ESTIMATING SUPERMASSIVE BLACK HOLE MASS THROUGH RADIO/X-RAY LUMINOSITY RELATION OF X-RAY BRIGHT GALACTIC NUCLEI

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ABSTRACT

It has been suggested that optically thin and geometrically thick accretion flows are responsible for the observed radio/X-ray luminosity relation of the X-ray bright galactic nuclei. If this is the case then central supermassive black hole masses can be estimated directly from measurements of the core radio luminosity and the X-ray luminosity, provided that properties of such accretion flows are known. Calculated ratios of the luminosities are presented in cases of the standard ADAF model and modified ADAF models, in which a truncation of inner parts of the flows and winds causing a reduction of the infalling matter are included. We compare the observed ratio of the luminosities with predictions from models of optically thin accretion flows. We also discuss the possible effects of the convection in ADAFs. We confirm that the supermassive black hole (SMBH) mass estimate is possible with the radio/X-ray luminosity relation due to ADAF models in the absence of a radio jet. We find that observational data are insufficient to distinguish the standard ADAF model from its modified models. However, the ADAF model with convection is inconsistent with observations, unless microphysics parameters are to be substantially changed. High resolution radio observations are required to avoid the contamination of other components, such as, a jet component. Otherwise, the SMBH mass is inclined to be over-estimated.

Subject headings: accretion disks – black hole physics – galaxies : nuclei – radiation mechanisms : nonthermal – radio continuum : galaxies – X-rays : galaxies
1. INTRODUCTION

Since the early days of research on quasars and active galactic nuclei (AGNs), supermassive black holes (SMBHs) have been considered as the most likely power sources of the activity in these objects (Lynden-Bell 1969; Rees 1984). SMBHs at the centers of all galaxies are now recognised as ubiquitous, whose mass $M_{\text{SMBH}}$ is proportional to the spheroidal bulge mass of the host galaxy or the galactic bulge luminosity (Kormendy & Richstone 1995; Magorrian et al. 1998; Richstone et al. 1998). Evidence for the existence of SMBHs has been found in the center of our Galaxy (Eckart & Genzel 1997; Genzel et al. 1997; Ghez et al. 1998) and in the weakly active galaxies NGC 1068, NGC 4258 (Miyoshi et al. 1995). Asymmetric Fe Kα emission in the X-ray spectra of AGNs (e.g., Tanaka et al. 1995) may show a signature of SMBHs, but this remains somewhat speculative as Fe Kα reverberation signature have not yet been observed (e.g., Reynolds 2000).

Searches for SMBHs are based on spatially resolved kinematics. In the case of AGNs, however, direct detection of nuclear SMBHs through stellar-dynamical methods has not been achieved due to technical difficulties. The reason is that bright AGNs are too bright to resolve the light from the surrounding stars and gas, and from the AGN itself on arcsecond and smaller angular scales. Reverberation mapping (Blandford & McKee 1982) avoids this problem. In this technique, the time delayed response of the emission lines to continuum variations is used to infer a size of the line-emitting region. We also have a velocity $V$, which is obtained from measurements of the Doppler widths of the variable line components. Combining these, a virial mass is estimated by $M_{\text{SMBH}} \approx V^2 R/G$, where $G$ is the gravitational constant.

On the other hand, several authors have pointed out that reverberation mapping yields systemically smaller SMBH masses at a given bulge luminosity than do dynamical models of spatially resolved kinematics (e.g., Wandel, Perterson, & Malkan 1999). In the case of
normal galaxies, the SMBH mass appears to correlate with the galactic bulge luminosity, with the SMBH to spheroidal bulge mass ratio $M_{\text{SMBH}}/M_{\text{bulge}} = 0.006$ (Magorrian et al. 1998; Richstone et al. 1998). In the case of AGNs, however, a significantly lower value of $M_{\text{SMBH}}/M_{\text{bulge}}$ has been found (Wandel 1999), indicating either a real difference between active and inactive galaxies, or that one or both of the methods of mass determination is somehow biased. Gebhardt et al. (2000) claim that masses derived from reverberation mapping are consistent with the recently discovered relation between the SMBH mass and the galaxy velocity dispersion derived from spatially resolved kinematics.

