CONSTRANTS ON THE VISCOSITY AND MAGNETIC FIELD IN HOT ACCRETION FLOWS AROUND BLACK HOLES

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ABSTRACT

The magnitude of the viscosity and magnetic field parameters in hot accretion flows is investigated in low luminosity active galactic nuclei (LLAGNs). Theoretical studies show that a geometrically thin, optically thick disk is truncated at mass accretion rates less than a critical value by mass evaporated vertically from the disk to the corona, with the truncated region replaced by an advection dominated accretion flow (ADAF). The critical accretion rate for such a truncation is a function of the viscosity and magnetic field. Observations of X-ray photon indices and spectral fits of a number of LLAGNs published in the literature provide an estimate of the critical rate of mass accretion and the truncation radius, respectively. By comparing the observational results with theoretical predictions, the viscosity and magnetic field parameters in the hot accretion flow region are estimated. Specifically, the mass accretion rates inferred in different sources constrain the viscosity parameter, whereas the truncation radii of the disk, as inferred from spectral fits, further constrain the magnetic field parameter. It is found that the value of the viscosity parameter in the corona/ADAF ranges from 0.17 to 0.5, with values clustered about 0.2–0.3. Magnetic pressure is required by the relatively small truncation radii for some LLAGNs and is found to be as high as its equipartition value with the gas pressure. The inferred values of the viscosity parameter are in agreement with those obtained from the observations of non-stationary accretion in stellar mass black hole X-ray transients. This consistency provides support for the paradigm that a geometrically thin disk is truncated by means of a mass evaporation process from the disk to the corona at low mass accretion rates.

Key words: accretion, accretion disks – black hole physics – galaxies: active – X-rays: galaxies

1. INTRODUCTION

The α viscosity prescription (Shakura & Sunyaev 1973) has proved to be a particularly valuable framework for accretion disk models, having been used successfully in the interpretation of observations of diverse phenomena ranging from dwarf novae and black hole X-ray binaries (BHXRBs) on the small scale to active galactic nuclei (AGNs) on the large scale. The physical mechanism of the viscosity, however, remains to be completely understood. Hydrodynamic as well as magnetohydrodynamic (MHD) turbulence have been proposed as the main sources (e.g., Balbus & Hawley 1991; Kato 1994), but the deduced viscosity parameter is smaller by an order of magnitude in comparison to the values required by observations as inferred from time-dependent accretion in X-ray transients (e.g., Smak 1999; Suleimanov et al. 2008; King et al. 2007).

It is generally accepted that the magnetic field is an important ingredient in the description of accretion flows and their emission. In particular, it is likely to be responsible for the accretion disk viscosity as suggested in the early work by Balbus & Hawley (1991). The emission due to synchrotron radiation and self-Compton scattering in advection dominated accretion flows (ADAFs) is sensitive to the strength of the magnetic fields and the hard X-ray emission in some objects can be due to magnetic flaring activity. Finally, a large scale magnetic field, as required for the formation of jets, can originate from small scale magnetic fields produced in the accretion flow by dynamo action. Although magnetic fields play a key role in the above, the strength of such magnetic fields in these flows remains unknown.

The mode of the accretion flow is generally believed to depend on the Eddington-scaled accretion rate. At high mass accretion rates, as revealed in the high/soft state of BHXRBs and luminous AGNs, the accretion is thought to occur via a geometrically thin, optically thick accretion disk as developed by Shakura & Sunyaev (1973). However, at low accretion rates in the low/hard state of BHXRBs and low luminosity AGNs (LLAGNs), the accretion occurs via a geometrically thick, optically thin ADAF (see Narayan & Yi 1994, 1995a, 1995b; Wandel & Liang 1991), connecting to an outer geometrically thin disk. The transition between these modes can be due to a thermal instability (Takeuchi & Mineshige 1998; Gő & Lu 2000; Lu et al. 2004), a result of radial conduction (Honma 1996; Mamotto & Kato 2000; Gracia et al. 2003) or a disk evaporation process (Meyer et al. 2000a, 2000b; Różańska & Czerny 2000a, 2000b; Spruit & Deufel 2002; Dullemond & Spruit 2005). In the context of these studies, the disk evaporation model is the most promising, which has been investigated to elucidate the disk truncation and spectral state transition behavior as a function of accretion rate in both BHXRBs and AGNs (e.g., Liu et al. 1999, 2002; Liu & Taam 2009; Meyer et al. 2000a, 2000b, 2007; Taam et al. 2012).

