Constraints on radiatively inefficient accretion history from Eddington ratio distribution of active galactic nuclei

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\section{INTRODUCTION}

Accretion onto massive black holes is believed to power active galactic nuclei (AGNs). The UV/optical continuum emission observed in luminous quasars is attributed to the thermal radiation from the accretion disks surrounding the massive black holes in quasars (e.g., Sun & Malkan 1989). In recent years, some different approaches are proposed to measure the masses of the central black holes in AGNs (e.g., Peterson 1993; Ferrarese & Merritt 2000; Gebhardt et al. 2000), and the central black hole masses of many AGNs can be measured fairly accurately. It is found that a fraction of luminous AGNs are accreting at extremely high rates. Their bolometric luminosities are around (or even higher than) the Eddington luminosity, for example, the black holes in many narrow-line Seyfert 1 galaxies are believed to be accreting at Eddington (or super-Eddington) rates (e.g., Sulentic et al. 2000; Warner et al. 2004; Bian & Zhao 2004; Chen & Wang 2004). Besides the luminous AGNs accreting at high Eddington rates ($\gtrsim 0.01$), many nearby low-luminosity AGNs are found to have similar characteristics as those luminous AGNs, but with relatively weaker broad-line emission and lower luminosities in different wavebands (Ho et al. 1997). Most of these low-luminosity AGNs are accreting at highly sub-Eddington rates ($L_{\text{bol}}/L_{\text{Edd}} \ll 0.01$). The Eddington ratios of AGNs can spread over more than ten orders of magnitude (from $\lesssim 10^{-10}$ to more than unity) (e.g., Wu & Cao 2005; Hopkins, Narayan & Hernquist 2006).

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accretion rate decreases with time. An AGN will die off, while the gases near the black hole are finally exhausted. How the accretion rate $\dot{m}$ evolves with time remains to be an open issue, though an exponentially time-dependent accretion rate $\dot{m}(t)$ was widely employed in many previous works (e.g., Park & Vishniac 1990; Haiman & Loeb 1999; Kauflmann & Haehnelt 2000). McMillan, Lightman & Cohen (1981) found accretion rate $\dot{m}(t) \propto t^{-2}$, if the gases accreted by the black hole are assumed to be supplied by stellar collisions or tidal disruptions in a dense star system surrounding the black hole. Compared with exponentially time-dependent accretion rate, this form of accretion rate changes very slowly with time. Many quasar evolution model calculations showed that the exponentially time-dependent quasar light curve (or simply a step function quasar light curve) can well reproduce the observed quasar luminosity functions (e.g., Haiman & Loeb 1999; Wyithe & Loeb 2002). Recently, the numerical simulations on the quasar activity triggered by the galaxy merger showed that the quasar accretion rate curve is very complicated (Springel, Di Matteo & Hernquist 2005; Di Matteo, Springel & Hernquist 2005). In their simulations, the gases near the black hole are blown away by the bright quasar radiation, and then accretion rate declines rapidly to switch off the quasar activity.

In principle, the evolution of the AGN light curve $L(t)$ can be derived from the Eddington ratio distribution of an AGN sample, because the Eddington ratio distribution $\propto [d \log (L/\dot{L}_{\text{Edd}})/d\log T_b]^{-1}$ (e.g., Begelman & Celotti 2004; Hopkins, Narayan & Hernquist 2006). However, it is still not straightforward to derive the time-dependent accretion rate $\dot{m}(t)$, because the radiative efficiency is no longer a constant when the accretion disk is evolving from slim disk (high-$\dot{m}$) (e.g., Abramowicz et al. 1988; Wang et al. 1999) to a RIAF (low-$\dot{m}$) (e.g., Narayan & Yi 1994).

In this work, we derive how the accretion rate $\dot{m}(t)$ evolves with time from an observed Eddington ratio distribution for a low-luminosity AGN sample in the local universe based on the standard disk/RIAF transition model. In our calculations, the physics of different accretion models and the accretion mode transition is properly considered.