Another possible way to infer the presence of SMBHs and to shed light on the physical condition is to examine spectral energy distribution over a wide range from the radio to the hard X-ray frequencies (e.g., Frank et al. 1992; Ho 1999). This emission spectrum is produced by an accreting matter, as the surrounding gas accretes onto the central SMBH. In such flows the core radio luminosity is low and dependent on the mass of the central SMBH (Ichimaru 1977; Rees et al. 1982; Narayan & Yi 1994, 1995a,b; Abramowicz et al. 1995). It has been suggested that advection-dominated accretion flows (ADAFs) are responsible for the observed radio and X-ray luminosities of some of the X-ray bright galactic nuclei (Fabian & Rees 1995; Di Matteo & Fabian 1997; Yi & Boughn 1998, 1999). In this case the central SMBH masses can be estimated directly from measurements of the X-ray and the core radio luminosities, provided that properties of such accretion flows are known. We demonstrate that it is relatively effective and consequently suitable to estimate SMBH masses of many candidates using a method we present in this paper.

This paper begins with model descriptions for the standard ADAF model and modified versions of the model in § 2. We deduce analytical expressions to describe the radio/X-ray luminosities for various models in § 2. We present the calculated ratios of the luminosities and compare them with the observational data in § 3. We discuss possible roles of the
convection in ADAFs and conclude in § 4.

2. RADIO/X-RAY EMISSION FROM ACCRETING SMBHs

When a mass accretion rate is below a critical rate, the radiative cooling is slower than the viscous heating. As a result of this, the dissipated accretion energy is inefficiently radiated away and advected inward to the central object with the accreted matter (see Narayan and Yi 1995b and references therein). The ions are heated by viscous dissipation at a rate of $q^+$ per unit volume and the heating is parameterised by the viscosity parameter $\alpha$. Since this flow is optically thin, the energy transfer from the ions to the electrons is inefficient so that the ions reach the virial temperature. The electrons cool via synchrotron, bremsstrahlung, and inverse Compton processes. Synchrotron radiation is responsible for the radio to submillimeter emission, bremsstrahlung emission and inverse-Compton scattering are submillimeter to X-ray emission. Detailed numerical calculations have been performed (Narayan et al. 1998), and the resulting spectra have been successfully applied to a number of extra galactic systems which are supposed to harbor SMBHs (e.g., Narayan et al. 1995; Lasota et al. 1996; Manmoto et al. 1997).

In this study we apply analytical scaling laws for self-similar solutions (Narayan & Yi 1994; Mahadevan 1997). We adopt the following dimensionless variables: mass of the SMBH $m = M/M_\odot$; radius from the SMBH $r = R/R_g$, where $R_g = 2GM/c^2 = 2.95 \times 10^5m$ cm; and mass accretion rate $\dot{m} = \dot{M}/\dot{M}_{\text{Edd}}$, where $\dot{M}_{\text{Edd}} = L_{\text{Edd}}/\eta_{\text{eff}}c^2 = 1.39 \times 10^{18}m$ g s$^{-1}$ (the Eddington accretion rate assuming $\eta_{\text{eff}} = 0.1$). We assume that the flows are spherically symmetric. The advection fraction $f$ is determined such that the ion and electron energy balance equations are met. The quantities of interest are the volume-integrated quantities which are obtained by integrating the heating rate and each cooling rates throughout the volume of the flows. As canonical values in a model for ADAFs parameters are taken to be
\( r_{\text{min}} = 3, \ r_{\text{max}} = 10^3, \ \alpha = 0.3, \ \text{and} \ \beta = 0.5 \) (see, e.g., Narayan & Yi 1995b). In this study, we assume that the electron temperature is constant for \( r < 10^3 \), as suggested by Narayan & Yi (1995b). For given \( m, \dot{m}, \alpha, \beta \), we may obtain the energy density spectrum with \( f, T_e \) determined as described below.

