Advection-dominated Accretion: From Sgr A* to other Low-luminosity AGNs

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Abstract.

This paper reviews our current understanding of low-luminosity AGNs (LLAGNs) in the context of the advection-dominated accretion flow. The best investigated source, the supermassive black hole in our galactic center, Sgr A*, is emphasized since the physics of accretion should be the same for various LLAGNs except for their different accretion rates. The important role of jets is discussed, but this is less well established.

1. Introduction

It is now widely recognized that most, if not all, galaxies host a supermassive black hole. Different degree of nuclear activity are manifested among them, ranging from the most active and luminous active galactic nuclei (AGNs), to less active low-luminosity AGNs (LLAGNs), until the least active quiescent galaxies such as our Galaxy. The activities in all these sources are believed to be powered by the release of the gravitational energy of the gas surrounding the black holes via the accretion process.

The equations of accretion onto a black hole allow two series of solutions, cool and hot ones. The standard thin disk model (Shakura & Sunyaev 1973) is the representative of the cool solution (another cool accretion solution corresponding to higher accretion rates is called “slim” disk). The temperature of the accretion flow in this solution is relatively low, $\sim 10^6 \text{ - } 10^7 \text{K}$. It is optically thick, geometrically thin (because of the low temperature), and radiatively efficient. This solution provides a good description to the big blue bump in the optical/UV band of the luminous AGNs (but see Koratkar & Blaes 1999) thus is believed to work in luminous or normal AGNs.

The advection-dominated accretion flow (ADAF) belongs to the hot series (Narayan & Yi 1994, 1995; Abramowicz et al. 1995; see Narayan, Mahadevan & Quataert 1998; Kato, Fukue & Mineshige 1998 for reviews). In an ADAF, the temperature of ions is virial while the electron temperature is lower but still very high, $T_e \sim 10^9 \text{ - } 10^{11} \text{K}$. This solution is optically thin and geometrically thick, and most importantly, its radiative efficiency is typically much lower than that of the standard thin disk, $\eta_{\text{ADAF}} \approx 0.1 \text{M}/M_{\text{crit}}$. Here $M_{\text{crit}} \approx \alpha^2 M_{\text{Edd}}$ is the critical accretion rate of ADAF beyond which the ADAF solution fails and is replaced by another hot solution (“luminous hot accretion flow”). There are
many observational evidence to indicate that ADAFs are very likely relevant for understanding LLAGNs. This will be the content of this review.

We will begin our review from Sgr A*, a supermassive black hole located at the center of our Galaxy. Traditionally our Galaxy is regarded as a normal galaxy rather than an AGN. However, physically as we will see that it also manifests some degree of activity, and the exactly same physical process as in normal AGNs—black hole accretion—is operating there. The only difference is that the accretion rate in Sgr A* is much smaller than in other AGNs and moderately smaller than in LLAGNs. So roughly saying, from Sgr A* to LLAGNs to normal AGNs, the increasing level of activity is simply because of the increasing accretion rate and radiative efficiency. Therefore, in this sense Sgr A* is the least luminous LLAGN. We emphasize Sgr A*, not only because it supplies us with the weakest end of the activity of AGN population, but as we will see in §2, it also provides a unique laboratory of low luminosity accretion.

After introducing the ADAF model for Sgr A* in §2, in §3 we will review our current understanding of LLAGNs in the context of ADAFs. Since jets seem to be always associated with ADAFs, in §4 we will discuss the role of jet.

2. Sgr A* as a unique laboratory of low luminosity accretion

2.1. Why unique? Observational constraints

The reason why Sgr A* is unique is first because it provides the best evidence to date for a supermassive black hole (e.g., Schödel 2002). Secondly, because of its proximity it allows us to observationally determine the dynamics of gas quite close to the BH, thus providing uniquely strict constraints on accretion models.

