Quenching Black Hole Accretion by Active Galactic Nuclei Feedback

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Abstract

Observations of many dim galactic nuclei in the local universe give good estimations of gas density and temperature at the Bondi radius. If we assume the black hole accretes at the Bondi accretion rate and radiates at the efficiency of a low-luminosity hot accretion flow, the predicted nuclei luminosity can be significantly higher than that seen in observations. Therefore, the real black hole mass accretion rate in these sources may be significantly smaller than the Bondi value. Active galactic nuclei feedback may be responsible for decreasing the black hole accretion rate to values much smaller than the Bondi rate. We perform two-dimensional simulations of low-angular-momentum accretion flow at parsec and subparsec scales around low-luminosity active galactic nuclei (LLAGNs). We take into account the radiation and wind feedbacks of the LLAGN. The cross section of particle–particle interaction can be several orders of magnitude larger than that of photon–particle interaction. Therefore, we find that for the LLAGNs, the effects of radiation feedback in decreasing black hole accretion rates are small. However, wind feedback can effectively decrease the black hole mass accretion rate. Due to the decrease of the accretion rate, the black hole luminosity can be decreased by a factor of ~33–400. These results may be useful for explaining why many galactic nuclei in the local universe are so dim.

Key words: accretion, accretion disks – black hole physics – galaxies: active – galaxies: nuclei

1. Introduction

Observations show that most nearby galactic nuclei are very dim. There are a few examples. The luminosity of the back hole accretion flow in our Galactic center (Sgr A*) is $L \sim 10^{-8} L_{\text{Edd}}$ ($L_{\text{Edd}}$ is Eddington luminosity; Yuan et al. 2003). In some nearby elliptical galaxies, including NGC 1399, 4636, and 4472, the black hole accretion flow luminosity is $L < 10^{-8} L_{\text{Edd}}$ (Loewenstein et al. 2001).

Pellegrini (2005) collected a sample of nearby galaxies of Chandra observations. For these galaxies, the black hole mass ($M_{\text{BH}}$), the X-ray luminosity of the nuclei, and the gas density and temperature at the Bondi radius are accurately estimated. The black holes in these galaxies are very dim, with $L < 10^{-4} L_{\text{Edd}}$. The Bondi accretion rate ($M_{\text{B}}$) of these sources can be very easily obtained based on the gas density and temperature at the Bondi radius. If a standard thin-disk (Shakura & Sunyaev 1973) operates in these sources, one would expect the luminosity of the black hole to be $L = \eta M_{\text{B}} c^2$. $\eta$ is the radiative efficiency, which depends on the black hole spin. For a moderately spinning black hole, $\eta = 0.1$ (Wu et al. 2013a). Pellegrini (2005) found that the luminosity of these nuclei is significantly smaller than $0.1 M_{\text{B}} c^2$. Therefore, the standard thin-disk model cannot be applied to these sources.

Observations of black hole X-ray binaries (BHBs) find that the black hole always transitions from soft to hard states at 2% $L_{\text{Edd}}$ (McClintock & Remillard 2006). The black hole accretion physics does not depend on black hole mass. Luminous active galactic nuclei (AGNs) correspond to the soft state of BHs. The accretion disk model of luminous AGNs is a standard thin disk. The low-luminosity active galactic nuclei (LLAGNs) correspond to the hard state of BHBs (Ho 2008). The accretion disk model of LLAGNs is a hot accretion flow (see Yuan & Narayan 2014 for reviews). Yuan & Li (2011) found that the boundary between LLAGNs and luminous AGNs is 2% $L_{\text{Edd}}$. The nuclei luminosity of galaxies collected by Pellegrini (2005) $L < 10^{-4} L_{\text{Edd}}$. Therefore, the accretion flows in these sources should be radiatively inefficient hot accretion flow.