### 2.1. Emission from 'Standard' ADAFs

The ions are heated by the viscous dissipation and the electrons gain energy from the ions by Coulomb interactions alone. We neglect the possibility of heating the electrons, since we expect that the fraction of viscous energy transferred to the electrons is in the mass ratio of the electron to the ion, \( \sim 1/2000 \).

The synchrotron photons are self-absorbed and give a blackbody radiation upto a critical frequency, \( \nu_c \). For a given \( T_e \), the synchrotron spectrum \( L_\nu^{\text{sync}} \) is given by

\[
L_\nu^{\text{sync}} = s_3(s_1s_2)^{8/5}m^{6/5}\dot{m}^{4/5}T_e^{21/5}\nu^{2/5},
\]

where \( s_1 = 1.42 \times 10^9\alpha^{-1/2}(1 - \beta)^{1/2}c_1^{-1/2}e_3^{-1/2} \), \( s_2 = 1.19 \times 10^{-13}x_M \), and \( s_3 = 1.05 \times 10^{-24} \).

\( x_M \equiv 2\nu/3\nu_0\theta_0^2 \), \( \nu_0 \equiv eB/2\pi m_e c \) (Narayan & Yi 1995b; Mahadevan et al. 1996; Mahadevan 1997). The radio luminosity \( L_R \) at \( \nu \) is defined by \( \nu L_\nu \). The highest radio frequency arises from the innermost radius of the accretion flows, \( r_{\text{min}} \sim 3; \ \nu_p = s_1s_2m^{-1/2}\dot{m}^{1/2}T_e^{-7/4}r_{\text{min}}^{-5/4} \). At this peak frequency the peak radio luminosity is given by

\[
L_R \equiv L_\nu^{\text{sync}} = s_3(s_1s_2)^{3}m^{1/2}\dot{m}^{3/2}T_e^{7}r_{\text{min}}^{-7/4}.
\]

We set \( \nu_{\text{min}} = 0 \), since \( \nu_{\text{min}} \) is much smaller than \( \nu_p \).
Bremsstrahlung emission is due to both electron-electron and electron-ion interactions. The total bremsstrahlung power is given by

$$P_{\text{brem}} = 4.74 \times 10^{34} \alpha^{-2} c^{-2}_1 \ln(r_{\text{max}}/r_{\text{min}}) F(\theta_e) \dot{m} r^2,$$

and the spectrum due to bremsstrahlung emission is given by

$$L_{\nu}^{\text{brem}} = 2.29 \times 10^{34} \alpha^{-2} c^{-2}_1 \ln(r_{\text{max}}/r_{\text{min}}) F(\theta_e) \dot{m} r^2 T^{-1}_e \exp(-h\nu/kT_e),$$

where

$$F(\theta_e) = 4 \left( \frac{2\theta_e}{\pi^3} \right)^{1/2} (1 + 1.781 \theta_e^{3.4}) + 1.73 \theta_e^{3/2} (1 + 1.1e + \theta^2 - 1.25 \theta^{5/2}), \quad \theta_e < 1,$$

$$= \left( \frac{9\theta_e}{2\pi} \right)[\ln(1.123\theta_e + 0.48) + 1.5] + 2.3 \theta_e (\ln 1.123\theta_e + 1.28), \quad \theta_e > 1.$$  

In this study we neglect the Comptonization of bremsstrahlung emission, and consider the Comptonization of synchrotron emission alone. A contribution by Compton up-scattered synchrotron photons to the hard X-ray luminosity becomes important as $\dot{m}$ increases, while bremsstrahlung emission dominates the hard X-ray luminosity when $\dot{m}$ is substantially low.

We approximate the Comptonized spectrum by assuming that all the synchrotron photons to be Comptonized have an initial frequency of $\nu_p$. The maximum final frequency of the Comptonized photon is $\nu_f = 3kT_e/h$, which corresponds to the average energy of the photon for saturated Comptonization in the Wien regime. On average, we assume that all the photons would see one half the total optical depth (Mahadevan 1997), which is written as $\tau_{es} = 6.2 \alpha^{-1} c^{-1}_1 \dot{m} r^{-1/2}$. The spectrum of the emerging photons at frequency $\nu$ has the power-law shape