Outer boundary conditions. The accretion starts at the Bondi radius where the gravitational potential energy of the gas equals the thermal energy. For uniformly distributed matter with an ambient density $\rho_0$ and sound speed $c_s$, the Bondi radius of a BH of mass $M$ is $R_{\text{Bondi}} \approx GM/c_s^2$ and the mass accretion rate is $\dot{M}_{\text{Bondi}} \approx 4\pi R_{\text{Bondi}}^2 \rho_0 c_s$. The high resolution Chandra observations infer gas density and temperature as $\approx 100$ cm$^{-3}$ and $\approx 2$ keV on 1” scales (Baganoff et al. 2003). The corresponding Bondi radius $R_{\text{Bondi}} \approx 0.04$ pc $\approx 1” \approx 10^5 R_s$ and $\dot{M}_{\text{Bondi}} \approx 10^{-5} M_\odot \text{yr}^{-1}$. The recent 3D numerical simulation for the accretion of stellar winds on to Sgr A* by Cuadra et al. (2006) obtains $\dot{M} \approx 3 \times 10^{-6} M_\odot \text{yr}^{-1}$, in good agreement with the estimation of Bondi theory. This simulation also tells us that the angular momentum is large, with a circularization radius of about $10^4 R_s$. The Bondi radius, Bondi accretion rate, electrons density and temperature, and the angular momentum at the Bondi radius constitute the outer boundary conditions any accretion models must satisfy.

Spectral energy distribution. The spectral energy distribution of Sgr A* is shown in Fig. 1. The radio spectrum consists of two component, a low-frequency power-law and a “sub-millimeter bump”, which implies that the radio emission comes from two different components. The X-ray emission comes in two states, namely quiescent and flare ones, with different spectral index. A large fraction of the X-ray flux in the quiescent state comes from an extended region. The bolometric luminosity of Sgr A* is only $L \approx 10^{36} \text{erg s}^{-1} \approx 3 \times 10^{-9} L_{\text{Edd}}$. 
Combined with the Bondi accretion rate, this luminosity implies an extremely low radiative efficiency, $\eta \sim 10^{-6}$.

**Variability.** At both IR and X-ray wavelengths, the source is highly variable. The amplitude of the variability at IR is $\sim 1 - 5$ (Genzel et al. 2003; Ghez et al. 2004); while at X-ray band, it can be as high as $\sim 45$ or higher (Baganoff et al. 2001). The variability at IR and X-ray bands are simultaneous, and the timescales of the variability are quite similar, typically $\sim$ an hour (Eckart et al. 2006; Yusef-Zadeh et al. 2006).

**Polarization.** A high level of linear polarization ($\sim 2\% - 10\%$) at frequencies higher than $\sim 150$ GHz was detected (e.g., Bower et al. 2003), which sets an upper limit on the rotation measure of $7 \times 10^5 \text{rad m}^{-2}$. This argues for a low density of the accretion flow at the innermost region of the ADAF.

### 2.2. The standard thin disk is ruled out

The Bondi theory provides a good estimation to the accretion rate at the outer boundary. If the gas were accreted at this rate onto the black hole via the standard thin disk, the expected luminosity would be $L \approx 0.1 \dot{M}_{\text{Bondi}} c^2 \approx 10^{31} \text{erg s}^{-1}$, 5 orders of magnitude higher than the observed luminosity. This is the strongest argument against a standard thin disk in Sgr A*. In addition, the spectrum shown in Fig. 1 does not look like the multitemperature blackbody spectrum predicted by a standard thin disk at all.

### 2.3. Understanding the observations of Sgr A* with an ADAF

The crucial point to modeling Sgr A* is that the accretion flow must be radiatively very inefficient, while the low efficiency is exactly the characteristic feature of an ADAF solution, as we emphasize in the introduction. In a standard thin disk, the viscously dissipated energy is radiated away locally, which results in a high efficiency. But in an ADAF, the radial velocity is much larger and the temperature is much higher than in a standard thin disk. Consequently, the density of the accretion flow is much lower. Therefore, the radiative timescale is much longer than the accretion timescale, thus most of the viscously dissipated energy is stored in the accretion flow as its thermal energy rather than radiated away. This is the main reason for the low radiative efficiency of an ADAF. For the details of the dynamics of ADAFs, we refer the reader to the review of Narayan, Mahadevan & Quataert (1998).

Narayan, Yi & Mahadevan (1995) first apply the ADAF model to Sgr A*. They successfully explain the most important feature of the source, namely its low radiative efficiency. The spectrum can also be roughly explained. However, in the “old” ADAF model, the accretion rate is assumed to be constant with radius. As a result, the rotation measure predicted in this model is much larger than that required from the polarization observation. This is a serious problem of this model.

