Possible evidence for the disk origin for the powering of jets in Sgr A* and nearby elliptical galaxies

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ABSTRACT

Recent VLBA observation indicates the existence of an elongated (jet) structure in the compact radio source Sgr A*. This is hard to explain in the context of advection-dominated accretion flow (ADAF) model for this source. On the other hand, the mass accretion rate favored by ADAF is 10-20 times smaller than that favored by the hydrodynamical simulation based on Bondi capture. If the latter were adopted, the predicted radio flux would significantly exceed the observation. A similar situation exists in the case of nearby giant ellipticals, where the canonical ADAF model – the widely assumed standard model for these sources – also significantly overpredict the radio flux. Based on these facts, in this paper we propose a truncated ADAF model for Sgr A* and three ellipticals M87, NGC 4649 and NGC 4636. We assume that the accretion disk is truncated at a certain radius $R_{\rm tr}$ within which the jet forms by extracting the energy of the disk. The radio flux is greatly suppressed due to the radiative truncation of the disk and the fits to the observational data are excellent. For example, for Sgr A*, the model fits the observational spectrum very well from radio including the "excess" below the break frequency to hard X-ray under a high accretion rate near the simulation value, and the predicted size-frequency relationship is also in excellent agreement with the observation; for M87, the predicted upper limit of the jet location is $24R_{\rm g}$, in excellent agreement with the observational result that the jet is formed on scales smaller than $30R_{\rm g}$, and the $\approx 20\%$ variability at ~ 1 Kev – which is hard to explain in another model succeeded in explaining the low radio flux of M87 – is also marginally interpreted. The success of the model supplies a possible evidence for the disk rather than the hole origin for the powering of jets.

Key words: accretion, accretion disks – black hole physics – galaxies: active – galaxies: individual (M87, NGC 4649, NGC 4636) – galaxies: jets – Galaxy: centre – hydrodynamics

1 INTRODUCTION

The energetic radio source Sgr A* located at the center of our Galaxy is widely believed to be a black hole with mass $M = 2.5 \times 10^6 M_\odot$ (Mezger, Duschl & Zylka 1996). Due to its proximity, the observational data are abundant, which makes it an ideal laboratory to test our accretion theories. Any successful model needs to explain its relative low-luminosity, the emergent spectrum from radio to X-ray wavelength, and the frequency-size relationship.

Several models have been put forward for Sgr A*. They include Bondi accretion (Melia 1992; 1994), emission from mono-energetic electrons (Duschl & Lesch 1994), jet model (Falcke, Mannheim & Biermann 1993; Falcke & Biermann 1999), and the most recent two temperature advection-

dominated accretion flows (ADAFs; Narayan, Yi & Mahadevan 1995; Manmoto, Mineshige, & Kusunose 1997; Narayan et al. 1998). Among them, ADAF model is the most dynamically self-consistent. However, two puzzles still remain in this model. First, as pointed out by Quataert & Narayan (1999), the mass accretion rate required in this model is more than 10 times smaller than that favored by three-dimensional hydrodynamical simulation based on the Bondi capture, with the former being $\approx 6.8 \times 10^{-5} \dot{M}_{\rm Edd}$ (Quataert & Narayan 1999) and the latter $\approx 9 \times 10^{-4} \dot{M}_{\rm Edd}$ (Coker & Melia 1997). Here $\dot{M}_{\rm Edd} = 2.2 \times 10^{-8} {\rm Myr}^{-1}$ denotes the Eddington accretion rate and M is the mass of the centre hole. Very recent Chandra observations of Sgr A* show that its $0.1 - 10$ kev luminosity is $L_X \approx 4 \times 10^{33}$ erg s^{-1} (Baganoff et al. 2000), considerably smaller than the upper limit used by Quataert

& Narayan (1999). Taking this into account, the accretion rate required in ADAF model would be smaller hence the discrepancy between the two accretion rates will be larger. If a higher accretion rate were adopted in an ADAF model, the bremsstrahlung and synchrotron radiations would yield an X-ray and a radio fluxes well above the observational limits.

Yuan (1999) find that the outer boundary condition of the accretion flow plays an important role in the dynamics and radiation of an optically thin accretion flow. This point was neglected in previous ADAF models in the literature. After considering this effect, it was found that since the specific angular momentum of the flow at the outer boundary is low, $\Omega_{out} \sim 0.15\Omega_{Kepler}$ as shown by the numerical simulation (Coker & Melia 1997), the accretion in Sgr A* should belong to Bondi-like (not Bondi type), characterized by a much larger sonic radius and a low surface density compared with the conventional disk-type ADAF. The bremsstrahlung radiation therefore is greatly suppressed (Yuan et al. 2000). However, the synchrotron radiation would still produce too much radio flux were the mass accretion rate favored by the simulation adopted.