Here, we adopt the disk evaporation model as the mechanism of disk truncation and spectral state transition. In this model, the accretion rate characterizing the transition as well as the truncation radius is a function of the viscosity and magnetic field parameters. Detailed spectral fitting to the transition or low/hard state spectrum can, in principle, yield these properties. An estimate of the viscosity and magnetic field parameters follows from comparing the model prediction with observations. From statistical studies based on observed spectra, a transition of the spectral energy distribution at a determined Eddington ratio can be used to constrain the average value of the viscosity parameter in the accretion flows around AGNs. In the next section, we
provide a description of disk truncation and spectral transition within the context of the mass evaporation model. Constraints on the viscosity and magnetic field parameters as obtained from the observations of AGN are provided in Section 3. We discuss our results and conclude in the last section.

2. DISK TRUNCATION AND SPECTRAL TRANSITION AS A CONSEQUENCE OF DISK CORONA INTERACTION

In the disk corona model (for dwarf novae see Meyer & Meyer-Hofmeister 1994; for black holes see Meyer et al. 2000a and Liu et al. 2002), a hot optically thin corona is presumed to lie above and below a geometrically thin standard disk, which could be formed by processes similar to those operating in the surface of the Sun, or by a thermal instability in the uppermost layers of the disk (e.g., Shaviv & Wehre 1986). Both the disk and corona are individually powered by the release of gravitational energy associated with the accretion of matter affected through viscous stresses. In the corona, the viscous heat is partially transferred to the electrons by means of Coulomb collisions and partially advected radially inward. The energy gained by the electrons is mainly conducted into the lower, cooler, and denser layer and radiated away in the chromosphere. If the density in the lower corona is too low to efficiently radiate this energy, which is the case for a steady accretion corona, then a suitable amount of cool matter is heated and evaporated into the corona. The mass accretion in the corona is maintained by a steady evaporation flow from the underlying cool disk.

In the accretion disk, gas is partially evaporated into the corona on the way to the accreting black hole. This diverts a part of the disk accretion flow into the corona. If the mass supply rate to the outer disk is too low, then the disk accretion flow can be completely evaporated into the corona at some distance from the black hole, interior to which there exists only a hot accretion flow. This results in disk truncation and a change of accretion flow from two-phase (cold disk + hot corona) accretion in the outer region to an ADAF in the inner region. On the other hand, if the mass supply rate to the disk is high, then the evaporation is limited by efficient Compton cooling of the corona due to the strong soft photon field originating from the inner disk. In this case, only a small fraction of the mass flow in the disk is evaporated into the corona. Hence, a geometrically thin disk extends to the innermost stable circular orbit (ISCO) and the corona is quite weak. Previous investigations of the disk corona interaction (e.g., Meyer et al. 2000a; Liu et al. 2002) reveal that there exists a maximal evaporation rate, above which the mode of accretion is dominated by a geometrically thin, optically thick accretion disk, and below which the accretion is dominated by an ADAF connected to a truncated outer disk with overlying corona. The maximal evaporation rate thus represents the accretion rate at the spectral state transition, and the corresponding truncation radius is the minimal radius of disk truncation before transit to a soft state.

The mass evaporation is a consequence of hydrodynamic equilibrium. It is calculated by solving a set of simplified differential equations including the continuity equation, momentum equation, and energy equations supplemented by an equation of state (for details see Liu & Taam 2009), which are listed as follows:

\[ P = \frac{3}{2}\mu \rho \left( T_i + T_e \right), \]  
\[ \frac{d}{dz} \left( \rho v_z \right) = \frac{2}{R} \rho v_R - \frac{2z}{R^2 + z^2} \rho v_z, \]

\[ \frac{d}{dz} \left( \rho v_z \right) = - \frac{dP}{dz} - \rho \frac{GMz}{(R^2 + z^2)^{3/2}}, \]  
\[ \frac{d}{dz} \left\{ \frac{\rho v_z}{2} \right\} + \frac{2}{R} \frac{\rho v_R}{\gamma - 1}\left( \frac{GM}{(R^2 + z^2)^{3/2}} \right) \right\} = \frac{3}{2} \alpha P \Omega - q_{ie} + \frac{3}{R} \frac{\rho v_R}{\gamma - 1}\left( \frac{GM}{(R^2 + z^2)^{3/2}} \right) \right\} - 2z \left( \frac{GM}{(R^2 + z^2)^{5/2}} \right) \right\}, \]  
\[ \frac{d}{dz} \left\{ \frac{\rho v_z}{2} \right\} + \frac{2}{R} \frac{\rho v_R}{\gamma - 1}\left( \frac{GM}{(R^2 + z^2)^{3/2}} \right) \right\} = \frac{3}{2} \alpha P \Omega - n_e n_i L(T) - q_{\text{comp}} \right\}