In the theoretical side, significant progress has been made in the past decades in our understanding of ADAFs. First, global, time-dependent, numerical simulations reveal that only a very small fraction of the mass that is available at large radii actually accretes onto the black hole and most of it is lost to a magnetically driven outflow or circulates in convective motions (Stone, Pringle & Begelman 1999; Hawley & Balbus 2002). Second, in the old ADAF
model, the turbulent dissipation is assumed to heat only ions. However, it was later realized that processes like magnetic reconnection is likely to heat electrons directly (Quataert & Gruzinov 1999).

Yuan, Quataert & Narayan (2003; 2004) present updated ADAF model (also called “radiatively inefficient accretion flow”) to Sgr A*, taking into account the above-mentioned theoretical developments, i.e., outflow and direct electron heating by turbulent dissipation. Fig. 1 shows the spectral modeling result. Specifically, the submm bump comes from the synchrotron emission of thermal electrons in the innermost region of the ADAF. Due to the existence of outflow, only about 1% of the gas available at the Bondi radius enters into the BH horizon, so the density in the region close to the BH is much lower than in Narayan et al. (1995). In this case, the rotation measure is much smaller and a high linear polarization is expected. The low-frequency radio and the IR emissions are assumed to be from some nonthermal electrons in the ADAF (since the plasma in ADAF is collisionless). But the low-frequency radio spectrum can also be explained by an assumed jet although the jet has not been directly detected (e.g., Yuan, Markoff & Falcke 2002). The IR and X-ray flares are explained by the synchrotron and/or SSC emissions from some transiently accelerated electrons due to processes like magnetic reconnection in the innermost region of ADAF (Yuan, Quataert & Narayan 2004).

After the publication of Yuan et al. (2003), some new observations appeared. A notable one is the size measurement of Sgr A* at radio wavebands (Bower et al. 2004; Shen et al. 2005). These results supply independent test to

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Figure 1. ADAF model for the quiescent state emission from Sgr A*. The dot-dashed line is the synchrotron and SSC emission by thermal electrons; the dashed line is the synchrotron emission by non-thermal electrons. The dotted line is the total synchrotron and SSC emissions while the solid line also includes the bremsstrahlung emission from the outer parts of the ADAF (long-dashed line). Adapted from Yuan, Quataert & Narayan (2003).
theoretical models. Yuan, Shen & Huang (2006) calculated the predicted size of Sgr A* by the Yuan et al. (2003) model and found satisfactory agreement with the observational results. This gives us strong confidence for this model, which should be taken as a baseline model when modeling other LLAGNs.

3. Accretion models for other low-luminosity AGNs (LLAGNs)

3.1. The main observational results for LLAGNs

LLAGNs are very common. The Palomar survey (Ho et al. 1997) indicates that over 40% of nearby galaxies contain LLAGNs. They bridge the gap between the normal galaxies and luminous AGNs. The following are the distinctive observational features of LLAGNs (Ho 2005).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{average_sed.png}
\caption{The average SED of low-luminosity AGNs (solid line), compared with the average SEDs of luminous radio-loud (dotted line) and radio-quiet (dashed line) quasars. Adapted from Ho (1999).}
\end{figure}

Low accretion power. LLAGNs are intrinsically faint. Their bolometric luminosity $L_{\text{bol}}/L_{\text{Edd}} \approx 10^{-5} - 10^{-3}$, which is typically lower than Seyferts by one or two orders of magnitude. Ho (2005) argues that the low power can not be only explained by the low accretion rate and a low radiative efficiency is required. This indicates that ADAFs must be operating in LLAGNs.

Unusual spectrum and iron line. Perhaps the most prominent feature of LLAGNs is the lack of big blue bump in their spectrum. The averaged spectrum of LLAGNs is shown by the solid line in Fig. 2. Also shown for comparison purpose is the typical spectra of radio-loud (dotted line) and radio-quiet (dashed line) quasars. We see from the figure that in LLAGNs the big blue bump is missing and instead there is a maximum peaking somewhere in the mid-IR. The big blue bump is usually associated with a standard thin disk. Thus the lack
of this feature in LLAGNs indicates that the thin disk must be absent or truncated. This picture is further strengthened by the narrowness of the detected iron Kα line. This is because if the thin disk had extended to the innermost stable circular orbit as in luminous AGNs, the line would be broad.