The second puzzle is that ADAF model strongly underpredicts the radio flux in the radio spectrum below a "break" frequency (Narayan et al. 1998). Mahadevan (1998) argued that the charged pion produced by the energetic proton collisions in ADAF will subsequently decay into e^-e^+, which will further produce synchrotron emission and could serve as the origin of the radio excess below the break. However, the result depends on the power-law index of the proton energy spectrum, which we are not clear. In fact, due to the existence of the threshold energy needed for pion production, these extra photons should be principally produced in the innermost region of the disk. This is in conflict with the observed intrinsic size of $\sim 72R_g$ at 43 GHz (Lo et al. 1998; see also Figure 2), here $R_g = 2GM/c^2$ is the Schwarzschild radius of the black hole.

More importantly, recent excellent near-simultaneous VLBA measurements show that the intrinsic source structure at 43 GHz is elongated along an essentially north-south direction, with an axial ratio of less than 0.3 (Lo et al. 1998). This is hard to explain in an ADAF model, while it provides a convincing evidence for the existence of a jet in the jet-nozzle model of Falcke et al. (1993). In this model the radio spectrum below the break is produced by a jet while those above the break is assumed to be produced by a "nozzle" located at the lower base of the jet. The question is, however, this model can not account for the entire spectral energy distribution from radio to X-ray, and we lack any detailed understanding to the "nozzle" which is crucial to the fit of the spectrum above the break. Considering this situation, recently Falcke (1999) and Donea, Falcke, & Biermann (1999) suggested that maybe we should combine the jet model with an accretion model, e.g., ADAF, Bondi-type accretion or others.

A similar situation exists in the case of nearby elliptical galaxies. The existence of a massive black hole and the hot gas pervading the galactic center is in sharp contrast to their low luminosity. Recently it was suggested that ADAF could serve as a feasible explanation for the quiescence of the galaxies (Fabian & Rees 1995). Recent observation, however, shows that the canonical ADAF model overpredicts

the radio flux by more than two orders of magnitude (Di Matteo et al. 1999). The current explanation is to drive a wind from the accretion disk, assuming the accretion rate $\dot{M} = (R/R_{out})^p \dot{M}_{out}$ (Di Matteo et al. 2000), where R_{out} is the radius from which the wind starts to play an important role and $\dot{M}_{out}$ is the mass accretion rate there. Since the electron is basically adiabatic, its temperature is determined by the compression work. When a strong wind is introduced, the density profile would become flatter which results in a significant decrease of the temperature and further the synchrotron radiation. The presence of a strong wind is based on the assumption that the Bernoulli parameter of an ADAF is positive therefore the flow is in some sense unstable (Blandford & Begelman 1999). As shown by Nakamura (1998) and Abramowicz, Lasota, & Igumenshchev (2000), however, the Bernoulli parameter is negative in most of the reasonable cases. Numerous numerical simulations also confirm the absence of winds from the disks (but jets do present in the innermost region of the disk in some cases) (Eggum, Coroniti, & Katz 1988; Molteni, Lanzafame, & Chakrabarti 1994; Igumenshchev & Abramowicz 1998; Stone, Pringle, & Begelman 1999; Koide et al. 2000). Thus the scenario of strong winds from ADAFs might be questionable. Even so, the fit is not very satisfactory in some aspects, as illustrated below. What is interesting is, all the sources in Di Matteo et al. (2000)'s sample have the extended and often highly collimated radio structures which are again the evidence for the existence of jets (e.g. Stanger & Warwick 1986).

Based on the above facts, in this paper, we propose an ADAF-jet model for Sgr A* and nearby elliptical galaxies.

2   TRUNCATED ADAF BY A JET

Jets are observed in many classes of astrophysical objects involving an accretion flow, ranging from AGNs and quasars, to old compact stars in binaries, and to young stellar objects. There are currently two main energetic mechanisms for jets (see recent reviews by Lovelace, Ustyugova & Koldota 1999 and Livio 1999). The first one is the Blandford-Znajek mechanism (Blandford & Znajek 1977). The rotation of the black hole drags the inertial frame near it and twists the magnetic field line supported by the surrounding disk. The resulted magnetic stress is then released as a Poynting flux away from the hole. In this mechanism, the powering of jets is provided by the rotating hole. The second is the electromagnetic output from the inner region of the accretion disk (Blandford 1976; Lovelace 1976; Blandford & Payne 1982; see Spruit 1996 for more references). The twisting of the field caused by the rotation of a Keplerian accretion disk results in outflows out of the disk, or the material in the disk is accelerated by the centrifugal force and magnetic pressure gradient force. In these models, the powering of jets is the energy output from the disk. We are not clear at present which mechanism plays the dominated role even after so many years' efforts.

But we are sure at this point that the jet must originates from the inner region of the disk. This conclusion is based on numerous observations. One evidence is that the jet velocity is always of the order of the escape velocity from the central objects in any case involving jets. Another good example comes from the observation of the jet in M87, as to be stated in this paper (for more evidence, see Livio 1999). Numerical

simulations also obtain the same result (e.g., Koide et al. 2000).