\[ q_{ie} = \frac{2}{\pi} \frac{3}{2} \frac{m_e c}{m_p} \ln \Lambda \sigma_T c n_e n_i (\kappa T_i - \kappa T_e) \left( \frac{T_c}{T_a} \right)^{3/2}, \]

\[ \frac{F_c}{cz} = - \kappa_0 \frac{e^2 \gamma}{z^2} \frac{dE_e}{dz}, \]

where Equation (4) is the energy equation for the ions, in which \( q_{ie} \) is the energy exchange rate between the electrons and the ions,

\[ q_{ie} = \frac{2}{\pi} \frac{3}{2} \frac{m_e c}{m_p} \ln \Lambda \sigma_T c n_e n_i (\kappa T_i - \kappa T_e) \left( \frac{T_c}{T_a} \right)^{3/2}, \]

\[ q_{\text{comp}} = \frac{4 \kappa T_e}{m_e c^2} \sigma_T c u, \]

with \( u \) being the energy density of the soft photon field. The thermal conduction flux, \( F_c \), is given by (Spitzer 1962)
depends on the viscosity parameter, $\alpha$ (2002). The maximal mass evaporation rate in the low state by numerical calculations (e.g., Meyer et al. 2000a; Liu et al. on the radiation in the low hard states, which has been confirmed that the evaporation characteristics are only weakly dependent layer is the Bremsstrahlung radiation important. This implies that the evaporation characteristics are only weakly dependent on the radiation in the low hard states, which has been confirmed by numerical calculations (e.g., Meyer et al. 2000a; Liu et al. 2002). The maximal mass evaporation rate in the low state depends on the viscosity parameter, $\alpha$. An increase in $\alpha$ leads to an increase in heating, which is partially transferred to the electrons through Coulomb collisions and conducted down to the transition layer, resulting in an increase in the mass evaporation rate. This effect is more important in the inner region of the corona since the Coulomb collisions in its outer region are very inefficient due to the low densities. Specifically, the maximum evaporation rate and its corresponding truncation radius vary with $\alpha$ approximately as (Qiao & Liu 2009)

$$m_{\text{max}} \approx 0.38\alpha^{2.34}$$ and $r_{\text{min}} \approx 18.80\alpha^{-2.00}$.  

(10)

Here, the evaporation rate is expressed in terms of the Eddington mass accretion rate and the radius in terms of Schwarzschild radii, $R_S = 2GM/c^2$, where $M$ is the mass of the black hole.

The effect of magnetic fields is a competition between its tendency to increase the evaporation as a result of the energy balance and to decrease the heating as a result of the pressure balance. The additional pressure contributed by the magnetic fields results in a greater heating via the shear stress. This effect is similar to an increase in $\alpha$ and leads to an increase of evaporation rate in the inner region with little effect in the outer region. On the other hand, the additional pressure contribution inhibits the evaporation at all distances as a result of force balance. The combined effect of the magnetic field leads to little change in the value of the maximal evaporation rate, but does lead to an inward shift of the maximal evaporation region to a smaller distance. As shown from our numerical calculations, the maximum evaporation rate varies only slightly with the magnetic field strength, parameterized by the ratio of gas pressure to the total pressure, $\beta$, though the truncation of the disk occurs at much smaller radii for smaller $\beta$ (for details see Qian et al. 2007). The dependence of the maximum evaporation rate and the corresponding truncation radius (which is the minimal truncation radius) on the magnetic field parameter for $\alpha = 0.3$ can be approximated by

$$m_{\text{max}} \approx 0.026\beta^{-0.41}$$ and $r_{\text{min}} \approx 209\beta^{4.97}$.  