**Double-peaked Balmer line.** Emission lines with double-peaked profiles are often found in LLAGNs. Fitting the line profile requires that the cool accretion disk must have a relatively large inner radius (Chen & Halpern 1989). This is consistent with the result inferred from the absences of the big blue bump and broad iron line mentioned above.

### 3.2. The current scenario of accretion flow for LLAGNs

As analyzed above, the accretion picture in LLAGNs is that the thin disk must be truncated at a certain radius. Within this “transition” radius, the thin disk is replaced by an ADAF. A jet is usually required to fit the radio spectrum of LLAGNs because an ADAF cannot produce enough radio flux. The possible role of the jet in other wavebands will be addressed in next section.

![Figure 3. ADAF model for the hard state of a black hole X-ray binary—XTE J1118+480. The dashed, dot-dashed, and solid lines show the emissions from the ADAF, the truncated thin disk, and their sum, respectively. Two sets of EUV data correspond to two different choices of $N_H$. The X-ray spectral break at $\sim 10^{17.7} \text{Hz}$ is not real (because of Chandra calibration issue). Adapted from Yuan, Cui & Narayan (2005).](image-url)

This picture of accretion is originally proposed to explain the hard state of black hole X-ray binaries (Narayan, McClintock & Yi 1996). Since this state is widely believed to be the counterpart of LLAGNs, and since so far perhaps the best evidence for the truncation of the thin disk still comes from one black hole
X-ray binary—XTE J1118+480, we first present this example before we discuss LLAGNs.

The modeling result for the hard state of XTE J1118+480 is shown in Fig. 3. The optical/UV spectrum is dominated by a truncated thin disk, while the X-ray emission comes from the Comptonization of the synchrotron photons in the inner ADAF. The transition radius is \( R_{\text{tr}} \approx 300R_s \). The model explains the EUV and X-ray data quite well. The under-prediction of the IR and radio fluxes is because we need to include the contributions of the jet, as we will discuss in §4. Two points need to be emphasized. The first is that there is a Balmer jump in the optical spectrum and this is believed to be the evidence for the thin disk origin of the optical emission. The more important point is on the EUV spectrum which is usually very hard to obtain for other sources because of the absorption. The high latitude location of XTE J1118+480 makes its detection feasible because the absorption is very weak. To fit the EUV spectrum, the thin disk must be truncated.

Another important observational result besides the spectrum is the detection of QPO with frequency of \( \sim 0.1 \) Hz. One of the most popular models for QPO requires the thin disk must be truncated and replaced by an ADAF. The global oscillation of the inner ADAF results in the QPO, and the QPO frequency is roughly determined by the Keplarian frequency at the transition radius (Gianinnios & Spruit 2004). For XTE J1118+480, the Keplarian frequency at 300\( R_s \) agrees with the detected QPO frequency very well within the model uncertainty. So two independent observations, spectrum and QPO, require the truncation of the thin disk and even give the same value of the transition radius.

Figure 4. Left: The standard thin disk (dotted) and truncated thin disk (solid) models for the optical/UV spectrum of M 81. The inner radius of the truncated disk is 100\( R_s \). Right: The spectral fitting result for a truncated thin disk plus an inner ADAF. Adapted from Quataert et al. (1999).

Fig. 4 shows the modeling result for an LLAGN—M 81 (Quataert et al. 1999). We can see that the optical/UV spectrum is very steep which is quite different from the canonical big blue bump in luminous AGNs. It is clear from the figure that such a spectrum cannot be fitted by a standard thin disk with-
out truncation (shown by the dotted lines in the left panel) but can be fitted reasonably well by a truncated disk (shown by the solid line in the left panel).