$$L_{\nu}^{\text{Comp}} \simeq L_{\nu_i} \left( \frac{\nu}{\nu_i} \right)^{-\alpha_c},$$

where $\alpha_c \equiv -\ln \tau_{es}/\ln A$. The total Compton power is therefore given by

$$P_{\text{comp}} = \int_{\nu_p}^{3kT_e/h} L_{\nu}^{\text{Comp}} d\nu.$$
\[ \nu_p L_{\text{sync}} = \frac{\nu_p L_{\text{sync}}}{1 - \alpha_c} \left\{ \left[ \frac{6.2 \times 10^{10} T_e}{\nu_p} \right]^{1-\alpha_c} - 1 \right\}, \tag{8} \]

where \( A \) is the mean amplification factor in a single scattering.

For given \( m, \dot{m}, \alpha, \beta \), the total heating of the electrons should be balanced to the sum of the individual cooling, \( Q^{ie} = P_{\text{sync}} + P_{\text{brem}} + P_{\text{comp}} \). The electron temperature is varied until this equality is satisfied.

### 2.2. Emission from Truncated ADAFs and ‘Windy’ ADAFs

ADAFs have the positive Bernoulli constant and, therefore, are susceptible to outflows (Narayan & Yi 1994). It might be the case that radio jets are present near the inner region of ADAFs. If so, the radio luminosity is dominated by jet emission. Instead, radio emission due to ADAFs at the high frequency will be suppressed. In order to simulate this situation, we truncate ADAFs at a certain inner radius. We suppose that the truncation occurs at 25\( r_g \). For instance, an observation of NGC 4486 (M87) indicates that the jet is formed in a smaller radius than \( r \approx 30r_g \) (Junor et al. 1999). This is also about where is the maximum radius that 15 GHz radio emission could be generated for \( m = 10^7, \dot{m} = 10^{-3}, T_e = 10^9 \).

Note that \( r = (1/60)^{-4/5} \times (\nu/15 \text{ GHz})^{-4/5}(m/10^7)^{-2/5}(\dot{m}/10^{-3})^{2/5}(T_e/10^9)^{8/5} \). We set \( r_{\text{min}} \) in equations in the previous subsection to 25\( r_g \) instead of 3\( r_g \) in corresponding equations in this case.

Since the gas in ADAF solutions is generically unbound, winds may carry away infalling matter (see, e.g., Blandford & Begelman 1999; Di Matteo et al. 1999; Quataert & Narayan 1999). We allow \( \dot{m} \) to vary as \( \dot{m} = \dot{m}_{\text{out}}(r/r_{\text{out}})^p \) (see, e.g., Blandford & Begelman 1999). The mass loss causes a significant effect on a model spectrum for a large value of \( p \) (Quataert & Narayan 1999). Bremsstrahlung emission decreases with increasing \( p \), synchrotron emission decreases strongly with increasing \( p \) due both to the lower density
and to the lower $T_e$ near $r \sim 3$. Compton emission decreases with increasing $p$ even more strongly than the other two emissions since it depends both on $\nu_p L_{\nu_p}$ and $\alpha_c$. A wind model is incompatible with observation, if microphysics parameters we adopt in the standard ADAF model are more or less correct. This conclusion, however, is inconclusive since there are qualitative degeneracies between the wind parameter, $p$, and microphysics parameters, $\alpha, \beta$, particularly the viscous heating parameter of the electrons, $\delta$ (Quataert & Narayan 1999). As $\dot{m}$ is replaced by $\dot{m}_{\text{out}}(r/r_{\text{out}})^p$ equations for the ’Standard ADAFs’ are to be modified as described below. The total heating for ions $Q^+$ is rewritten as

$$Q^+ = 9.39 \times 10^{38} \frac{1 - \beta}{f} c_3 \dot{m}_{\text{out}} r_{\text{out}}^{-p} \frac{1}{p - 1} \left( r_{\text{max}}^{p-1} - r_{\text{min}}^{p-1} \right),$$  \hspace{1cm} (9)$$