The earliest version of hot accretion flow is advection-dominated accretion flow (ADAF; Narayan & Yi 1994, 1995). In an ADAF solution, outflow is absent and the accretion rate is a constant with radius. According to the ADAF model, the mass accretion rate at the black hole horizon is equal to $M_{\text{B}}$. The radiative efficiency of ADAF is much smaller than 0.1. Pellegrini (2005) found that the predicted luminosity by the ADAF model can be consistent with that of observations of a few nearby galactic nuclei. However, for many other galactic nuclei, the ADAF predicted luminosity is still too high.

There are also two other types of radiatively inefficient hot accretion flow. The first one is the adiabatic inflow–outflow solution (ADIOS; Blandford & Begelman 1999, 2004; Begelman 2012). The ADIOS model assumes that outflow can be launched at any radii. Due to the presence of outflow, the mass accretion rate is not a constant with radius. The mass accretion rate decreases toward the black hole. According to the ADIOS model, the mass accretion rate at the black hole horizon can be significantly smaller than $M_{\text{B}}$. The second one is the convection-dominated accretion flow (CDAF; Narayan et al. 2000; Quataert & Gruzinov 2000; Inayoshi et al. 2018). The CDAF model assumes that convective motions dominate the dynamics of accretion flow. With accretion, more and more gas will be locked in convective eddies. The mass accretion rate decreases toward the black hole. The CDAF model also predicts that the mass accretion rate at the black hole horizon can be significantly smaller than $M_{\text{B}}$. Therefore, both the ADIOS and CDAF models may be able to explain the low emission level of the observed nearby galactic nuclei.

We note that both the ADIOS and CDAF models can only be applied to high-angular-momentum accretion gas. In the ADIOS and CDAF models, at any radius, the gas angular
momentum is comparable to the local Keplerian angular momentum. We define “circularization radius” \( r_c \) as follows. The specific angular momentum of gas at the Bondi radius is equal to the Keplerian angular momentum at \( r_c \). If \( r_c \) is significantly smaller than the Bondi radius, the ADIOS and CDAF models cannot be applicable. Then, the question is that if the ADIOS and CDAF models are not applicable, how can we explain the low emission level of the observed nearby galactic nuclei?

AGN feedback (Fabian 2012) is a possible mechanism to reduce the black hole accretion rate. The outputs of an AGN include radiation, wind, and a jet. The AGN-emitted photons can heat or cool the gas at large radii via Compton heating/cooling (Ciotti & Ostriker 1997, 2001, 2007; Ciotti et al. 2009). The heating/cooling rate depends on nuclei luminosity, the Compton temperature of AGN-emitted photons and accretion gas temperature at large radii. Recent numerical simulations of LLAGNs with radiative feedback found that the AGN-emitted photons can Compton heat the gas around the Bondi radius. The gas temperature around the Bondi radius can be much higher than the local virial temperature. Thus, outflows can be launched around the Bondi radius (Bu & Yang 2018; Yang & Bu 2018). Radiation pressure can also directly push gas away. For example, for a quasar, the not fully ionized gas can absorb the UV photons. Consequently, line force will be exerted on the accreting gas. Line force can exceed black hole gravity significantly. Strong outflow can be launched by line force (e.g., Murray et al. 1995; Murray & Chiang 1997; Proga et al. 2000; Liu et al. 2013; Nomura et al. 2016; Nomura & Ohsuga 2017). Recently, we found that if a hot corona exists above a standard thin disk, the radiation force due to Thomson scattering can also drive wind from the hot corona (Yang et al. 2018).

AGN wind can also effectively interact with gas surrounding the AGN (e.g., Ostriker et al. 2010; Gan et al. 2014; Weinberger et al. 2017, 2018; Yuan et al. 2018). Wind can directly blow the gas surrounding the AGN away, which will result in the decrease of the black hole accretion rate.