Fig. 5 shows another example of LLAGNs—NGC 1097. This source is also well known due to its double-peaked Balmer line. It has been known for a long time that to fit such a kind of line profile the thin disk must be truncated (Chen & Halpern 1989). For NGC 1097, the innermost radius of the thin disk obtained is $R_{tr} = 252R_s$ (Storchi-Bergmann et al. 2003). On the other hand, to fit the continuum spectrum at optical/UV band, we again require that the thin disk must be required. Although the value of the transition radius is hard to be determined as precisely as in the case of fitting the line profile, it is shown that the value of $R_{tr} = 252R_s$ can fit the optical/UV spectrum satisfactorily (Nemmen et al. 2006). So for this source, like XTE J1118+480, both two independent observations require a truncated thin disk and give the same value of the transition radius.

In addition to the above individual examples, ADAF has been proposed to exist in elliptical galaxies (Fabian & Rees 1995), FR Is (Reynolds et al. 1996; Wu, Yuan & Cao 2007), XBONGs (Yuan & Narayan 2004), Blazar (Marašči & Tavecchio 2003) and even some Seyfert 1 galaxies (Chiang & Blaes 2003).

Several models have been proposed for the mechanism of the transition from an outer thin disk to an inner ADAF. Two notable ones are the evaporation and the turbulent diffusion (e.g., Meyer & Meyer-Hofmeister 1994; Liu et al. 1999; Manmoto & Kato 2000). In the former, the thin disk is sandwiched by hot corona. The cool matter in the thin disk will be converted into the hot gas in the corona due to the thermal conduction between the corona and disk, and finally at a certain radius the whole thin disk will evaporate thus the transition occurs. In the latter model, turbulent diffusion can transfer energy from the
inner ADAF to the outer thin disk thus supply energy for the cool thin disk to make the transition occur.

4. Open questions: the role of jets

It looks like that we now have a good picture of accretion flow for LLAGNs. However, many details remain to be investigated. For example, recently in the hard state of a couple of black hole X-ray binaries some cool material is found to exist very close to the innermost stable circular orbit of the black hole. This seems to imply a standard thin disk without truncation. The iron lines with broad profile are also claimed to be found in these sources (e.g., Miller et al. 2006a, 2006b). If confirmed, how to reconcile these results within our model will be an interesting and challenging project.

Another example of complexity is the possible role of the jet. Observationally we know jets are usually associated with ADAFs rather than the standard thin disk, but the physical reason has not been well understood. In the context of spectral fitting, it is almost certain now that the radio emission of most LLAGNs (and hard state of black hole X-ray binaries) comes from the jet rather than the ADAF (e.g., Yuan, Cui & Narayan 2005). But at other wavebands, the role of jets is still unclear. We can imagine that if the ratio of the mass loss rate in the jet to the mass accretion rate in the ADAF is high enough (this could be due to, e.g., a rapidly spinning BH), and if the radiative efficiency of the jet is high enough (this could be due to the fact that the shock in the jet is radiative rather than adiabatic), the spectrum of the source will be dominated by the jet. This seems to be the case of NGC 4258 (Yuan et al. 2002).

An interesting question is that what is the role of jet systematically in producing the observed spectrum at other bands? For the general sources, it seems unlikely that the jet will dominate over the ADAF in energy bands above radio, say X-ray (e.g., Narayan 2005). Recently much attention has been paid to the radio–X-ray correlation of BH sources (e.g., Merloni et al. 2003). Note this correlation does not mean that the X-ray and radio emissions must have the same origin—jets. This is because if the accretion rate in the ADAF is positively correlated with the mass loss rate in the jet, which is very likely, we would naturally expect such a correlation.

Based on the Merloni et al. (2003) correlation and some assumptions to the physics of jets, Yuan & Cui (2005) argue that in the X-ray band the (synchrotron) emission of the jet may dominate over the underlying ADAF, when the X-ray luminosity of the system is below a critical value determined by:

\[
\log\left(\frac{L_{\text{x, crit}}}{L_{\text{Edd}}}\right) = -5.356 - 0.17\log\left(\frac{M}{M_\odot}\right).
\]

The modeling results to a sample of FR Is seems to support this prediction (Wu, Yuan & Cao 2007; see also other possible observational evidences presented in Yuan & Cui 2005). The sample adopted only consists of eight sources which is too few. A much larger sample and better data are required to examine this prediction.

Acknowledgments. I think the organizers of the conference for their invitation. This work is supported in part by Bairen Program of CAS.
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