2 SPECTRA OF RADIATIVELY INEFFICIENT ACCRETION FLOWS

The transition of a standard thin disk to a RIAF occurs, when the accretion rate $\dot{m}$ decreases to a value below $\dot{m}_{\text{crit}}$. The structure of the RIAF is well described by the self-similar solution, except the region near the black hole (Narayan & Yi 1995; Yi 1996). The spectrum of a RIAF, $L_{\nu}(\dot{M}_{\text{bh}}, \dot{m}, \alpha, \beta)$, can be approximated by the self-similar solution (e.g., Mahadevan 1997; Chang, Choi & Yi 2002; Wu & Cai 2005), if the parameters $\dot{M}_{\text{bh}}, \dot{m}, \alpha,$ and the fraction of the magnetic pressure $\beta$, are specified. However, the physical quantities of a self-similar RIAF deviate significantly from the global solution of the RIAF in its inner region, which may lead to inaccuracy for its spectral calculation, because most gravitational energy of the accreting matter is released in the inner region of the accretion flow.

In this work, we calculate the global structure of the accretion flows surrounding massive Schwarzschild black holes. The accretion flow is described by a set of general relativistic hydrodynamical equations (see Mamnott 2004, for the details). All the radiation processes are included in the calculations of the global accretion flow structure. Integrating these equations from the outer boundary of the flow at $R = R_{\text{out}}$ inwards the black hole, we can obtain the global structure of the accretion flow passing the sonic point smoothly to the black hole horizon. In our calculations, the values of some parameters adopted are different from those in Mamnott (2004), which will be discussed in Section 7. We can then calculate the spectrum of the accretion flow based on this global structure of the RIAF. In the spectral calculations, the gravitational redshift effect is considered, while the relativistic optics near the black hole is neglected. We only calculate the total luminosity radiated from the RIAF without considering its inclination. The derived spectrum in this way can be taken as an average spectrum for AGNs, which is a good approximation, as AGNs should have randomly distributed orientations.

3 SPECTRA OF STANDARD DISKS

For a standard thin disk, the flux due to viscous dissipation in unit surface area is (Shakura & Sunyaev 1973)

$$F_{\text{vis}}(R) \approx \frac{3GM_{\text{bh}}M}{8\pi R^3} \left[1 - \left(\frac{3R_{\text{in}}}{R}\right)^{1/2}\right],$$

where $R_{\text{in}} = 2GM_{\text{bh}}/c^2$. The local disk temperature of the thin cold disk is

$$T_{\text{disk}}(R) = \frac{F_{\text{vis}}(R)}{\sigma T_b^4},$$

by assuming local blackbody emission. In order to calculate the disk spectrum, we include an empirical color correction for the disk thermal emission as a function of radius. The correction has the form (Chiang 2002)

$$f_{\text{col}}(T_{\text{disk}}) = f_\infty - \frac{(f_\infty - 1)[1 + \exp(-\nu_b/\Delta\nu)]}{1 + \exp[(\nu_b - \nu_0)/\Delta\nu]},$$

where $\nu_b \equiv 2.82k_bT_{\text{disk}}/h$ is the peak frequency of blackbody emission with temperature $T_{\text{disk}}$. This expression for $f_{\text{col}}$ goes from unity at low temperatures to $f_\infty$ at high temperatures with a transition at $\nu_b \approx \nu_0$. Chiang (2002) found that $f_\infty = 2.3$ and $\nu_b = 15\times10^{15}$ Hz can well reproduce the model disk spectra of Hubeny et al. (2001). The disk spectra can therefore be calculated by

$$L_{\nu} = 32\pi^2 \left(\frac{GM_{\text{bh}}M}{c^2}\right)^2 \frac{h\nu^3}{c^2} \int_{r_{\text{in}}}^{\infty} f_{\text{col}}[\exp(h\nu/f_{\text{col}}k_bT_{\text{disk}}) - 1] dr,$$

where $r_{\text{in}} = R_{\text{in}}/R_b$ is the inner radius of the standard disk. At a high accretion rate, $\dot{m} > \dot{m}_{\text{crit}}$, the standard thin disk extends to the minimum stable orbit of the black hole, $r_{\text{in}} = 3$, for a non-rotating black hole. For a RIAF+standard thin disk system, the spectrum emitted from the standard disk region can be calculated by using the transition radius $r_{\alpha}$ ($r_{\alpha} = R_{\alpha}/R_b$) instead of $r_{\text{in}}$ as the lower integral limit in Eq. (4).

4 TRANSITION RADIUS $R_{\alpha}$ BETWEEN RIAF AND STANDARD THIN DISK

In this work, we assume the transition from a standard thin disk to a RIAF to occur whenever $\dot{m} \lesssim \dot{m}_{\text{crit}}$, i.e., so-called "strong principle" (e.g., Narayan, Mahadevan & Quataert 1998). The RIAF is naturally expected to match a standard thin disk at the transition...
radius \( r_{\text{tr}} \). The detailed physics, causing such a transition of a standard thin disk to a RIAF, is still unclear. It is suggested that the standard thin disk transits is truncated at an initial transition radius \( r_{\text{tr},0} \) and a RIAF is present within this radius, when \( m = m_{\text{crit}} \).