For our purpose, in this paper we adopt the "disk" origin of jets. We assume the jet forms from a certain radius $R_{\rm tr}$ by extracting the energy of the ADAF. Since the jet power is generally comparable with the total accretion power of the disk (Rawlings & Saunders 1991), we expect that winthin $R_{\rm tr}$ a large fraction of the energy (and mass, maybe) of the disk will be transferred into the jet. The detailed physical mechanism is very complicated and is an open problem. According to the numerical simulation, in addition to the electromagnetic process, hydrodynamic adiabatic expansion may also play a role (e.g. Koide et al. 2000). As a result, the temperature of the disk within $R_{\rm tr}$ will significantly decrease compared with an ADAF without jet. Since the synchrotron radiation, which is the dominant radiation process in the innermost region of ADAF (the bremsstrahlung emission can be neglected here), is very sensitive to the temperature, $L_\nu \propto T_e^{21/5}$ for the "general" frequency and $\nu L_\nu \propto T_e^7$ for the peak frequency (Mahadevan 1997), we here for simplicity assume that within $R_{\rm tr}$ the radiation of the disk (if it still exists) is completely suppressed, i.e., ADAF is radiatively truncated by the jet.

The resulted spectrum of the truncated ADAF can be qualitatively understood by the following simple estimate. The synchrotron photons emitted at a radius R in an ADAF, which are responsible for radio spectrum, are highly self-absorbed and give a blackbody spectrum, up to a critical frequency $\nu_c(R)$ above which the radiation becomes optically thin. The emergent spectrum of the ring at radius R is peaked at this frequency and the total radio spectrum is the superposition of each ring of ADAF. Therefore each point along the radio spectrum corresponds to a certain radius in an ADAF (Mahadevan 1997),

$$\nu_c(r) \approx 30 m_9^{-1/2} \dot{m}_{-4}^{1/2} T_{e9}^2 r^{-5/4} {\rm GHz} \qquad (1)$$

Here, $m_9 = M/(10^9 M_\odot)$, $\dot{m}_{-4} = \dot{M}/(10^{-4}\dot{M}_{\rm Edd})$, $T_{e9} = T_e/10^9 {\rm K}$, and $r = R/R_g$. Therefore, the truncation of ADAF at $R_{\rm tr}$ will "take away" the high-frequency part of the radio spectrum from $\nu(R_{\rm tr}/R_g)$ up to the previous radio peak $\nu(r=1)$, as illustrated by the comparison between the thin solid and dotted lines in Figure 1. Thus the radio flux is strongly suppressed.

The procedure to calculate the spectrum of the truncated ADAF is as follows. Bremsstrahlung and synchrotron radiations amplified by Comptonization are taken into account and two-temperature plasma assumption is adopted. For simplicity we set the outer boundary at $10^4 R_g$ and the temperatures of electrons and ions at $R_{\rm out}$ are set as $T_{\rm i,out} \approx T_{\rm e,out} \approx 7 \times 10^7 {\rm K}$. Strictly, we should set the outer boundary at the radius where the accretion begins, and adopt the flow's temperature and angular momentum there as the outer boundary condition, like in the case of Sgr A* in Yuan et al. (2000). Our previous calculation to Sgr A* shows that if only we set the outer boundary far enough from the hole, say $\gtrsim 10^4 R_g$ in the present case, the effects due to different $T_{\rm out}$ are not large. However, the angular momentum of the accretion flows in both Sgr A* and ellipticals is very small, we therefore set $\Omega_{\rm out} \lesssim 0.2\Omega_{\rm Kepler}$ in all the cases thus the accretion mode is of Bondi-like under the parameters we adopt. Other parameters we generally set

are $\alpha = 0.1$ and $\beta = 0.5$. Here α is the viscosity parameter in Shakura & Sunyaev-type viscous description and β denotes the ratio of the gas pressure to the sum of the magnetic and gas pressures. Note since we assume a strict equipartition between the magnetic pressure and the gas pressure, the truncation radii we obtain below are all upper limits. We self-consistently solve the set of equations describing the radiation hydrodynamics of the accretion flow, as we did for a "not-truncated" ADAF in Yuan et al. (2000), i.e. we require the solution must satisfy the outer boundary condition at $R_{\rm out}$ and the sonic point condition at a sonic point. This is reasonable because the flow outside of $R_{\rm tr}$ can't sense the formation of the jet in the *supersonic* part of the accretion flow. However, since the disk is radiatively truncated at $R_{\rm tr}$, when we calculate the emergent spectrum, we only integrate from the outer boundary to the truncation radius $R_{\rm tr}$ rather than to the horizon. $R_{\rm tr}$ is treated as a free parameter in our model.