(11)

Taking into account these two effects, we find that the maximal evaporation rate and corresponding truncation radius is dependent on the viscosity and magnetic parameters as (see Taam et al. 2012),

$$m_{\text{max}} \approx 0.38\alpha^{2.34}\beta^{0.41}$$

(12)

$$r_{\text{min}} \approx 18.80\alpha^{-2.00}\beta^{4.97}.$$  

(13)

An important feature of Equation (12) is that the transition accretion rate ($m_{\text{max}}$) strongly depends on the viscosity parameter. However, the influence of the magnetic field on $m_{\text{max}}$ is limited to within a factor of 1.33 from zero-magnetic field ($\beta = 1$) to an equipartition field ($\beta = 0.5$), as shown in Figure 1. This indicates that the accretion rate characterizing the state transition is primarily determined by the viscosity. On the other hand, the truncation radius is more sensitive to the magnetic field parameter than to the viscosity parameter. The increase in viscosity or magnetic field results in a decrease in the truncation radius before a transit to a soft spectral state, as shown in Figure 2. Hence, the observed transition luminosity (Eddington ratio) provides a constraint on the viscosity parameter and the observationally inferred truncation radius constrains the magnetic field parameter (see Equation (13)). An approximate estimate of the value of the viscosity and magnetic field parameters in terms of the transition accretion rate ($m_{\text{trs}}$) and the corresponding truncation radius ($r_{\text{trs}}$) is

$$\alpha = 0.20 \left(\frac{m_{\text{trs}}}{0.01}\right)^{0.459} \frac{r_{\text{trs}}^{0.038}}{100} \approx 0.20 \left(\frac{m_{\text{trs}}}{0.01}\right)^{0.459}.$$  

(14)
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Figure 2. The variation of the minimal truncation radius (in terms of the Schwarzschild radius) with respect to the viscosity parameter (left panel) and magnetic field parameter (right panel). An increase in $\alpha$ or $\beta$ and a decrease in $\beta$ results in a decrease in the truncation radius.

$\beta = 0.73 \left( \frac{\dot{m}_{\text{trs}}}{0.01} \right)^{0.185} \left( \frac{r_{\text{trs}}}{100} \right)^{0.216}$.  

These equations show that the viscosity parameter is determined by the transition accretion rate, which is little affected by the uncertainty in the truncation radius. On the other hand, the magnetic field parameter is constrained by both the transition accretion rate and the corresponding innermost radius. Such results can be understood as follows. A transition is triggered when the mass supply rate reaches the maximal mass evaporation rate. This maximal evaporation rate depends strongly on the viscosity parameter ($\propto \alpha^{2.34}$) because an increase in $\alpha$ leads to efficient heating in the inner corona. The effect of the magnetic field on the maximal evaporation rate is much weaker than the effect of viscosity due to a competition between its tendency to increase the evaporation as a result of energy balance and to decrease the evaporation as a result of pressure balance. Thus, the transition accretion rate is mainly determined by the viscosity, providing a constraint on $\alpha$. However, the corresponding truncation radius depends both on $\beta$ and $\alpha$.

Objects with very low accretion rates are far from the transition state. In this case, the disk is truncated at a large distance, $r_t > r_{\text{trs}}$. The truncation radius depends not only on the viscosity and magnetic field parameters, but also on the accretion rate. An approximate fit to the numerical data for $\alpha = 0.3$ and $\beta = 1$ yields an expression for the truncation radius given by

$r_t \approx 15.9 \dot{m}^{-0.886}$.  

This relation is extrapolated for different values of the viscosity and magnetic field parameters as (for details see Taam et al. 2012),

$r_t \approx 940 \left( \frac{\dot{m}}{0.01} \right)^{-0.886} \left( \frac{\alpha}{0.3} \right)^{0.07} \beta^{4.61}$,  

which is only valid for accretion rates less than half of the maximal accretion rate. The dependence of truncation radius on the magnetic field parameter and the accretion rate is shown in Figure 3. It can be seen from the figure and Equation (17) that the truncation radius is strongly dependent on the magnetic field parameter, while it is only very weakly dependent on the viscosity parameter, unlike the minimal truncation radius at transition (Equation (13)). That is, the viscous parameter little affects the truncation radius if $\alpha$ in the hot accretion flow is not significantly different from 0.3. Therefore, the magnetic field parameter can also be constrained by the accretion rate and truncation radius from spectral fits to the observations of low/hard state objects by the expression

$\beta \approx \left( \frac{\dot{m}}{0.01} \right)^{0.192} \left( \frac{r_t}{1000} \right)^{0.217}$.  

