Accretion rates and accretion efficiency in AGNs

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Abstract

We used the standard geometrical thin accretion theory to obtain the accretion rates in Seyfert 1 galaxies and quasars. Combining accretion rates with the bolometric luminosity, we obtained the accretion efficiency. We found most of Seyfert 1 galaxies and radio quiet quasars have lower accretion efficiencies while most of the radio loud quasars possess higher accretion efficiencies. This finding further implies most of radio loud quasars possess Kerr black holes while Seyfert 1 galaxies and radio quiet quasars may not possess Kerr black holes. Considering the difference of the accretion efficiency we found there is a strong correlation between the accretion rate in units of the Eddington accretion rate and the width of the H\textsc{\textbeta} emission line and most of AGNs are not accreting at Super-Eddington rates.

Key words: accretion:accretion disks — galaxies: active — galaxies: nuclei — galaxies: Seyfert.

1. Introduction

A fundamental component of the standard model of active galactic nuclei (AGNs) is an accretion disk around a central supermassive black hole. For an accretion disk there are several parameters to be defined: black hole mass, the accretion rate, the disk inclination to the line of sight. At the same time there are three parameters to describe a black hole: mass, angular momentum, and charge. For a non-rotational black hole the maximum accretion efficiency converting of the accretion mass to energy is 5.7% while for a maximally rotating one the accretion efficiency is 32.4% (Laor, Netzer 1989).

Through many years’ effort, reliable central black hole masses have been estimated for many nearby galaxies and active galaxies. Several methods were used to estimate the central black hole mass, such as stellar dynamical studies (review from Kormendy, Gebhardt 2001), the reverberation mapping method (Wandel et al. 1999; Kaspi et al. 2000), the relation between central black hole masses and the bulge velocity dispersion (Merritt, Ferrarese 2000), the monochromatic luminosity at 5100˚ (Laor, Netzer 1989).

The advantage of knowing the reliable black hole mass is that it gives an additional constraint in the accretion theory, which depends now only on the accretion rate and the inclination(Collin et al. 2002). Recent black hole mass estimation provides the possibility of constraining the accretion rate in the frame of the standard accretion theory.

Although black hole masses can be preferably determined, it is difficult to determine whether a black hole is rotating. X-ray spectra of AGNs commonly show an iron K\textalpha emission line at about 6keV. The line is often extremely broad and skewed, especially in Seyfert galaxies. The observation of iron K\textalpha emission line in AGNs provides the possibility of defining the spin of the black hole. However, the iron K\textalpha data fit equally well with rotating (Kerr) and non-rotating (Schwarzschild) black hole models (Nandra et al. 1997). Wilms et al. (2001) recently presented XMM observations of MCG-6-30-15 containing a spectral feature that is best described as an extremely broad and redshifted X-ray reflection feature and suggested that it possesses a Kerr black hole (see also Iwasawa et al. 1996; Dabrowski et al. 1997).

Elvis et al. (2002) use the integrated spectrum of the X-ray background and quasar’s spectral energy distribution to derive the contribution of quasars to the energy output of the universe. They showed that the accretion process in quasars must be, on average, very efficient: at least 15% of the accretion mass must be transformed into radiation energy, which further implies that most supermassive black holes are rotating rapidly.

In this Letter we obtain the accretion rates and the accretion efficiencies in AGNs from the reliable central black hole masses and the monochromatic luminosity at 5100˚ in the framework of standard accretion disk theory. The method is described in section 2. Section 3 contains the data and results. In section 4 we present our discussion. The last section is devoted to the conclusion. All cosmological calculations in this paper assume $H_0 = 75 \, \text{km s}^{-1}, \Omega = 1.0, \Lambda = 0$. 