The transition radius \( r_{\text{tr}} \) increases with decreasing accretion rate \( \dot{m} \) as

\[
  r_{\text{tr}} \propto \dot{m}^{-p},
\]

where \( p = 2 \) is predicted, based on the scenario of transition triggered by the thermal instability, by Abramowicz et al. (1995); or \( p \approx 0.8 - 1.3 \) is expected by the disk evaporation induced transition scenarios (Liu et al. 1999; Rozanska & Czerny 2000; Spruit & Deufel 2002). In either one of these transition scenarios, the transition radius \( r_{\text{tr}} \) always increases with decreasing accretion rate \( \dot{m} \). The precise initial transition radius \( r_{\text{tr},0} \) is still unknown, though it should be small. In this work, we adopt \( r_{\text{tr},0} = 20 \) in all our calculations.

5 THE OBSERVED DISTRIBUTION OF THE EDDINGTON RATIO \( L_B/L_{\text{edd}} \)

In this work, we adopt the sample given by Ho (2002), in which 74 nearby supermassive black holes with both measured masses and B-band luminosities. The black hole masses of the sources in this sample have been measured by using two different approaches: stellar and gas kinematics and reverberation mapping. Terashima, Ho & Pak (2000) found that X-ray luminosities in 2-10 keV of LINERs (low-ionization nuclear emission-line regions) with broad H\(\alpha \) emission in their optical spectra are proportional to their H\(\alpha \) luminosities. This indicates that the dominant ionizing source in LINERs is photoionization by hard photons from low-luminosity AGNs. The B-band luminosities of the sources in this sample are estimated from the line emissions, which are supposed to be photo-ionized by the nuclear radiations. This may cause some uncertainties for individual sources, but the derived Eddington ratio should still be reliable in statistical sense. This sample includes 17 PG quasars, which may not be in the same population with those low-luminosity counterparts and are accreting at higher rates \( \dot{m} > m_{\text{crit}} \). As we are focusing on the inefficient accretion history of AGNs, we leave out these 17 PG quasars, which leads to 57 sources. The Eddington ratio distribution for this sample is plotted in Fig. 1. This sample was used to explore the evolution of low-luminosity AGNs by Hopkins, Narayan & Hernquist (2006). The selection effects of this sample were extensively analyzed in their work (see Section 2.1 in their paper for the details).

They found that, the FR I radio galaxies from the sample used by Marchesini, Celotti & Ferraresso (2004) exhibit significant different luminosity distribution from that of the sample by Ho (2002), while both of these two sample exhibit similar Eddington ratio distributions. This means that the results of AGN evolution derived from either one of these two samples would be qualitatively unchanged, which may imply that the derived results are not affected significantly by selection effects.

The maximal distance for the sources measured by reverberation mapping method is about 3 times that of the subsample measured by the stellar/gas kinematics. Hopkins, Narayan & Hernquist (2006) suggested to multiply the relative fraction of the sources measured kinematics by \( 3^3 \) to account for the different subsample volumes. The derived distribution for this tentatively volume-corrected sample is also plotted in Fig. 1.

6 THE TIME-DEPENDENT ACCRETION RATE \( \dot{M}(T) \) DERIVED FROM THE EDDINGTON RATIO DISTRIBUTION

The light curve of AGNs at B-band can be derived from the observed Eddington ratio distribution \( \frac{dN}{d\log(L_B/L_{\text{Ed}})} \):

\[
  \frac{d}{dt} \frac{dN}{d\log(L_B/L_{\text{Ed}})} = N_{\text{tot}} \left( \frac{d}{dt} \frac{dN}{d\log(L_B/L_{\text{Ed}})} \right)^{-1},
\]

where \( N_{\text{tot}} \) is the total number of the sources in the sample, and \( t \) is normalized to unity. The time-dependent accretion rate \( \dot{m}(t) \) can be derived from the light curve by

\[
  \frac{d\dot{m}(t)}{dt} = \frac{d}{dt} \frac{dN}{d\log(L_B/L_{\text{Ed}})} \left( \frac{d}{d\dot{m}} \frac{dN}{d\log(L_B/L_{\text{Ed}})} \right)^{-1},
\]

where \( d\log(L_B/L_{\text{Ed}})/d\dot{m} \) is available based on spectral calculations for the accretion mode transition model described in Sections 2-4. Here, we have to assume that all sources have the same time-dependent accretion rate \( \dot{m}(t) \), and it evolves monotonically with time. The latter assumption may not be the case for some individual sources in short timescales, but it should be reasonable in statistic sense for a sample of AGNs, because accretion rates should decline in a long timescale. Substituting Eq. 6 into Eq. 7, we obtain

\[
  \frac{d\dot{m}(t)}{dt} = N_{\text{tot}} \left( \frac{dN}{d\dot{m}} \right)^{-1}. \tag{8}
\]