In this paper, we study how the slowly rotating gas falls from the Bondi radius to the black hole. Our computational domain covers a region from 500 \( r_c \) (\( r_c \) is Schwarzschild radius) to the region beyond the Bondi radius. We focus on LLAGNs whose luminosities are smaller than 2\% Ledd. We define an LLAGN to be the accretion flow inside the inner boundary of the simulation domain. In this sense, the LLAGN is not resolved. We take into account the radiation and wind feedbacks from the LLAGN. For the radiation feedback, we consider the Compton heating/cooling effects. Also, the radiation pressure due to the Thomson scattering is taken into account. The feedback by the jet is not taken into account. The reason is as follows. The jet is well collimated with a very small opening angle. In this case, the jet may just pierce through the galaxy and have negligible effects on the gas close to the galactic center. We note that the jet may be important at galaxy cluster scales (Guo 2016; Guo et al. 2018). Our goal is to study the effects of LLAGN feedback on decreasing black hole accretion rate. This may be useful to explain the low emission level of the observed nearby galactic nuclei.

As mentioned above, recent work have studied low-angular-momentum accretion flow around LLAGNs (Bu & Yang 2018; Yang & Bu 2018). In these two works, only the radiation feedback of the LLAGN is taken into account. In the present paper, in addition to radiation feedback, we also consider wind feedback. We find that wind feedback is more effective at decreasing the black hole accretion rate.

We organize our paper as follows. In Section 2, we introduce the numerical method and physical assumptions. In Section 3, we present our results; Section 4 is devoted to a summary and discussion.

2. Numerical Method

In this paper, we set the black hole mass \( M_{\text{BH}} = 10^8 M_\odot \), where \( M_\odot \) is solar mass. We perform two-dimensional numerical simulations using the ZEUS-MP code (Hayes et al. 2006). In spherical coordinates \((r, \theta, \phi)\), we solve the following equations:

\[
\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0, \tag{1}
\]

\[
\rho \frac{dv}{dt} = -\nabla p - \rho \nabla \Phi + \rho F_{\text{rad}}, \tag{2}
\]

\[
\rho \frac{d(e/\rho)}{dt} = -p \nabla \cdot \mathbf{v} + Sc - Br, \tag{3}
\]

where \( \rho, \mathbf{v}, \) and \( e \) are density, velocity, and internal energy, respectively. We adopt the ideal gas equation \( p = (\gamma - 1) \epsilon r \) and set \( \gamma = 5/3 \). The black hole potential is \( \Phi_{\text{BH}} = -GM_{\text{BH}}/(r - r_c) \), with \( G \) being the gravitational constant. \( Br = 3.8 \times 10^{-2} n^2 \sqrt{T} \) is the bremsstrahlung cooling. \( n = n/\mu m_p \) is the number density of gas, with \( \mu \) and \( m_p \) being mean molecular weight and proton mass, respectively. We set \( \mu = 0.5 \). \( T \) is the temperature of the accreting gas.

We summarize the implementations of physics in the simulations in Table 1, and describe them in detail in the following subsections.

2.1. Radiation Feedback

The radiation of the central LLAGN can assert radiation pressure on the accretion gas. In Equation (2), \( p F_{\text{rad}} = \frac{\chi L}{4 \pi r^2} \) is the radiation pressure due to Compton scattering. \( L \) is the luminosity of the LLAGN. The calculation of the luminosity of the central LLAGN will be introduced below. \( \chi \) is the Compton scattering opacity. In addition to radiation pressure, the photons emitted by the LLAGN can also Compton heat/cool the accretion gas. The Compton heating/cooling rate in Equation (3) is

\[
Sc = 4.1 \times 10^{-35} n^2 (T_X - T) \xi, \tag{4}
\]

where \( T_X \) is the Compton temperature of the photons emitted by the central LLAGN. Xie et al. (2017) found that for an LLAGN, the Compton temperature \( T_X \) of the photons is \( \sim 10^8 \) K. In this paper, we set \( T_X = 10^8 \) K. \( \xi = L e^{-\gamma}/n r^2 \) is the ionization parameter, where \( \tau = \int_0^r \rho \omega dr \) is the X-ray scattering optical depth. We set \( \omega_X = 0.4 \) cm\(^2\) g\(^{-1}\).

2.2. Wind Feedback

Winds are frequently observed through blueshifted absorption lines in luminous AGNs (e.g., Crenshaw et al. 2003; Tombesi et al. 2010, 2014; Gofford et al. 2015; King & Pounds 2015; Liu et al. 2015) and soft state of BHBs (e.g.,
Neilsen & Homan 2012; Díaz Trigo & Boirin 2016; Homan et al. 2016).