For completeness, for some sources we calculate the radiation of the jet as well. However, compared with ADAF, there are much more free parameters in the general jet model developed especially for BL Lac objects (e.g. Ghisellini, Maraschi, & Treves 1985). Here we follow Falcke & Biermann (1999) to calculate the radiation of the jet. The formula are derived from the Blandford & Konigl (1979) model which calculate the synchrotron emission of a freely expanding, pressure driven jet as a function of jet power. The free parameters include the jet power $Q_{\rm jet}$, the characteristic electron Lolentz factor γ_e, and the angle between the sight line and the jet axis i. We set the scale height of the acceleration zone $Z_{\rm nozz}$ – a free parameter in Falcke & Biermann (1999)'s model – to equal to the scale height of the disk at $R_{\rm tr}$. We should note that the formula we adopt is somewhat simplified. For example, it assumes the electron energy distribution is quasi-monoenergetic rather than the more realistic power law. Since in almost all practical cases, the synchrotron radiation is highly self-absorbed, the final spectrum results from the superposition of the radiation from different radii. Therefore, even though the energy distribution were power law, the result should be roughly the same if only the maximum Lolentz factor is not too large, which is reasonable if the radiative zone is not too far away from the base of the jet hence the electrons have not been accelerated to a power law by, e.g. a shock. We sum the radiation of the disk and the jet to obtain the total spectrum.

3 APPLICATIONS TO INDIVIDUAL SOURCES

3.1 Sgr A*

Figure 1 shows the calculated spectrum for Sgr A* together with the observational data taken from Narayan et al.(1998) except that the new Chandra data denoted by a filled square is taken from Baganoff et al. (2000). The thin solid line is for a truncated ADAF with $\dot{M} = 1.5 \times 10^{-4}\dot{M}_{\rm Edd}$, the dashed line is for a jet, and the thick-solid line denotes the total spectrum of the ADAF-jet system. The truncation radius $R_{\rm tr} = 10R_g$. The dotted line is for the "not-truncated" ADAF with the same parameters and outer boundary conditions except $\beta = 0.9$. Even though we adopt such a weak magnetic field, we find that the synchrotron process
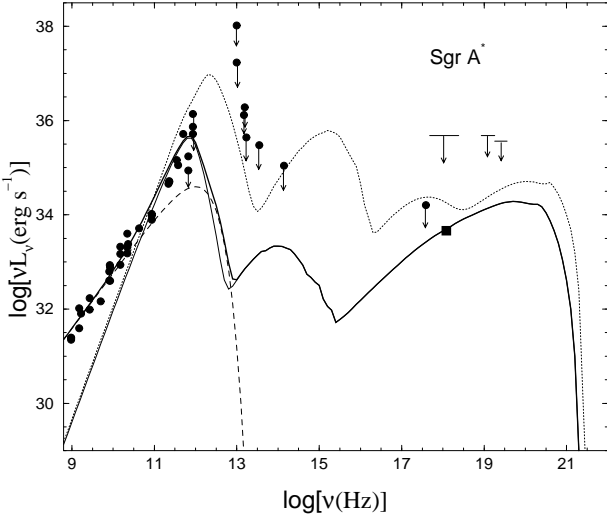
Figure 1. The predicted spectrum of the ADAF-jet model for Sgr A* together with the observation taken from Narayan et al. (1998) except the new Chandra data denoted by a filled square. The dotted line is for the "not-truncated" ADAF with the mass accretion rate $1.5 \times 10^{-4} \dot{M}_{\rm Edd}$. The thin-solid line is for the truncated ADAF with the same accretion rate, the truncation radius is $R_{\rm tr} = 10 R_{\rm g}$. The dashed line is for the jet and the thick-solid line is the sum of the truncated ADAF and the jet. Other parameters are $M = 2.5 \times 10^6 M_{\odot}, \gamma_e = 125, i = 45°$, and $Q_{\rm jet} = 10^{38.4}$ erg s^{-1}.

still emits too much radio flux and the Comptonization of the synchrotron photons produces a X-ray flux well above the observational measurement. Compared with the "not-truncated" ADAF, the radio flux is significantly suppressed in the truncated ADAF and the X-ray emission is also reduced due to the reduction of Comptonized synchrotron photons. From the figure we find that the spectrum below ~ 50 GHz is mainly contributed by the jet while those above is principally produced by the disk and the fit to the observation is good.

Although the accretion rate favored in our model is ~ 6 times smaller than the numerical simulation of Coker & Melia (1997), we note that such a discrepancy could be reduced by ~ 3 times if we adopted a larger viscous parameter $\alpha = 0.3$ because of the scaling law $\rho \propto \dot{M}/\alpha$. In this case, the viscous dissipation will produce more energy hence the electron temperature will increase. As a result, more radio flux will be emitted by the synchrotron process. Then the conflict between the "not-truncated" ADAF and the observation will be more serious, while in the truncated ADAF model, a slightly larger truncation radius $R_{\rm tr}$ is then required to give a satisfactory fit.