Using the X-ray luminosity function of AGNs given by Ueda et al. (2003), we calculate number density of AGNs in comoving space as a function of redshift. It is found that the number density of AGNs in the local universe is about 45 per cent of that at \( z = 0.5 \), which implies that the AGNs at low redshifts are roughly in a steady evolving state with switching on and off being in balance. The cosmological evolution of AGNs at low redshifts should be unimpor-

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tant, which will affect our results very little, as the sample used in this work is limited to the sources in the local universe.

7 RESULTS

The detailed physics of the viscosity in accretion disks is still quite unclear, and it is usually described by the viscosity parameter $\alpha$. Assuming accretion to be driven by turbulent stresses generated by the magnetorotational instability, the three-dimensional MHD simulations suggest that the viscosity parameter $\alpha$ in the accretion flows is $\sim 0.1$ (Armitage 1998), or $\sim 0.05 - 0.2$ (Hawley & Balbus 2002). The critical accretion rate $\dot{m}_{\text{crit}} \approx 0.01$ for accretion mode transition is suggested by different authors either from observations or theoretical arguments (see, e.g., Narayan, Mahadevan & Quataert 1998). Our numerical calculations for the global structure of the flows show $\dot{m}_{\text{crit}} \approx 0.01$ for $\alpha = 0.2$. In this work, we adopt the $\alpha$-viscosity, $\alpha = 0.2$, and limit our calculations of the RIAF structure to hydrodynamics, but the magnetic pressure is included by a parameter $\beta$. The parameter $\beta$, defined as $p_m = (1 - \beta)p_{\text{tot}}$, describes the magnetic field strength of the gases in the flow. This parameter is in fact not a free parameter, which is related to the viscosity parameter $\alpha$ as $\beta \approx (6\alpha - 3)/(4\alpha - 3)$, as suggested by the MHD simulations (Hawley, Gammie & Balbus 1996; Narayan, Mahadevan & Quataert 1998). For $\alpha = 0.2$, $\beta \approx 0.8$ is required. Mannert (2000) adopted very small values of $\delta$ in the calculations, as those of traditional advection dominated accretion flow (ADAF) models (see Narayan 2002, for a review, and references therein). It was pointed out that such a small $\delta$ adopted in traditional ADAF models is very unlikely, because a significant fraction of the viscously dissipated energy (up to $\delta \sim 0.5$) could go into electrons by magnetic reconnection, if the magnetic fields in the flow are strong (Bisnovatyi-Kogan & Lovelace 1997).

8 DISCUSSION

For a RIAF+standard thin disk system, its optical emission is mostly from the outer thin accretion disk region, if its accretion rate $\dot{m}$ is close to the critical value $\dot{m}_{\text{crit}}$, because the transition radius is small for this case. For a large transition radius, corresponding to a low $\dot{m}$, the temperature of the standard thin disk region is very low, and the optical emission is dominantly from the inner RIAF (see Fig. 2). The optical luminosity drops rapidly with $\dot{m}$, when the flow is accreting at $\dot{m} \lesssim \dot{m}_{\text{crit}}$.

In Fig. 2 we find that the luminosity decreases rapidly after the accretion mode transition at $\dot{m} = \dot{m}_{\text{crit}} \sim 0.01$. It is found that the light curves $L_B(\dot{m})$ are almost same for $p = 1$ and $p = 2$, except the accretion rate $\dot{m}$ is in the range of $\sim 0.004 - 0.01$. When the accretion rate $\dot{m}$ is slightly lower than $\dot{m}_{\text{crit}}$, the emission is dominantly from the outer thin disk regions, because the standard thin disks still extend to small radii. The emission becomes domi-
inated by the radiation from the inner RIAFs, when the accretion rate \( \dot{m} \lesssim 5 \times 10^{-5} \).