where $p < 1$. Similarly, $Q^{ie}$ is given by

$$Q^{ie} = 1.2 \times 10^{38} g(\theta_e) \alpha^{-2} c_1^{-2} c_3 \dot{m}_{\text{out}}^{2} r_{\text{out}}^{-2p} \frac{1}{2p - 1} \left( r_{\text{max}}^{2p-1} - r_{\text{min}}^{2p-1} \right)$$  \hspace{1cm} (10)$$

where $p \neq 1/2$. We assume that $x_M$ and $T_e$ are constants with $r$ and $\dot{m}$ for simplicity as a first order approximation. Given $x_M$, the cutoff frequency at each radius is given as

$$\nu_c = s_1 s_2 m^{-1/2} r_{\text{out}}^{-p/2} T_e^{7/2} r^{-(2p-5)/4}. \hspace{1cm} (11)$$

The peak frequency and the radio luminosity at the peak frequency are correspondingly reduced so that we have

$$\nu_p L_{\nu_p}^{\text{sync}} = s_3 (s_1 s_2)^{3/2} m^{1/2} r_{\text{out}}^{3/2} r^{2p-7} T_e^{21/4 - 2p/2} \nu_p^{4p-2}. \hspace{1cm} (12)$$

The total synchrotron power is also rewritten by

$$P_{\text{sync}} \simeq \int_0^{\nu_p} L_{\nu_p}^{\text{sync}} d\nu = (2p - 5) \nu_p L_{\nu_p}^{\text{sync}}. \hspace{1cm} (13)$$

For bremsstrahlung emission the total power and the spectrum are respectively given by

$$P_{\text{brem}} = 4.74 \times 10^{34} \alpha^{-2} c_1^{-2} m^{2} r_{\text{out}}^{-2p} F(\theta_e) \frac{1}{2p} \left[ r_{\text{max}}^{2p} - r_{\text{min}}^{2p} \right], \hspace{1cm} (14)$$

$$L_{\nu_p}^{\text{brem}} = 2.29 \times 10^{24} \alpha^{-2} c_1^{-2} m^{2} r_{\text{out}}^{-2p} F(\theta_e) T_e^{-1} \exp(-h\nu/kT_e) \frac{1}{2p} \left[ r_{\text{max}}^{2p} - r_{\text{min}}^{2p} \right]. \hspace{1cm} (15)$$
Note that as the exponent $p$ approaches to 0, $[\frac{1}{2p}(r_{max}^{2p} - r_{min}^{2p})]$ becomes $\ln(r_{max}/r_{min})$. For the Comptonization of the synchrotron photons we take $\tau_{es}$ as $\tau_{es} = 6.2\alpha^{-1}c^{-1}\dot{m}_{out}^{-p}(r_{max}^{(2p-1)/2} - r_{min}^{(2p-1)/2})$. The Compton spectrum and the total Compton power are respectively given by

$$L_{\nu}^{\text{Comp}} \propto L_{\nu_i}(\frac{\nu}{\nu_i})^{-\alpha_c},$$

$$P_{\text{comp}} = \frac{\nu_p L_{\nu_p}^{\text{sync}}}{1 - \alpha_c} \left\{ \left[ \frac{6.2 \times 10^{10} T_e}{\nu_p} \right]^{1-\alpha_c} - 1 \right\}.$$  