Figure 2 shows the predicted size-frequency relationship of our ADAF-jet model together with the observational data taken from Lo et al. (1998) (for 43 GHz) and Krichbaum et al. (1998) (for 86 and 215 GHz) [*]. The solid one is the result of our ADAF-jet model, with the line below and
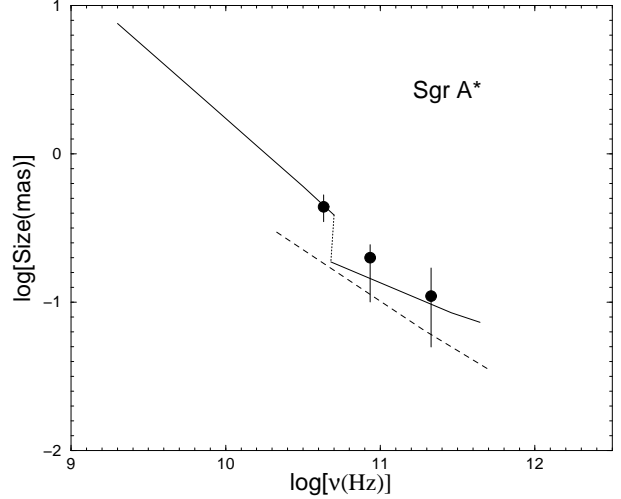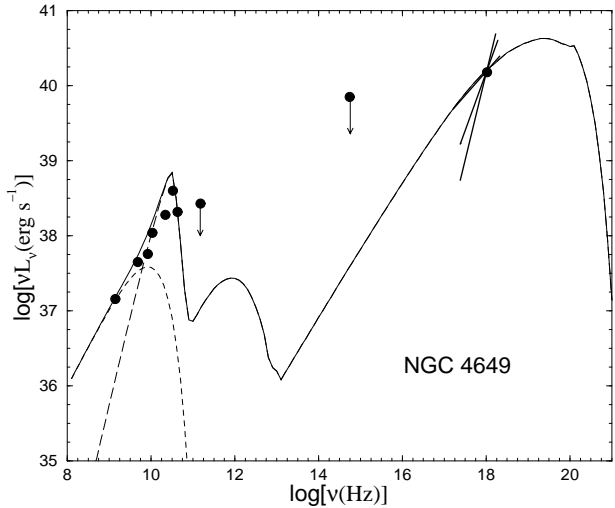

Figure 2. The predicted size-frequency relationship together with the observation for Sgr A*. The thick solid line is the result of our ADAF-jet model with the line above the vertical dotted line being for the jet and the line below for the truncated ADAF. The long-dashed line is for a "not-truncated" ADAF. A distance of 8.5 kpc is assumed.

above the break frequency at around ~ 50 GHz resulted by the jet and the truncated ADAF respectively. For comparison, we also show by the dashed line the prediction of a best-fit "not-truncated" ADAF model similar with that in Quataert & Narayan (1999), [†], but with a smaller accretion rate of $\dot{M} = 5.7 \times 10^{-5} \dot{M}_{\rm Edd}$ because of the new Chandra upper limit. Other parameters are $\alpha = 0.1, \beta = 0.5, T_{\rm i,out} \approx T_{\rm e,out} \approx 7 \times 10^7$ K, and $\Omega_{\rm out} \approx 0.45 \Omega_{\rm Kepler}$. Note in this ADAF model, $\Omega_{\rm out}$ is large so it is of disk-like hence $\dot{M}$ is smaller than our Bondi-like model. We see that the two models are both compatible with the data at 86 and 215 GHz, but our ADAF-jet model gives a better fit to the observation at 43 GHz because of the inclusion of the jet. In this context, we note that although the "ADAF+wind" model of Quataert & Narayan (1999) could also interpret the spectrum, even though the high accretion rate favored by simulation were adopted, the predicted size-frequency relationship would be in conflict with observation at 43 GHz, since that model should produce a similar frequency-size relationship with the "not-truncated" ADAF model.

[†] In addition to the difference of the mass accretion rate, the different prediction of the "not-truncated" ADAF between the present result (dashed line) and that in Narayan et al. (1998) is due to the difference of the adopted electron adiabatic index γ_e. We take it to be that of a monatomic ideal gas, as in Quataert & Narayan (1999), while in Narayan et al. (1998) γ_e includes the contribution of the magnetic density as well. Compared with ours, the choice in Narayan et al. (1998) results in a lower electron temperature therefore a larger radio source size is needed to produce the observed flux at a given frequency. Due to the same reason, in Quataert & Narayan (1999) and the present paper, a noticeably smaller mass accretion rate than Narayan et al. (1998) is required to fit the observation. However, as argued by Quataert & Narayan (1999), γ_e should not include the contribution of the magnetic density.