There are few observations of wind from LLAGNs and the hard state of BHBs. The reason for this may be that hot accretion flow is fully ionized. Therefore, it is hard to detect absorption lines. In recent years, we have found some indirect evidence that wind can also be generated in a hot accretion flow (e.g., Crenshaw & Kraemer 2012; Wang et al. 2013; Cheung et al. 2016; Homan et al. 2016). Recently, the detailed properties of wind from a hot accretion flow were studied by numerical simulations (e.g., Tchekhovskoy et al. 2011; Narayan et al. 2012; Yuan et al. 2012, 2015; Li et al. 2013; see also Moller & Sadowski 2015) and analytical works (e.g., Cao 2011; Wu et al. 2013b; Gu 2015).

Simulations of hot accretion flow with large angular momentum (e.g., Yuan et al. 2015) find that wind can be generated outside 10r_s. Large angular momentum means that the gas angular momentum is comparable to the local Keplerian angular momentum. The absence of wind inside 10r_s is due to the very strong gravity very close to the black hole. The wind is generated by the combination of gas pressure gradient, magnetic pressure gradient, and centrifugal forces. Due to the presence of wind, the mass accretion rate decreases inward. The black hole mass accretion rate can be described as follows (e.g., Yuan et al. 2012, 2015):

$$M_{\text{BH}} = M_{\text{Ro}} \left( \frac{10r_s}{R_H} \right)^{0.5},$$

$R_H$ is the outer boundary of the hot accretion flow; $M_{\text{Ro}}$ is the mass accretion rate at $R_H$. As mentioned in Section 1, in this paper we study slowly rotating accretion flow. We set the circularization radius $r_c = 350r_s$, which is much smaller than the inner radial boundary of the computational domain. When gas flows through the inner boundary, we assume that gas will freely fall to $r_c$. When gas arrives at $r_c$, a viscous hot accretion flow will form. Wind will be generated from the viscous hot accretion flow. Therefore, the outer boundary of the hot accretion flow in Equation (5) is $R_H = r_c$. The mass accretion rate at $R_H$ is equal to the mass accretion rate calculated at the inner radial boundary of our simulation domain ($M_{\text{BH}}$). The mass flux of wind generated in the viscous hot accretion flow is

$$\dot{M}_{\text{wind}} = \dot{M}_{\text{in}} - \dot{M}_{\text{BH}}.$$  \hfill (6)

Yuan et al. (2015) have shown that the radial velocity of wind is only a function of wind-launching radius:

$$v_{\text{wind},r} = 0.21v_k(R_{\text{wind}}).$$  \hfill (7)

$R_{\text{wind}}$ is the wind-launching radius, and $v_k(R_{\text{wind}})$ is the Keplerian velocity at wind-launching radius. Once wind is launched, its radial velocity will not change with the outward propagation of wind. This is because acceleration forces are always exerted on wind with the outward motion of the wind. The work done by these forces can compensate for the increase of the gravitational energy of wind (Yuan et al. 2015). As mentioned above, wind can be generated by hot accretion flow in the region $10r_s < r < R_H$. We can calculate the mass-flux-weighted radial velocity of wind as follows:

$$\bar{v}_{\text{wind},r} = \frac{\int_{10r_s}^{R_H} d(M_{\text{wind}}(r)/dM_{\text{in}}) \cdot v_{\text{wind},r} dr}{\int_{10r_s}^{R_H} d(M_{\text{wind}}(r)/dM_{\text{in}}) dr}. $$  \hfill (8)

According to Equation (6), $dM_{\text{wind}} / dr = dM_{\text{in}} / dr$, with $M_{\text{in}}(r) = M_{\text{Ro}} \left( \frac{r}{R_H} \right)^{0.5}$ (Yuan et al. 2015). We find that with $R_H = r_c = 350r_s$, the mass-flux-weighted wind radial velocity is $0.42v_k(350r_s)$. $v_k(350r_s)$ is the Keplerian angular velocity at $350r_s$. Yuan et al. (2015) found that $v_k$ of wind is negligibly small than the radial velocity. Thus, we set the $v_k$ of wind to be zero. The rotational velocity of wind is found to be just slightly smaller than Keplerian velocity (Yuan et al. 2012, 2015). In this paper, we set the rotational velocity of wind to be

$$V_{\phi,\text{wind}} = 0.9v_k(R_H).$$  \hfill (9)

