | 1.0  | 20$^*$                    | 9300                          | 8    | 18900          | 15000                         | 9    | 10667         |
|              |      |                           | 28500                         | 4    | 9900           |                               | 8    |               |
|              |      |                           |                               |      |                |                               |      |               |
| NGC 3227     | 1.5  | 40$^*$                    | 11400                         | 1    | 16500          | 11800                         | 1    | 11650         |
|              |      |                           | 21600                         | 4    | 11500          |                               | 5    |               |
| NGC 3516     | 1.5  | 1.5                       | 15500                         | 1    | 15500          | 14800                         | 1    | 13900         |
|              |      |                           |                               |      |                |                               |      |               |
| NGC 3783     | 1.2  | 25$^*$                    | 9900                          | 6    | 9900           | 9900                          | 9    | 9900          |
| NGC 4051     | 1.0  | 1.0                       | 6070                          | 2    | 6070           | 10800                         | 5    | 10800         |
| NGC 4151     | 1.5  | 1.5                       | 9000                          | 6    | 9000           | 9000                          | 9    | 10000         |
| Mrk 766      | 1.5  | 1.5                       | 3118$^\ddagger$              | 11   | 3118$^\ddagger$| 7200                          | 5    | 7200          |
|              |      |                           |                               |      |                |                               |      |               |
| NGC 4593     | 1.0  | 1.0                       | 14000                         | 6    | 14000          | 14549$^\ddagger$             | 12   | 17205         |
|              |      |                           |                               |      |                | 20092$^\ddagger$             | 13   |               |
|              |      |                           |                               |      |                | 16974$^\ddagger$             | 14   |               |
| MCG –6—30—15 | 1.0  | 1.0                       | 5196$^\ddagger$              | 15   | 5196$^\ddagger$| 6500                          | 6    | 6500          |
| IC 4329A     | 1.0  | 1.0                       | 15600                         | 6    | 22800          | 22000                         | 16   | 22000         |
|              |      |                           |                               |      |                |                               |      |               |
| NGC 5548     | 1.5  | 50$^*$                    | 14900                         | 1    | 14900          | 15400                         | 1    | 13300         |
|              |      |                           |                               |      |                |                               |      |               |
| Mrk 841      | 1.5  | 1.5                       | 23500                         | 17   | 11700          | 11700                         | 5    | 11700         |
| Mrk 509      | 1.2  | 1.2                       | 12900                         | 1    | 11700          | 15100                         | 1    | 13100         |
|              |      |                           | 10500                         | 9    | 11100          |                               | 8    |               |
| NGC 7469     | 1.0  | 1.0                       | 7800                          | 1    | 7800           | 8500                          | 1    | 9900          |
|              |      |                           |                               |      |                |                               |      |               |
| MCG –2—58—22 | 1.2  | 1.2                       | 23700                         | 8    | 24750          | 22700                         | 7    | 19150         |
|              |      |                           | 25800                         | 2    | 15600          |                               | 8    |               |

$^*$ Rokaki et al. (1992)
$^\dagger$ A simple average value is adopted.
$^\ddagger$ Estimated by FWZI = $2\sqrt{3}$ FWHM (Wandel, Yahil 1985).
# References, (1) Osterbrock 1977; (2) Osterbrock, Shuder 1982; (3) Padovani, Rafanelli 1988; (4) van Groningen, van Weeren 1989; (5) Padovani et al. 1990; (6) Steiner 1981; (7) Ward et al. 1978; (8) Rafanelli 1985; (9) Elvis et al. 1978; (10) Hooimeyer et al. 1992; (11) Osterbrock, Pogge 1985; (12) Marfan, McHardy 1990; (13) Borgman et al. 1979; (14) Peterson et al. 1982; (15) Crènshaw 1986; (16) Pineda et al. 1980; (17) Marziani et al. 1992; (18) Eracleous, Halpern 1993.
Table 3: The correlation coefficients.

| Model    | $\text{FWZI}(H_\alpha) / L_X^{0.25}$ | $\text{FWZI}(H_\beta) / L_X^{0.25}$ |
|----------|-------------------------------------|-------------------------------------|
| Model A  | -0.125                              | -0.360                              |
| Model B  | -0.239                              | -0.331                              |
| Model C  | -0.306                              | -0.638                              |
Fig. 1.— Comparison of $\sin i_{AD}$ with $\text{FWZI}(H\alpha)/L_X$ (left panels) and with $\text{FWZI}(H\beta)/L_X$ (right panels).
Fig. 2.— Comparison between $\sin i_{AD}$ and $\sin i_{BLR}$ studied by Rokaki et al. (1992) for the following four Seyfert nuclei: a, 3C 120; b, NGC 3783; c, NGC 3227; d, NGC 5548.

Fig. 3.— Schematic illustration of the possible geometrical configuration between the Fe K emitting region ($r < 0.001$ pc) and the BLR ($r > 0.01$ pc) in a warped accretion disk.
Rotation axis of the BLR
Rotation axis of the accretion disk