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[*] Because of the existence of two components, jet and disk, and the reason stated in Krichbaum et al. 1998, their "case 2" result is more reasonable and is adopted here. See Krichbaum et al (1998) for details
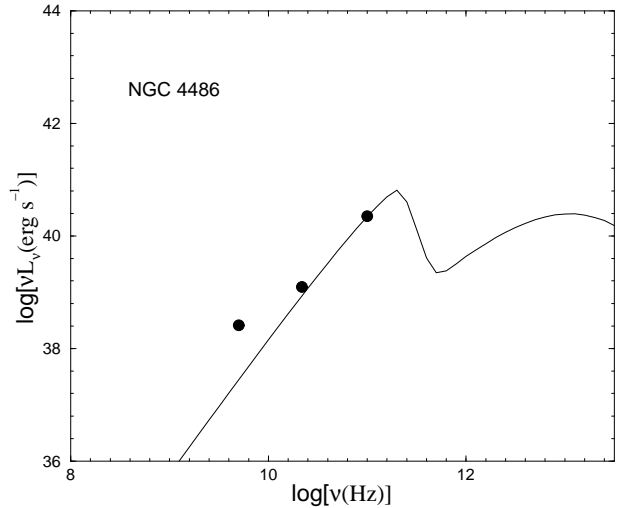
Figure 3. The predicted spectrum of the ADAF-jet model for NGC 4649 together with the observation. The long-dashed line is the result of the truncated ADAF, the short-dashed line is for the jet, and the solid line shows the sum. The parameters are $M = 4 \times 10^9 M_\odot, \dot{M} = 8 \times 10^{-3} \dot{M}_{\text{Edd}}, Q_{\text{jet}} = 10^{40.7}$ erg s^{-1}, $i = 20°, R_{tr} = 40 R_g$, and $\gamma_e = 200$.

3.2 Nearby Elliptical Galaxies

Encouraged by the above success, we further apply our model to the six ellipticals presented in Di Matteo et al. (2000), where jets also exist. Due to the successful applications of Falcke's jet model to other sources like M81, GRS 1915+105, and NGC 4258 (Falcke & Biermann 1999), we assume here that for our purpose this model can give an enough description to the weak jets (excluding M87) in ellipticals as well. We find that due to the suppression of the radio flux by the truncation of the disk, the predicted spectra are in good agreement with the observations. We present below three sources as illustrations. The observational data are taken from Reynold et al. (1996) (for M87) and Di Matteo et al.(1999) (for NGC 4649 and NGC 4636).

3.2.1 NGC 4649

We first model NGC 4649 because it has the best observational constraints in Di Matteo et al. (2000)'s sample. Figure 3 shows the predicted spectrum of this source together with the observation. The long-dashed line is the result of the truncated ADAF disk, the short-dashed line is for the jet, and the solid line shows the sum. As clearly shown, this source, which can be matched well by the ADAF with winds, also can be matched quite well by a truncated ADAF. However, in the wind model, if we assume the wind were to start at the outer boundary $10^4 R_g$, the radius where the accretion starts, a fairly strong suppression of the X-ray emission above ~ 5keV is introduced, which is in conflict with the ASCA data (Di Matteo et al. 2000). As stated by Di Matteo et al. (2000), this is because the introduction of winds at $10^4 R_g$ strongly decreases the bremsstrahlung emissivity at $10^3 \sim 10^4 R_g$, where the X-ray emission $\gtrsim 10$ keV mainly originates from. Therefore, in their model, they have to assume the winds to start at a certain radius much

Figure 4. The predicted spectrum of the truncated ADAF for NGC 4486 (M87) together with the observation. The parameters are $\dot{M} = 3 \times 10^{-2} \dot{M}_{\text{Edd}}$ and $M = 3 \times 10^9 M_\odot$. The truncation radius R_{tr} equals $24 R_g$.

smaller than $10^4 R_g$, which is not easy to understand. [‡] In our model, the X-ray emission above ~ 5keV doesn't show any suppression, in agreement with ASCA observation. This is because out of the (small) truncation radius R_{tr}, ADAF is the canonical one in the sense that no winds are introduced. In addition, due to the introduction of the jet, the radio flux near 1 GHz, which ADAF with winds model underpredict it greatly, can be interpreted as the contribution from the jet, as in the case of Sgr A*.

3.2.2 NGC 4486 (M87)

This is the only source in our examples for which we have clear observational evidence for the existences of a strong jet and a disk. Its jet is famous, while HST spectroscopy of its nucleus has given strong evidence for a rapidly rotating ionized gas disk at its center (e.g., Ford et al. 1994). Although its high frequency radio data is consistent with the canonical "not-truncated" ADAF model, the X-ray emission in this case is due to Comptonization of the synchrotron photons and the predicted slope is too soft to be consistent with the ASCA data. Therefore the radio flux must also be significantly smaller than the prediction of a canonical ADAF (Di Matteo et al. 2000). Figure 4 shows the predicted radio spectrum of this source by the truncated ADAF together with the observation. Three points need to be emphasized. First, compared with the wind model, the truncated ADAF