Yuan et al. (2015) found that the internal energy of wind is about 0.6 times the gravitational energy. In this paper, we set the wind internal energy:

$$e_{\text{wind}} = \frac{0.6GM_{\text{BH}}}{R_H}. $$  \hfill (10)
inner radial boundary in the region $30^\circ < \theta < 70^\circ$. The injected mass flux of wind is given by Equation (6). In the region $30^\circ < \theta < 70^\circ$, we assume that the wind mass flux is independent of $\theta$.

2.3. Luminosity of the Central LLAGN

The luminosity of the central LLAGN depends on the black hole mass accretion rate, and radiative efficiency of hot accretion flow. The black hole accretion rate is calculated by Equation (5). Xie & Yuan (2012) found that the radiative efficiency depends on black hole accretion rate and the parameter $\delta$ that describes the fraction of direct viscous heating to electrons. The radiative efficiency is as follows (Xie & Yuan 2012):

$$\epsilon (M_{\text{BH}}) = \epsilon_0 \left( \frac{100M_{\text{BH}}}{M_{\text{Edd}}} \right)^a,$$

$$M_{\text{Edd}} = L_{\text{Edd}}/0.1c^2$$ is the Eddington accretion rate; $\epsilon_0$ and $a$ for the case of $\delta = 0.5$ can be described as

$$\epsilon_0, a = \begin{cases} 
(1.58, 0.65) & \text{if } \frac{M_{\text{BH}}}{M_{\text{Edd}}} \lesssim 2.9 \times 10^{-5}; \\
(0.055, 0.076) & \text{if } 2.9 \times 10^{-5} < \frac{M_{\text{BH}}}{M_{\text{Edd}}} \lesssim 3.3 \times 10^{-3}; \\
(0.17, 1.12) & \text{if } 3.3 \times 10^{-3} < \frac{M_{\text{BH}}}{M_{\text{Edd}}} \lesssim 5.3 \times 10^{-3}. 
\end{cases}$$

When $\frac{M_{\text{BH}}}{M_{\text{Edd}}} > 5.3 \times 10^{-3}$, the radiative efficiency $\epsilon (M_{\text{BH}})$ is simply set to be 0.1.

2.4. Initial and Boundary Conditions

In the radial direction, our computational domain is 500 $r_s \leq r \leq 10^9 r_s$. In the $\theta$ direction, we have $0 \leq \theta \leq \pi/2$. In total, we have 140 $\times$ 80 grids. In the $r$ direction, the grids are logarithmically spaced. In the $\theta$ direction, grids are uniformly spaced. Initially, in the whole computational domain, gas has uniform density ($\rho_0$) and temperature ($T_0$). The specific angular momentum of gas is equal to the Keplerian angular momentum at $r_c = 350r_s$.

In the models with wind feedback, at the inner radial boundary, in the region $30^\circ < \theta < 70^\circ$, wind is injected into the computational domain. The density, velocity, and internal energy of injected wind are set according to Equations (6), (8)–(10). In the regions $0^\circ < \theta \leq 30^\circ$ and $70^\circ \leq \theta < 90^\circ$, we use outflow boundary conditions. For the outflow boundary conditions, gas is not allowed to flow into the computational domain. The physical variables in the ghost zones are set to be equal to those in the first active zone. In the models without wind feedback, at the inner radial boundary, for the whole $\theta$ angle ($0^\circ \leq \theta \leq 90^\circ$), we use outflow boundary conditions.