3. BLACK HOLE MASSES AND RADIO/X-RAY LUMINOSITIES

Figure 1 shows a plot of the ratio of the 15 GHz radio luminosity to the 2-10 keV X-ray luminosity versus the X-ray luminosity. The solid lines are standard ADAF model predictions for SMBH masses of $10^6 - 10^9 M_\odot$, the dotted lines are ADAF model predictions with truncations at $25r_g$. The short dashed lines and the long dashed lines are ADAF model predictons with winds, where $p = 0.4$ and $p = 0.99$, respectively. When $p = 1$, results may represent a case where the convection is present in ADAFs (Quataert & Narayan 1999). For each curve, $\dot{m}$ or $\dot{m}_{out}$ for windy models varies from $10^{-4}$ (upper left corner) to $10^{-1.6}$ (lower right corner). The open circles denote the observed core radio luminosity at 15 GHz, and the filled circles the spatially resolved core radio luminosity which are converted from 5 GHz to 15 GHz using the $\nu^{7/5}$ power law. When the accretion rate $\dot{m}$ is large the change of the properties of the flows is considerable in the ratios. As long as the canonical model parameters remain unchanged, the ADAF models with large $p$, which represent the convection, seem to be ruled out by the observational data. In Figure 2, the core radio luminosity is shown as a function of the SMBH mass, with SMBH candidates whose mass estimates are available. From top to bottom, for each set of lines, the mass accretion rate corresponds to $10^{-2}$ and $10^{-4}$. The open circles indicate the observed core radio luminosity at 15 GHz, and the filled circles the converted core radio luminosity from 5 GHz to 15 GHz,
as in Figure 1. Although the radio flux data is in high angular resolution, there appears a somewhat wide range of radio luminosities, which is likely the result of radio jets or other components of various frequencies rather than pure ADAF emission. In Figure 3, the X-ray luminosity for the 2-10 keV band is shown as a function of the SMBH mass.

Radio flux values at 15 GHz of Sgr A*, NGC 1068 are quoted from Kormendy & Richstone (1995); Gallimore et al. (1996), NGC 3079, NGC 3628, NGC 4151, and NGC 4388 are quoted from Carral et al. (1990), NGC 3031 (M81), NGC 4258, NGC 4736 (M94), and NGC 5194 (M51) are quoted from Turner & Ho (1994), respectively. Radio flux data at 5 GHz of NGC 1365 and NGC 3310 are quoted from Saikia et al. (1994), and NGC 224 (M31), NGC 3377, NGC 4374 (M84), NGC 4486 (M87), and NGC 4594 (M104) are quoted from Franceschini et al. (1998), respectively.

X-ray fluxes (2-10 keV) of Sgr A*, NGC 224, NGC 1068, NGC 1365, NGC 3031, NGC 3079, NGC 3310, NGC 3628, NGC 4151, NGC 4258, NGC 4374, NGC 4388, NGC 4594, NGC 4736, and NGC 5194 are quoted from Koyama et al. (1996); Trinchieri et al. (1999); Turner et al. (1997); Iyomoto et al. (1997); Ishisaki et al. (1996); Cagnoni et al. (1998); Ptak et al. (1999); Ptak et al. (1998); Nandra et al. (1997); Makishima et al. (1994); Colbert & Mushotzky (1999); Iwasawa et al. (1997), Forster et al. (1999); Ptak et al. (1998); Roberts et al. (1999); Terashima et al. (1998), respectively. Quoted X-ray fluxes of NGC 4486 and NGC 3377 should be considered as upper limits (Reynolds et al. 1999; Pellegrini 1999). Note that the observed X-ray flux of NGC 3377 in the energy band of 0.2 - 4 keV is converted to the value in the energy band of 2 - 10 keV, assuming a power-law with the canonical spectral index for Seyfert 1 galaxies, i.e., $\Gamma = 1.7$. High resolution X-ray images have revealed discrete X-ray sources for NGC 224 (Trinchieri et al. 1999), NGC 3031 (Ishisaki et al. 1996), NGC 4736 (Roberts et al. 1999). For these sources we adopt core or bulge X-ray fluxes.
The mass estimates of Sgr A*, NGC 1068, NGC 3031 (M81), NGC 3079, NGC 4374 (M84), 4594 (M104) come from Eckart & Genzel (1997); Greenhill et al. (1996); Ho (1999); Ferrarese & Merritt (2000); Ho (1999); Ferrarese & Merritt (2000), respectively. NGC 224 (M31) is one of strongest SMBH candidates because of the fast rotation and the large velocity dispersion (Richstone et al. 1990). The estimates of SMBH mass come from Dressler & Richstone (1988), Bacon et al. (1994). NGC 224 seems to harbour a double nucleus (Lauer et al. 1993; Bacon et al. 1994). The mass estimate of NGC 3377 comes from Kormendy & Richstone (1995) and Magorrian et al. (1998). Besides M32, NGC 3377 is the second elliptical galaxy with stellar dynamical evidence for SMBHs. The mass of NGC 4151 have been measured by reverberation mapping method (Wandel et al. 1999; Gebhardt et al. 2000). The mass estimate of NGC 4258 comes from Miyoshi et al. (1995). NGC 4258 belongs to LINERs (e.g., Osterbrock 1989), which is one of successful applications of ADAFs (Lasota et al. 1996). The mass estimates of NGC 4486 (M87) come from Ford et al. (1994), Reynolds et al. (1996), Magorrian et al. (1998), and Ho (1999). NGC 4486 is a radio-loud elliptical galaxy with an optical jet which is approximately perpendicular to a disk of ionized gas.