[‡] Although they argue that if the specific angular momentum of the flows at the accretion radius $\sim 10^4 R_g$ is a small fraction(ξ) of the corresponding Keplerian value, then the angular momentum will start to dominate the flow at $r \sim \xi^2 10^4 R_g$, where the winds start to play an important role. However, according to our numerical calculation (Yuan et al. 2000), when the specific angular momentum at the accretion radius is rather low, it will remain highly sub-Keplerian throughout the way to the hole rather than dominate the flow at a certain small radius. This is the so-called Bondi-like accretion. See also Abramowicz (1998).

can fit the 100GHz VLBI data much better. Although the 5 GHz VLBI data is still strongly underpredicted, the excess may again be due to the contribution of the jet, like in the cases of Sgr A* and NGC 4649. Second, both winds and the truncated ADAF models can give a good match to the spectrum of this source (and others), but they are intrinsically different. One point reflecting the difference is that, the wind starts at a much larger radius, typically several hundreds of R_g, while in the latter, the theoretically predicted truncation radius at which the jet forms is much smaller. For M87, this radius equals $24R_g$. Were it larger, the ADAF would predict a radio flux well below the observed one. On the other hand, as a triumph of precision astronomy, the excellent 43GHz observation for this source by Junor, Biretta & Livio (1999) indicates that the jet is formed on scales smaller than $\sim 30R_g$ from the black hole, in excellent agreement with our prediction.

The last point we want to emphasize concerns the variability of M87. Another intrinsic difference between the wind model and ADAF-jet model is that the density of the disk at moderate radius differs greatly under a same accretion rate. Due to the large mass loss through the wind, the surface density of the disk in the wind model is much smaller than the latter. As a result, the bremsstrahlung emissivity within the wind-starting radius is strongly reduced. Therefore, the radius near which most of the bremsstrahlung emission flux at frequency ν can be produced – r_ν – increases and the dynamical time scale relevant to the bremsstrahlung variability at r_ν – $t_d(r_\nu)$ – increases. Since for variability we have,

$$\frac{\delta L_\nu(\delta t)}{L_\nu} \sim A \operatorname{Min}\left(1, \left[\frac{\delta t}{t_d(r_\nu)}\right]^{3/2}\right), \qquad (2)$$

thus, on timescale of ≈ 6 months to a year only $\lesssim 1\%$ variability is expected, therefore, the $\approx 20\%$ variability observed by the ROSAT HRI (~ 1 keV) of the core of M87 is hard to reconcile in a wind model (Di Matteo et al. 2000), while it can be marginally interpreted if the jet originates at $\sim 30R_g$. This is the very case of our truncated ADAF model.

3.2.3 NGC 4636

We can imagine that there may exist such a case that the jet originates at a moderate large radius so that the radio peak decreases a lot according to eq. (1) and it is the jet rather than the disk dominates the radio spectrum. This might be the case for NGC 4636, as Figure 5 illustrates. For this source, the wind model predicts a synchrotron peak with a much higher frequency than expected by the radio and sub-mm measurements (Di Matteo et al. 2000). Actually, in that model to fit the peak correctly, a black hole with much larger mass, $10^9 M_\odot$, than the observational value $3\times10^8 M_\odot$, must be used. Figure 5 shows this puzzle can be solved in the truncated ADAF model if the truncation radius is as large as $100R_g$. To confirm this conclusion, polarization should be observed in radio band, and the future low-frequency radio observation should not exhibit "excess" as in Sgr A*, NGC 4649, and M87.
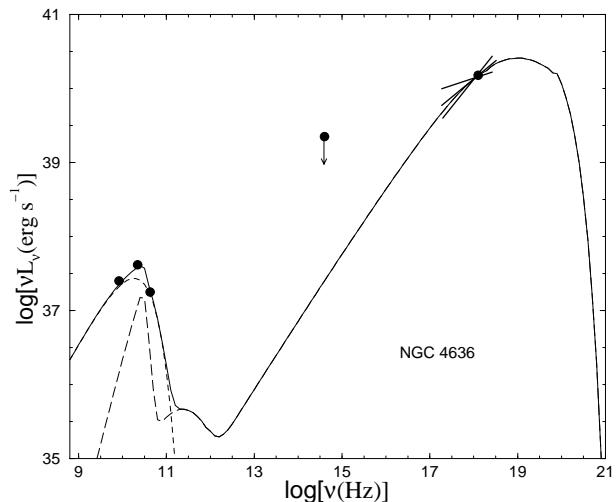
Figure 5. The predicted spectrum of ADAF-jet model for NGC 4636 together with the observation. The long-dashed line is the spectrum of the truncated ADAF, the short-dashed line is for jet, and the solid line is the sum. The parameters are $\dot{M} = 3 \times 10^{-2}\dot{M}_{\mathrm{Edd}}, M = 3 \times 10^8 M_\odot, Q_{\mathrm{jet}} = 10^{41.3}$ erg s$^{-1}, i = 15°, R_{tr} = 100R_g$, and $\gamma_e = 300$.