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2. Method

2.1. Formula of the monochromatic luminosity

Here we use the geometrically thin and optically thick standard $\alpha$-prescription accretion disk model (Shakura, Sunayev 1973) for radio quiet and radio loud AGNs. The relation between the black hole mass $M$, accretion rate $\dot{M}$, and intrinsic luminosity $\lambda L_{\lambda}$ at a wavelength $\lambda$ (cosi=0.5 is assumed) is (Bechtold et al. 1987)

$$\log \dot{M} + \log \dot{M} = 1.5\log(\lambda L_{\lambda}) + 2\log\lambda + 0.213.$$  \hspace{1cm} (1)

where $\dot{M}$ is in units of solar masses, $\dot{M}$ is in units of solar masses per year, $\lambda$ in units of Å, and $\lambda L_{\lambda}$ in units of $10^{44} \text{ergs}^{-1}$. We can derive the accretion rate if we know the back hole mass and the luminosity at a wavelength. Standard accretion disk theory usually adopts $\alpha$-prescription for the turbulent viscosity. However, assuming that the accretion disk radiates locally like a blackbody, the viscosity prescription does not appear in Eq. 1 and has no effect on the optical luminosity (Collin et al. 2002).

2.2. Accretion efficiency and accretion rate

The fundamental process at work in AGNs is the conversion of mass to energy, which can be described by accretion efficiency, $\eta$. The energy available from mass $M$ is $E = \eta M c^2$. The luminosity emitted by the nucleus ($L = dE/dt$) gives us the rate at which energy must be supplied to the nucleus source by accretion,

$$\eta = \frac{L_{\text{bol}}}{\dot{M} c^2}. \hspace{1cm} (2)$$

where $L_{\text{bol}}$ is the bolometric luminosity, $\dot{M} = dM/dt$ is the accretion rate and $c$ is the velocity of light.

The Eddington accretion rate $\dot{M}_{\text{Edd}}$ is usually defined by $\dot{M}_{\text{Edd}} = \frac{L_{\text{bol}}}{L_{\text{Edd}}}$, where $L_{\text{Edd}}$ is the Eddington luminosity and $\eta$ is the accretion efficiency. We can calculate the accretion rate in units of the Eddington accretion, $\dot{m} = \frac{\dot{M}}{\dot{M}_{\text{Edd}}}$,

$$\dot{m} = \frac{\dot{M}}{0.23\dot{M}_{\text{Edd}}}. \hspace{1cm} (3)$$

where $\dot{m}$ is the accretion efficiency, $\dot{M}$ is the accretion rate in units of solar mass per year, and $\dot{M}_{\text{Edd}}$ is the black hole mass in units of $10^8$ solar mass.

3. Data and Results

3.1. Seyfert galaxies and PG quasars

Using the reverberation mapping method, the BLRs sizes and then the central black hole masses of 17 Palomar-Green quasars and 17 Seyfert 1 galaxies are obtained (Wandel et al. 1999; Kaspi et al. 2000). The strong correlation between the black hole mass and the bulge velocity dispersion for AGNs (Nelson 2000; Wang, Lu 2001) showed that the black hole mass from reverberation mapping method is reliable. Kaspi et al. (2000) also gave the reliable monochromatic luminosity at 5100Å, whose error bars are of order 1%-2%. From equation 1 we can calculate the accretion rates for 34 AGNs in the sample of Kaspi et al. (2000), which also were similarly obtained by Collin et al. (2002) and Bian and Zhao (2002).

The bolometric luminosity is usually estimated as $L_{\text{bol}} \approx 9 \times \lambda L_{\lambda}(5100\text{Å})$ (Kaspi et al. 2000). In order to investigate the relation between black hole mass and bolometric luminosity, Woo and Urry (2002) have determined bolometric luminosity by integrating all available flux points in the spectral energy distribution (SED). For the sample of Kaspi et al. (2000) we also use the bolometric luminosity from Woo and Urry (2002). From equation 2 we can calculate the accretion efficiency ($\eta1$) using $9\lambda L_{\lambda}(5100\text{Å})$ as the bolometric luminosity. The errors of $\eta1$ are calculated from the errors of the central black holes for 34 AGNs (Kaspi et al. 2000). We also use the bolometric luminosity obtained by Woo and Urry (2002) to calculate the accretion efficiency ($\eta2$). From equation 3 we also calculate the accretion rates in units of the Eddington accretion rate.