We note from Equations (14) and (15) or (18) that the viscosity and magnetic field parameters predicted by the disk evaporation model are in a range, i.e., $\alpha \sim 0.1–0.5$ and $\beta \sim 0.5–1$ for the typical accretion rate and truncation radius either immediately before transition or in the low hard state. The values of $\alpha$ and $\beta$ do not vary steeply with accretion rate and truncation radius. Therefore, we expect that the viscosity and magnetic field parameters can be approximately constrained by combining

Figure 3. The variation of the truncation radius (in terms of the Schwarzschild radius) with respect to the magnetic field parameter $\beta$ in the low/hard state as predicted by the disk evaporation model. The truncation radius depends strongly on the magnetic field. The effect of the accretion rate is shown by the different curves. Since there is little influence from the viscosity parameter, $\alpha$ is fixed at 0.3.
the model predictions and observational data, provided that the spectral state transition and disk truncation are determined (Meyer et al. 2000b; Liu et al. 2002; Liu & Taam 2009; Taam et al. 2012).

3. CONSTRAINTS ON THE VISCOSITY AND MAGNETIC FIELDS FROM OBSERVATIONS

Given the mass of the black hole and the luminosity of objects near transition, the accretion rate ($\dot{m}_{\text{tr}}$) can be determined. The viscosity parameter is estimated from the disk evaporation model; that is, $\alpha$ is calculated from Equation (14) where the truncation radius can be taken as $100R_{\text{G}}$ as its value only very slightly affects $\alpha$. If this radius during transition can also be determined from the fitting of observed spectra, then the magnetic field parameter can be estimated from Equation (15). In this manner, both the viscosity and magnetic field parameters in objects at state transition are constrained. For objects in a very low state, which are far from the transition state, the magnetic field parameter is estimated from Equation (18), if the accretion rate and truncation radius can be determined from modeling the observed spectrum. However, the viscosity parameter for systems in a very low state can not be well constrained by the disk evaporation model since it does not affect the evaporation rate at large distances (see Equation (17)).

3.1. Constraint from Statistical Investigations

Observationally, it is very difficult to detect the state transition of AGNs as the timescale for global accretion flow variability for supermassive black holes is much longer than for BHXRBs. Thus, it is not possible to constrain the viscosity directly from the transition luminosity, as has been done in BHXRBs (Qiao & Liu 2009). Nevertheless, evidence has been presented for a change in the accretion mode based on large-amplitude X-ray variability (Yuan et al. 2004) and the break of the X-ray photon index (see Constantin et al. 2009). The turning point in the relation between the photon index and the Eddington ratio occurs near $L/L_{\text{Edd}} \approx 0.01$ (Constantin et al. 2009), which is similar to that exhibited by BHXRBs, and provides empirical evidence for an intrinsic switch in the accretion mode. This yields an estimate for the averaged value of $\alpha$ at a transition of $\sim 0.2$ as calculated from Equation (14).

In a recent complementary investigation by Best & Heckman (2012), a similar conclusion is deduced based on a large sample of radio-loud AGNs, showing that sources characterized by highly excited optical emission features typically have accretion rates between 1% and 10% of the Eddington rate, whereas low-excitation sources predominately accrete at rates below 1% Eddington. This implies a change of accretion mode taking place at an Eddington ratio of 0.01 from a thin disk in the high-excitation sources to an ADAF in the low-excitation sources. The value of the viscosity parameter is also estimated to be $\alpha \sim 0.2$ in average based on the critical accretion rate of 0.01 for these radio loud AGNs.

3.2. Constraint from Spectral Fits to AGN-powered LINERs

Radiations in the optical, UV, and X-ray bands of AGNs are commonly thought to originate from a cold disk and hot accretion flow. To fit the observed optical, UV, and X-ray (and even radio) emissions of LLAGNs, a truncated disk connected to an inner ADAF is often adopted. The accretion rate and truncation radius of the disk are determined from spectral fits, as shown by Quataert et al. (1999), Yuan & Narayan (2004), Xu & Cao (2009), and Nemmen et al. (2006, 2013). Specifically, the accretion rate and truncation radius are taken as the main fitting parameters. The overall continuum from radio to X-rays is dominantly produced by the ADAF, where the mass flow rate (expressed as a function of radius, $\dot{m} \propto r^\beta$ for $r < \alpha r_{\text{tr}}$) determines the spectral shape. The truncated disk can contribute to the optical/UV or infrared as its strength and peak frequency depend on the truncated radius and accretion rate. The fitting results from the literature have been compared with the disk evaporation model in detail in Taam et al. (2012). In Table 1, we list the accretion rate and truncation radius determined from the spectral fits to LINERs, and the values for the inferred viscosity and magnetic field parameters. It can be seen that the viscosity parameter is $\sim 0.2$–0.33 and the magnetic field parameter is $0.5 < \beta < 1$. The inferred values of $\beta$ indicate that the magnetic pressure is less than or comparable to its equipartition value with gas pressure.