4 SUMMARY AND DISCUSSION

The predicted radio flux for nearby ellipticals by the canonical ADAF model is well above the observations. If the mass accretion rate favored by the numerical simulation were adopted, the ADAF model would also produce too much radio flux in the case of Sgr A*. On the observational side, strong evidence for the existence of jets in Sgr A* and these ellipticals are observed. Based on these facts, in this paper we propose an ADAF-jet model for Sgr A* and the nearby giant elliptical galaxies. We assume that the advection-dominated accretion disk is truncated by a jet at a certain radius R_{tr} within which most of the energy of the disk (if it still exists) is extracted for the powering of the jet therefore its radiation is completely suppressed. We calculate the spectrum of the ADAF-jet system for Sgr A* and three ellipticals and find that the radio overprediction are solved and the fits to the observation are excellent. For example, for Sgr A*, we can reproduce the break around the 50 GHz point in the radio wavelength, and the predicted size-frequency relation is in good agreement with the observation. For M87, the truncation radius favored by our model, $R_{\mathrm{tr}} \approx 24R_g$, agrees with the most recent joint observation by VLBI, VLA and other instruments which shows the jet should originate from within $\sim 30R_g$ to the center black hole.

In our model we assume that the disk is radiatively truncated at radius R_{tr} by the jet. It is interesting to note that this idea has been invented in the study to the black hole X-ray binary GRS 1915 +105 where we have much better observational constrains. Radio-infrared oscillation with periods of 10-60 min have been found to follow X-ray dips (Mirabel et al. 1998). The oscillation has been found to be due to synchrotron emission from repeated small ejections, i.e., jet, possibly resulted from suffering strong adiabatic expansion losses (Fender et al. 1997; Eikenberry et al. 1998), while the X-ray dips have been interpreted as the

repeated *disappearance* of the inner accretion disk (Belloni et al. 1997).

The suppression of the radio flux also can be accessed by ADAF with strong winds (Blandford & Begelman 1999; Quataert & Narayan 1999; Di Matteo et al. 2000). Our truncated ADAF model is different with their wind model. The wind model is based on the assumption that the Bernoulli parameter of ADAF is positive therefore strong winds are inevitable. The validity of this assumption is in debate at present. On the other hand, our model is based on the observation that jets really exist in the inner region of these sources therefore may has more reliable physical basis. The predictions of these two models are also different. Comparisons between the prediction and observation on the location of the jet origin in M87, the $\approx 20\%$ variability at ~ 1 keV of M87, and the frequency-size relationship of Sgr A*, incline to support our model.

Noting that in nearby ellipticals and Sgr A*, two kinds of sources where ADAF is assumed to exist, jets are observed. In NGC 4258, another source where ADAF is assumed to exist (Gammie, Narayan, & Blandford 1999), a jet also exists (e.g., Herrnstein et al. 1998). Moreover, in black hole X-ray binary a steady jet is usually present at the hard/low state, while this state is typically interpreted as an inner advection dominated accretion disk plus an outer standard thin disk (Fender 1999; Esin, McClintock, & Narayan 1997). Thus, it seems that a jet always be present in an ADAF. If it is the case, we should check some result obtained under the frame of an canonical ADAF. An example is the radio/X-ray luminosity relation obtained by Yi & Boughn (1998) in the frame of the standard ADAF. Since the radio spectrum below a possibly existed break frequency ν_{break} (as in the sources presented in this paper) may be dominated by the jet while that above a frequency the spectrum may disappear due to the truncation of the disk at r_{tr}, their conclusion holds only if the radio frequency ν satisfies,

$$\nu_{\mathrm{break}} \lesssim \nu \lesssim 20 m_7^{-1/2} \dot{m}_{-3}^{1/2} T_{e9}^2 \left(\frac{r_{\mathrm{tr}}}{20}\right)^{-5/4} \mathrm{GHz}. \qquad (3)$$

Here $r_{\mathrm{tr}} = R_{\mathrm{tr}}/R_g$.

The crucial factor in our model is to assume that the powering of the jet is the energy output from the disk rather than from the hole. The excellent agreement between the predictions of our model and the observations for both Sgr A* and elliptical galaxies in turn confirms the correctness of our assumption, and supports the "disk" origin of jets. In this context we note Livio, Ogilvie & Pringle (1999) recently argue that since there is no reason to suppose that the magnetic field threading the central spinning black hole differs significantly in strength from that threading the central regions of the disk, and the hole is a very poor conductor compared to the surrounding disk material, the electromagnetic output from the inner disk region is expected to dominate over B-Z mechanism. We want to note that this conclusion doesn't contradict the possibility that the rotation of the hole may play a role in the powering of the jets. This is because a strong magnetic field may be created due to the frame dragging in the ergo-sphere of the Kerr black hole, therefore the energy extraction from the disk will be more efficient compared with the Schwarzschild black hole case (Koide et al. 2000).

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