The accretion rates $log(\dot{M})$ distribution is $<log(\dot{M})> = -0.10 \pm 0.17$ with a standard deviation of 1.02. The accretion efficiency $\eta1$ distribution is $<log(\eta1)> = -1.77 \pm 0.08$ with a standard deviation of 0.49. $\eta2$ distribution is $<log(\eta2)> = -1.61 \pm 0.09$ with a standard deviation of 0.55. We should notice that there are only two radio loud quasars (PG 1226, PG 1704) in the sample of Kaspi et al. (2000).

3.2. Radio loud quasars

In order to obtain the accretion efficiency of the radio loud quasars, we use the sample of Gu et al. (2001) (Cao, Jiang 2001), which has 86 radio loud quasars (including 55 flat-spectrum (FS) sources and 31 steep-spectrum (SS) sources). The accretion rates distribution in 86 radio loud quasars is $<log(\dot{M})> = 0.40 \pm 0.07$ with a standard deviation of 0.67. The accretion efficiency distribution in 86 radio loud quasars is $<log(\eta)> = -0.90 \pm 0.07$ with a standard deviation of 0.62. We also calculate the $\dot{M}$ and $\eta$ distributions of SS quasars and FS quasars. The distributions of the accretion rates and the accretion efficiency for different samples are listed in Table 1.

3.3. Correlation between accretion rate and radio loudness, the width of $H\beta$ emission line

There is an idea that the jet power is coming from the spin of the central black hole (Moderski et al. 1998). The radio loudness parameter $R = \frac{L_{5GHz}}{L_{4400\text{Å}}}$ is a good indicator of the ratio of jet power to accretion power, at least for steep-spectrum quasars (Gu et al.2001). We plot the radio loudness versus the accretion efficiency. However there is no apparent correlation between them. It may imply that the jet formation is not related to the accretion efficiency. For flat-spectrum quasars, the radio emission is strongly beamed to us, and the optical emission may also be contaminated by the synchrotron emission from the jet(Gu et al.2001).

It is suggested that the NLS1s have large accretion rates
in units of the Eddington accretion rate (Mineshige et al. 2000; Bian, Zhao 2003). Here we plot the accretion rate in units of the Eddington accretion rate versus the FWHM of H$\beta$ emission line in figure 1 and we find there is a strong anti-correlation between them. Objects with higher FWHM of H$\beta$ have smaller accretion rates in units of the Eddington accretion rate.

4. Discussion

4.1. Accretion rate and accretion efficiency

From Table 1 we can find the mean accretion rate in quasars is larger than in Seyfert 1 galaxies. Our calculated accretion rates in AGNs is about one solar mass per year. Quasars have higher accretion rates compared with Seyfert 1 galaxies. This provides further evidence that the difference of Seyfert galaxies and quasars lies mainly about their different accretion rates. Higher accretion in quasars can provide higher luminosity, which favors the unified scheme of active galactic nuclei.

The mean accretion efficiency in radio loud quasars is larger than in radio quiet quasars and Seyfert 1 galaxies. We applied the Kolmogorov-Smirnov test on the difference of the radiation efficiency between radio loud and radio quiet AGNs. The statistic d=0.673 and the possibility of the radiation efficiency between radio loud and radio quiet AGNs are not the same one. It is known that the maximum accretion rates ($\eta$) of non-rotating black holes is about 5.6%, log$\eta$=-1.252. Therefore we find central massive black holes in most of the radio loud quasars are spinning while the black holes in radio quiet quasars and Seyfert 1 galaxies are not rotational. Elvis et al. (2002) also showed that most massive black holes in quasars must be rapidly rotating. The calculated accretion efficiency in radio loud quasars is consistent with the result of Elvis et al. (2002). However in our radio quiet sub-sample in Kaspi et al. (2000) we find the mean accretion efficiency is smaller than 5.6%, which suggests that the black hole in most of radio quiet quasars may not be rotational.