| Source | $\dot{m}/\dot{m}_{\text{Edd}}$ | $\alpha/\beta$ | $\alpha$ | $\beta$ | Reference |
|--------|-----------------|----------------|---------|---------|-----------|
| M81    | 0.01            | 1              | 0.2     | 0.73    | (1)       |
| NGC 4579 | 0.02        | 1              | 0.33    | 0.89    | (2)       |
| XMM J021822.3–050615.7 | 0.01 | 2              | 0.2     | 0.66    | (3)       |
| NGC 1097 | 6.4 × 10$^{-3}$ | 3              | ...     | 0.67    | (4)       |
| M87    | 10$^{-4}$       | 3              | ...     | 1       | (5)       |
| NGC 3398 | 10$^{-3}$   | 3              | ...     | $\geq 0.56$ | (6)       |
| NGC 4278 | 10$^{-3}$ | 3              | ...     | 0.51    | (7)       |

Notes. Objects with relatively high accretion rates are assumed to be near transition so that both $\alpha$ and $\beta$ can be constrained, whereas objects with small accretion rates are regarded as in low/hard state, and hence only $\beta$ can be constrained. References. (1) Quataert et al. 1999; (2) Yuan & Narayan 2004; (3) Nemmen et al. 2013.

3.3. Constraint from Spectral Fits to Simultaneous Optical-to-X-Ray Observations of AGNs

Recently, Vasudevan & Fabian (2009) and Vasudevan et al. (2009) modeled the simultaneous optical to X-ray emission of AGNs with a full disk (extending to the ISCO) plus a power law. From the spectral fits over a wide wavelength coverage the bolometric luminosity and hard X-ray luminosity can both be determined, thus allowing a determination of the bolometric correction for observations based on hard X-rays alone, defined as the ratio of the bolometric luminosity to the 2–10 keV luminosity. For the low absorption AGN sample (Vasudevan et al. 2009) the bolometric corrections for the hard X-rays (2–10 keV) are found to cluster within 10–20, with the hard X-ray photon indices ranging from 1.5 to 2. These features are in contrast to the properties of high luminosity AGNs (HLAGNs; Vasudevan & Fabian 2009) and are more similar to LLAGNs (Ho 2008). Combining the spectrum features with the low Eddington ratios (mostly a few percent or lower) for this sample, we speculate that the objects are in an intermediate state, where the emission can originate from an ADAF surrounded by a corona and a disk truncated at a small radius. In this case, the optical radiation from these objects can be fit by a thermal spectrum produced by a multi-color blackbody from the truncated disk. This can be seen from the effective temperature of a truncated
Figure 4. The multi-color blackbody spectrum for a typical LLAGN with black hole mass of $10^8 M_\odot$ and accretion rate $\dot{M} = 0.02 \dot{M}_{\text{Edd}}$. Curves are labeled corresponding to a truncation radius $R_\text{tr} = 3 R_s, 30 R_s, 100 R_s, 200 R_s$. The disk emission extends to higher wavebands (i.e., optical or UV) with decreasing truncation radius.

Figure 5. The distribution of the viscosity parameter of AGNs listed in Tables 1 and 2. It is shown that the value of viscosity parameter is clustered in 0.2–0.3.
Table 2
Viscosity Parameter Constrained from Simultaneous Optical-to-X-Ray Observations of AGNs