4. DISCUSSION AND CONCLUSION

One of important predictions of the ADAF model is the radio/X-ray luminosity relation which can be directly used to estimate central SMBH masses. We demonstrate with an improved statistical significance that if ADAFs are confirmed by observations with a high angular resolution, the inherent radio/X-ray luminosity relation provides a direct estimate of the central SMBH mass. Several nearby extra galaxies have consistent ratios of radio to X-ray luminosities with the ADAF predictions for an estimated mass of the central SMBH. We plot ADAF model predictions for the radio/X-ray luminosities in terms of the
SMBH mass in Figure 1. The observations for several extra galactic objects are consistent with the predictions of ADAF models, as seen in Figures 2 and 3. Although the mass estimates of NGC 4374, NGC 4486, NGC 4594 appear more consistent with the predictions with truncated ADAF models or windy ADAF models, there is no obvious signs of the truncation or the wind in ADAFs. It is, however, interesting to note that the models with the convection are exclusive unless the microphysics in the standard ADAF model has to be modified significantly.

The predicted mass of NGC 224 (M31) is smaller than the estimated mass at least by two orders of magnitude. NGC 224 has an extremely low core radio luminosity, which is even lower than predicted with the mass accretion rate that the X-ray luminosity implies on the basis of an ADAF model. NGC 224 seems to harbor a double nucleus (Lauer et al. 1993; Bacon et al. 1994). It is unclear whether ADAF is viable under such circumstance. Predicted masses of NGC 1068, NGC 3031 (M81), NGC 3079, NGC 4151 are $\sim 10^8$ to $\sim 10^9$ $M_\odot$. On the other hand, reported mass estimates of SMBHs of these galaxies are less than $\sim 10^7$. Masses of these sources are over-estimated due to high radio luminosities resulting from strong jet-related activities. Moreover, uncertainties in X-ray flux measurements and intrinsic variations could cause errors in our predictions. NGC 1068 is famous in that it has a strong compact radio source, which results in a much higher radio/X-ray luminosity ratio than other Seyferts (Gallimore et al. 1996). The radio core of NGC 3031 (M81) is highly variable on many timescale (Ho 1999). Moreover, NGC 3031 is substantially brighter in X-rays relative to the UV than in luminous AGNs (Ho 1999), and its core luminosity in the 2-10 keV band varies by a factor of $\sim 2$ in a timescale of years (Ishisaki et al. 1996). The unresolved radio map of NGC 3079 at 15 GHz shows an intriguing feature, which appears just like a jet (Carral et al. 1990). The high radio luminosity may be due to an unresolved small-scale jet. The radio morphology of NGC 4151 suggests that the emitting material has been energized from the nucleus and that the
jet interacts with the ambient medium (Carral et al. 1990).

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Fig. 1.— A plot of the ratio of the radio luminosity to 2-10 keV X-ray luminosity versus the X-ray luminosity. The sources are spatially resolved, and the core luminosities are adopted in order to avoid possible contaminations due to other components such as jets. SMBH masses are denoted by the log scale at the top of each curve. See text for detailed discussions and references.

Fig. 2.— The core radio luminosity is shown as a function of the SMBH mass, with SMBHs whose masses are available. Mass accretion rates are denoted by the log scale at each line. Lines correspond to same models as in Figure 1 and symbols represent same observational data points as in Figure 1.

Fig. 3.— Similar plot as Figure 2. But the X-ray luminosity for the 2-10 keV band is shown, with the mass-known SMBHs. Lines correspond to same models as in Figure 1.