4.2. Errors in our calculation

The uncertainties of the monochromatic luminosity at 5100Å should be discussed, since it is related to bolometric luminosity and the BLR sizes. From equation 1, the accretion rate ($\dot{M}$) is proportionate to $L_{5100}^{1.5} M^{-1}$. The error of the accretion rate is from the errors of the black hole mass and the monochromatic luminosity at 5100Å. From equation 2, the accretion efficiency is proportionate to $\dot{M}^{-1} L_{5100}^{0.5} \times L_{5100}^{0.5} M$. The error of the accretion efficiency is from the errors of the bolometric luminosity and the accretion rate. The monochromatic luminosity at 5100Å is variable by a factor of about two, which will lead to about 0.15 dex in the estimation of the accretion efficiency. The luminosity depends on the cosmological constants. The adoption of higher $H_0$ of 75 km s$^{-1}$ Mpc$^{-1}$ will lead to a smaller luminosity by a factor of two than we adopt smaller $H_0$ of 50 km s$^{-1}$ Mpc$^{-1}$. For Palomar-Green QSOs the nuclear fraction of the measured luminosity is 0.64-0.97 (Surace et al. 2001). The effect of the host contribution to the optical luminosity is to overestimate the accretion rate and underestimate accretion efficiency, especially in not too luminous Seyfert 1 galaxies. However the distribution of accretion efficiency for not too luminous Seyfert 1 galaxies is wide. The empirical size-luminosity relation is $B_{BLR} \propto L^{0.7}$ (Kaspi et al. 2000) while $B_{BLR} \propto L^{0.5}$ is expected from the photoionization model. The host contribution in low luminous Seyfert 1 galaxy provides a clue to this difference. Some authors use 10 times of the monochromatic luminosity at 5100Å as the bolometric luminosity, which influences the calculated accretion efficiency very little. The uncertainty of the accretion efficiency is mainly from the uncertainty of the accretion rate, namely, the uncertainty of the central black hole masses. It is urgent to obtain accurate black hole masses when we want to obtain accurate accretion efficiency. The uncertain determination of lower limits of black hole masses in five AGNs (IC4329A; NGC3227; NGC7469; PG 1700; PG 1704) leads that it is impossible to determine the upper limits of the accretion rates and the lower limits of the accretion efficiency. Considering the errors of the accretion efficiency $\eta_1$, we find black holes in only two AGNs (3C390.3; NGC5548) are rotational. If we consider $\eta_2$, we find black holes in four AGNs (3C390.3; NGC5548; PG1226; PG1617) are rotational.

We should notice that the errors of the accretion efficiency are calculated only from the errors of the black hole (Kaspi et al. 2000). However there are some uncertainties of the reverberation mapping method. The uncertainties of the black hole masses in Kaspi et al. (2000) sample could amount to a factor of 3 in each direction (Krolik 2001) considering the geometry and dynamics of the BLRs (such as the inclination of the disk to the line of sight). In equation 1, we assume that cos$i$=0.5. The smaller inclination will lead to smaller accretion rate and then the higher accretion efficiency. The small inclination of $i$ will decrease accretion rate by $1.5\log (\cos (60^o)/\cos (i))$. If $i < 60^o$, the accretion rate will decrease and then the accretion efficiency will increase. The inclination will influence the determination of the BLR velocity from the FWHM of H$\beta$ emission line. Some authors have discussed the inclinations for Seyfert galaxies and quasars (Nandra et al. 1997; Wu, Han 2001; Bian, Zhao 2002; McLure 2002). Nandra et al. (1997) have found the mean inclination for 18 Seyfert galaxies is about 30 deg, which will increase the accretion efficiency by 0.36 dex. The accretion efficiency will increase by 0.45 dex for face-on AGNs.