| Source                | $\Gamma$ | $k_{2-10\text{ keV}}$ | $L_{\text{bol}}/L_{\text{Edd}}$ | Reference | Viscosity Parameter $\alpha$ |
|-----------------------|----------|------------------------|---------------------------------|-----------|-------------------------------|
| 1RXS J045205.0+493248| 1.86     | 12                     | 0.067                           | 1         | 0.48                          |
| 2MASX J21140128+8204483| 1.85    | 8.1                    | 0.025                           | 1         | 0.30                          |
| 3C 120                | 1.78     | 12.4                   | 0.030                           | 1         | 0.33                          |
| 3C 390.3(1)           | 1.74     | 6.33                   | 0.047                           | 2         | 0.41                          |
| 3C 390.3(2)           | 1.75     | 9.29                   | 0.074                           | 1         | 0.50                          |
| Ark 120               | 1.90     | 17.79                  | 0.028                           | 1         | 0.32                          |
| ESO 490-G026          | 1.91     | 12.1                   | 0.022                           | 1         | 0.29                          |
| ESO 548-G081          | 2.03     | 13.06                  | 0.015                           | 1         | 0.24                          |
| Fairall 9             | 1.81     | 10.5                   | 0.019                           | 2         | 0.27                          |
| IRAS 05589+2828       | 1.61     | 11.2                   | 0.008                           | 1         | 0.18                          |
| MCG +04−22−042        | 1.94     | 12.97                  | 0.021                           | 1         | 0.28                          |
| Mrk 1018              | 1.95     | 12.07                  | 0.027                           | 1         | 0.31                          |
| Mrk 279               | 1.88     | 9.83                   | 0.007                           | 1         | 0.17                          |
| Mrk 509               | 1.83     | 14.84                  | 0.019                           | 1         | 0.27                          |
| Mrk 590               | 1.88     | 8.8                    | 0.01                             | 2         | 0.20                          |
| Mrk 79                | 1.91     | 10.5                   | 0.031                           | 2         | 0.34                          |
| Mrk 841               | 1.89     | 16.9                   | 0.021                           | 1         | 0.28                          |
| NGC 3783(1)           | 1.53     | 7.02                   | 0.043                           | 2         | 0.39                          |
| NGC 3783(2)           | 1.50     | 8.0                    | 0.036                           | 2         | 0.36                          |
| NGC 4051              | 2.07     | 15.1                   | 0.015                           | 2         | 0.24                          |
| NGC 4151(1)           | 1.50     | 15.64                  | 0.056                           | 2         | 0.44                          |
| NGC 4151(2)           | 1.50     | 17.38                  | 0.062                           | 2         | 0.46                          |
| NGC 4593(1)           | 1.87     | 7.7                    | 0.037                           | 2         | 0.36                          |
| NGC 4593(2)           | 1.62     | 9.89                   | 0.009                           | 1         | 0.19                          |
| NGC 5548(1)           | 1.65     | 10.1                   | 0.024                           | 2         | 0.30                          |
| NGC 5548(2)           | 1.51     | 8.8                    | 0.009                           | 1         | 0.19                          |
| NGC 7469              | 1.98     | 14.33                  | 0.010                           | 1         | 0.20                          |
| NGC 985               | 1.80     | 12.3                   | 0.020                           | 1         | 0.28                          |
| WKK 1263              | 1.68     | 23                     | 0.032                           | 1         | 0.34                          |

References. (1) Vasudevan et al. 2009; (2) Vasudevan & Fabian 2009.

We point out that the Eddington ratio inferred from the spectral fits is smaller when a truncated disk is used to model the optical observations than when modeled by a full disk (Vasudevan et al. 2009; Vasudevan & Fabian 2009). This follows from the fact that there is no contribution from the inner region cut out from the disk, leading to a smaller disk luminosity (see Figure 4). This effect can be approximately neglected when the X-rays from the ADAF and the corona are the dominant component to the bolometric luminosity. With a small bolometric correction to the 2–10 keV luminosity for objects listed in Table 2, the Eddington ratios calculated from the spectral fits with a full disk+power law (Vasudevan & Fabian 2009; Vasudevan et al. 2009) are a reasonable approximation to the intrinsic Eddington ratio even if the innermost disk is truncated. We note that a decrease in the Eddington ratio by a factor of five, for example, due to the absence of an innermost disk, leads to only a decrease in the estimated viscosity parameter by a factor of two, for which $\alpha$ would be in a range of 0.1–0.25. Accurate spectral fits to the sources are reserved for a future study, but it will only slightly modify the value of the inferred viscosity parameter.

If the broad line region is associated with the disk through winds (e.g., Emmering et al. 1992), then the truncation of the disk leads to the truncation of the broad line region (Liu & Taam 2009). The presence of broad emission lines could be in conflict with a model where the inner disk is truncated. However, the disk is not truncated at a large distance ($R \lesssim 200 R_S$) for objects with relatively high accretion rates and relatively strong magnetic fields. The emission lines can still occur, though they would not be expected to be very broad. This is not in contradiction with the fact that emission lines are observed in some of the objects listed in Table 2.