Based on the relations between accretion rate \( \dot{m} \) and B-band luminosity \( L_B(\dot{m}) \) given in Fig. 2 we can derive the time-dependent accretion rates \( \dot{m}(t) \) from the observed Eddington ratio distributions for AGNs. In Fig. 2 we plot the derived \( \dot{m}(t) \) for the cases with two different values of \( p \) for variable transition radius models, from the Eddington ratio distribution of the \( H_2 \) sample or the sample and with effective volume-corrected (see Section 5), respectively. We find that there is a rapid decrease of \( \dot{m}(t) \) from \( 10^{-2} \) to \( 10^{-4} \) either for the cases with different values of \( p \) or from different Eddington ratio distributions (the original one or the effective volume-corrected one). It is not surprising to find that the derived time-dependent accretion rates \( \dot{m}(t) \) are quite similar for the cases with \( p = 1 \) or \( p = 2 \), because the theoretical curves \( L_B(\dot{m}) \) are very similar for these two different values of \( p \) (see Fig. 2). For the Eddington ratio distribution of the effective volume-corrected sample, there are more sources with low luminosities, i.e., less sources with \( \dot{m} \) close to \( \dot{m}_{\text{crit}} \), so the derived time-dependent \( \dot{m}(t) \) decreases more rapidly than that from the original sample. We find that the main feature of the time-dependent \( \dot{m}(t) \) has not been changed by this effective volume-corrected sample. Cao (2005) calculated the hard X-ray emission from all RIAFs in faint AGNs, and compared them with the observed X-ray background. It was found that the accretion rate should decrease rapidly to the value below the critical rate within a timescale shorter than 5 per cent of bright quasars’ lifetime, which is consistent with our present time-dependent accretion rates \( \dot{m}(t) \) derived from the Eddington ratio distributions. The present derived time-dependent \( \dot{m}(t) \) is based on the assumption of monotonical evolution with time. From Eq. (8), we find that \( \frac{d\dot{m}(t)}{dt} \) also represents the distribution of accretion rates \( \dot{m} \) for the sample.

The present sample may have overlooked a number of sources with very low Eddington ratios (\( \lesssim 10^{-7} \)), which means a complete sample should include more sources accreting at very low rates \( \lesssim 10^{-6} \) than the present sample. This implies that the relative timescale of the rapid drop of accretion rate from 0.01 to \( 10^{-4} \) should be even shorter than those plotted in Fig. 2 if a complete sample is adopted. Such a complete sample is still unavailable now, however, the main feature of \( \dot{m}(t) \) with a rapid declining between 0.01 and \( 10^{-4} \) derived in this work will not be changed qualitatively.

The fraction of the viscously dissipated energy that directly goes into electrons, \( \delta = 0.5 \), is adopted in this work, as suggested by Bisnovatyi-Kogan & Lovelace (1997). The precise value of \( \delta \) is still unknown, and it may slightly be lower than 0.5. If a slightly lower \( \delta \) is adopted, the derived light curves \( L_B(\dot{m}) \) have the similar form, but they should be systematically lower than those in Fig. 2. Thus, the main feature of \( \dot{m}(t) \), a rapid decrease after the accretion mode transition, will still be present as those plotted in Fig. 2.

The RIAF may have winds, and a power-law \( r \)-dependent accretion rate is assumed, though the detailed physics is still unclear (Blandford & Begelman 1999). When the accretion rate \( \dot{m} \) is close to 0.01, the optical emission is dominated by that from the outer standard thin disk region (see Fig. 2). Thus, the optical spectrum of the RIAF+standard thin disk system will not be affected by the winds of the RIAF, when \( \dot{m} \) is close to 0.01. The optical emission from the RIAFs is attributed to Compton up-scatterings of the soft synchrotron photons by the hot electrons in the accretion flows. Our numerical calculations on the RIAF spectra show that most optical emission (more than 90 per cent) is from the regions within 10 \( R_S \).

In principle, one has to consider the activity trigger rates of galaxies along the cosmic time in the study of AGN evolution. However, it is difficult to have a complete sample including both bright and faint AGNs, which can be used to explore the evolution of bright quasars to faint AGNs. In this work, we only explore the time-dependent \( \dot{m}(t) \) for \( \dot{m} \lesssim \dot{m}_{\text{crit}} \) and the sources in the sample we used are limited in the local universe. Thus, the results may not be affected by the unknown trigger rates, though it is unclear if the derived \( \dot{m}(t) \) in this work is valid for the AGNs at high redshifts.

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