4.3. Comparison with previous works

We assume that the luminosity at 5100Å is entirely due to a steady thin accretion disc and from the standard thin disc accretion theory we calculate the accretion rates. We suggested the Eddington ratio is smaller than one in most AGNs when we consider the effect of the accretion efficiency (see figure 1). From these reasonable results we found the standard thin accretion disc theory is enough to contribute to the luminosity at 5100Å. Collin and Hure (2001) claimed a considerable problem with accretion disc
luminosity and show that a standard accretion disc cannot account for the observed optical luminosity, unless it radiates at super-Eddington rates. We don’t find any evidence for such effect. In equation 1 we adopt cosi=0.5 and then from equation 2 we obtain the accretion efficiency, which has the mean value of $10^{-1.77}$ (Table 1). Collin and Hure (2001) adopted $\eta = 0.1$ and cosi=1, which leads to lower accretion rates and then explains their conclusion about disc luminosity that is too low. From figure 1 we find most of the $\dot{m}$ is less than 1, namely, most of the objects are not accreting at Super-Eddington rates when we consider the effect of the accretion efficiency. Woo and Urry (2002) also presented the black hole masses and the bolometric luminosity for a larger assembled sample of AGNs. They found that $\dot{m}$ is less than 1 in most AGNs and there is no significant difference in $\dot{m}$ between radio loud and radio quiet AGNs (see their figure 6-8), which are consistent with our results (see our figure 1).

4.4. Theoretical uncertainties

The significative difference of the accretion efficiency in different types of AGNs can also be due to other causes. Theoretical uncertainties have been discussed in some papers (Collin, Hure 2001; Collin et al. 2002). In equation 1 we assume the influence of the outer radii and the inner radii is negligible. The disk may be truncated at a large inner radius and the disk may become gravitationally unstable at a large outer radius(Collin, Hure 2001; Bian, Zhao 2002). The inner and outer boundary condition will lead to the uncertainty of the computed accretion rates. At the same time, the disk can be non-steady, owning to the existence of the instabilities or the the ejection of a part of the accretion mass close to the black hole. Up to now evidences are not sufficient to help distinguishing these causes.

5. Conclusion

We summarize the main conclusions here.

- We also found the accretion process in most of the radio loud quasars is very efficient and their central black holes are rotating rapidly, which is consistent with the result of Elvis et al. (2002). At the same time, we found most of Seyfert 1 galaxies and radio quiet quasars have lower accretion efficiency, which further implied Seyfert 1 galaxies and radio quiet quasars may not possess Kerr black holes.

- There is a strong anti-correlation between FWHM of $H\beta$ and the accretion rate in units of the Eddington accretion rate. Objects with smaller FWHM of $H\beta$ have larger accretion rate in units of the Eddington accretion rate. NLS1s have the higher accretion rates in units of the Eddington accretion rate compared with the Broad line AGNs.

- We found most of the objects are not accreting at Super-Eddington rates when we consider the effect of the accretion efficiency, which is different from the results of Collin and Hure (2001).

Fig. 1. The accretion rate in units of the Eddington accretion rate versus the FWHM of $H\beta$ emission line.

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Table 1. The distributions of the accretion rates and the accretion efficiency in Seyfert 1 galaxies and quasars.

| Type              | log($\dot{M}$) | $SE_{\dot{M}}$ | log($\eta_1$) | $SE_{\eta_1}$ |
|-------------------|----------------|----------------|---------------|---------------|
| Seyfert and PG    | -0.10± 0.17    | 1.02           | -1.77±0.08    | 0.49          |
| Seyfert galaxies  | -0.54± 0.20    | 0.84           | -1.79±0.13    | 0.54          |
| PG quasars        | 0.73± 0.18     | 0.76           | -1.75±0.11    | 0.44          |
| RL quasars        | 0.40± 0.07     | 0.67           | -0.90±0.07    | 0.62          |
| SS RL quasars     | 0.26± 0.17     | 0.87           | -0.85±0.15    | 0.81          |
| FS RL quasars     | 0.47± 0.07     | 0.53           | -0.92±0.06    | 0.48          |

* Col.1: Type; Col.2: log of the accretion rates; Col.3: The standard deviation of log of accretion rates; Col.4: log of the accretion efficiency; Col.5: The standard deviation of log of accretion efficiency.

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