4. DISCUSSION AND CONCLUSION

The viscosity and magnetic field parameters in the accretion flow around black holes are estimated for low and intermediate luminosity AGNs. According to the disk corona evaporation/condensation model, the accretion in low-accretion systems occurs via an inner ADAF connected to an outer disk as a consequence of the interaction between the disk and corona. The truncation radius of the thin disk in the low hard state is determined by the accretion rate, magnetic field, and viscosity parameters. A transition from an ADAF dominant accretion state to a full geometrically thin disk is triggered when the accretion rate reaches a critical value dependent on the viscosity parameter. In the framework of this model, the viscosity parameter in the hot accretion flow is constrained from the observed transition luminosity, and the magnetic field parameter can be estimated from the spectral fits to the low hard states. It is found that the viscosity parameter is $\sim 0.17$–0.5, but with values clustered about 0.2–0.3. Such values are consistent with those inferred from BHXRBs, which undergo outburst and are high compared to those deduced from hydrodynamical turbulence models (e.g., Kato 1994) and from MHD simulations (for a review see King et al. 2007). The magnetic field parameter is found to range from 1 to 0.5, corresponding to disk truncation where magnetic field effects are unimportant to cases where the magnetic pressure is in equipartition with the gas pressure.
4.1. Origin of Hard X-Ray Emissions

The hard X-ray emission in the low/hard state is assumed to originate from the ADAF in this study. This is reasonable for objects with Eddington ratios higher than $10^{-6}$–$10^{-3}$ according to the prediction of Yuan & Cui (2005). Observational investigations of AGN-powered LINERs support an ADAF origin, however, the contribution of a jet based on the fits to the fundamental plane (Younes et al. 2012) cannot be excluded. In addition, spectral fits to the LLAGN (Nemmen et al. 2013) also show that both the jet and ADAF can fit the spectrum with different parameters for most of the objects in their sample.

A high-spatial resolution study of the spectral energy distribution (SED) of the nearest LLAGNs (Fernández-Ontiveros et al. 2012) shows a large diversity in the SED shapes in the LLAGN sample, some of which are very well described by the self-absorbed synchrotron process, while others present a thermal-like bump at ~1 μ. The SEDs in the sample intrinsically differ from the SEDs of bright AGNs, suggesting that the inner accretion flow of AGNs undergoes changes with the decrease of the mass accretion rate, probably from a thin accretion disk to an ADAF.

4.2. The Compton Effect

Compton scattering can become especially important for a strong external seed photon field, contributed by the central accretion flow and local underlying disk. In the low/hard states as considered here, the radiation from the inner ADAF is inefficient. Radiations from the outer disk are important for Compton cooling only at accretion rates close to the maximal evaporation rate. This can cause a decrease in the maximal evaporation rate by a factor of ~1/2, leading to an underestimate of the viscosity parameter by a factor of ~1.3 for objects near transition. If a magnetic field is taken into account, then it leads to a decrease of the evaporation rate at a given distance. As a consequence, the coronal density decreases and the disk radiation increases as more mass remains in the disk. The net result is that the Compton effect for disks with a magnetic field would be similar to the case without a magnetic field, as estimated above. Nevertheless, since the disk is truncated at a smaller region before state transition, the Compton scattering could be important at small distances. We plan to investigate this possibility in the future.

The existence of a geometrically thin disk at the transition from the soft to hard state, in contrast to the transition from the hard to soft state, results in strong Compton cooling of the corona. This leads to a lower transition luminosity compared to that from the hard to soft state transition. Such an effect has been interpreted as due to a hysteresis effect in the state transitions observed in the outbursts of BHXRBs (Meyer-Hofmeister et al. 2005; Liu et al. 2005). If the analogy of the accretion process in stellar mass black holes to super massive black holes extends to this phenomena as well, then the AGNs with intermediate luminosities (corresponding to accretion rates ~0.006–0.03) can be either in a soft state approaching a transition to a hard state, or in a hard state evolving toward a soft state. An object evolving from a disk dominant state could lead to an underestimate of the parameters by up to a factor of two. This could be the case for some of the objects listed in Table 2. That is, an object evolves close to disk truncation, with most of the disk gas evaporated into the corona, leading to a weak un-truncated disk and relatively strong corona.

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A recent investigation on the local-radio AGN populations shows that the distribution of Eddington-scaled accretion rates in the high excitation radio galaxies (HERG) is distinctly higher, on average, than in the low excitation radio galaxies (LERG), supporting the scenario of thin disk dominant accretion in HERG and an ADAF dominant accretion in LERG (Best & Heckman 2012). The overlap region in Eddington ratio for LERG and HERG may be analogous to the intermediate state observed in BHXRBs. Here, systems evolving from a soft state to this intermediate state could exhibit high excitation lines with relatively weak radio emission, whereas systems evolving from the hard state may be characterized as low excitation radio loud sources. The overlap region corresponding to an Eddington ratio in the range of 0.001 to 0.03, as shown in Figure 6 of Best & Heckman (2012), suggests an intriguing connection within the framework of such a model.

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