We set the outer radial boundary conditions as follows. If the radial velocity at the last active zone at a fixed $\theta$ angle is negative, at this $\theta$ angle, we inject gas into the computational domain. The density, temperature, and specific angular momentum of the injected gas are equal to those for the initial conditions. If the radial velocity at the last active zone at a fixed $\theta$ angle is positive, at this $\theta$ angle, we use outflow boundary conditions. Gas is not allowed to flow into the computational domain.

At the rotational axis, axis-of-symmetry boundary conditions are applied. We use reflecting boundary conditions at the equatorial plane.

3. Results

In what follows, we use “wind” to denote the mass output of the central LLAGN, which is injected into the computational domain at the inner radial boundary (see Section 2.2) in models with wind feedback. We use “outflow” to denote the outward moving gas in the computational domain of our simulations.

The properties of wind and radiation generated from the central LLAGN are introduced in Section 2. We now compare the powers and momentum fluxes carried by wind and radiation.

The power of wind includes kinetic power and thermal power,

$$\dot{E}_{\text{wind}} = M_{\text{wind}} \left( \frac{1}{2}v_{\text{wind}}^2 + e_{\text{wind}}/\rho_{\text{wind}} \right).$$

For the momentum flux of wind, we only consider the radial momentum flux,

$$\dot{P}_{\text{wind}} = M_{\text{wind}} v_{\text{wind},r}.$$  

The momentum flux of radiation from the central LLAGN is

$$\dot{P}_{\text{rad}} = L/c.$$
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### Table 2
Simulation Parameters and Results

| Model     | Radiation Feedback | Wind Feedback | \(\rho_0\) \(\times10^{24}\) g cm\(^{-3}\) | \(M(\tau_{\text{in}})/M_\odot\) | \(L/L_{\text{Edd}}\) | \(P_\text{K}(\tau_{\text{in}})\) \(L_{\text{Edd}}\) |
|-----------|-------------------|--------------|-------------------------------|------------------|------------------|------------------|
| noFB26    | OFF               | OFF          | 0.01                          | 0.1              | 1.2 \times 10^{-10} | 1.4 \times 10^{-11} |
| radFB26   | ON                | OFF          | 0.01                          | 0.11             | 1.3 \times 10^{-10} | 1.5 \times 10^{-11} |
| windFB26  | OFF               | ON           | 0.01                          | 3.9 \times 10^{-2} | 3.3 \times 10^{-11} | 5.4 \times 10^{-10} |
| fullFB26  | ON                | ON           | 0.01                          | 2.8 \times 10^{-2} | 2.1 \times 10^{-11} | 3.5 \times 10^{-10} |
| noFB24    | OFF               | OFF          | 1                             | 0.12             | 3.9 \times 10^{-7}  | 1.5 \times 10^{-9}  |
| radFB24   | ON                | OFF          | 1                             | 0.12             | 3.8 \times 10^{-7}  | 1.49 \times 10^{-9} |
| windFB24  | OFF               | ON           | 1                             | 3.7 \times 10^{-2} | 6.2 \times 10^{-8}  | 4.9 \times 10^{-8}  |
| fullFB24  | ON                | ON           | 1                             | 1.9 \times 10^{-2} | 2.4 \times 10^{-8}  | 2.2 \times 10^{-8}  |
| noFB22    | OFF               | OFF          | 100                           | 1.05             | 1.5 \times 10^{-2}  | 0                |
| radFB22   | ON                | OFF          | 100                           | 0.42             | 5.8 \times 10^{-3}  | 2.7 \times 10^{-9}  |
| windFB22  | OFF               | ON           | 100                           | 1.5 \times 10^{-2} | 10^{-4}              | 6.4 \times 10^{-6}  |
| fullFB22  | ON                | ON           | 100                           | 6.2 \times 10^{-2} | 4.5 \times 10^{-4}  | 4.3 \times 10^{-5}  |

**Note.** Column 1: model names. Column 4: the density for initial condition. Column 5: time-averaged mass accretion rate (in units of Bondi rate) measured at the inner boundary of the simulation domain. Column 6: time-averaged luminosity of the black hole. Column 7: time-averaged mechanical energy flux (in units of Eddington luminosity) of outflow measured at the outer boundary. For models with \(\rho_0 = 10^{-24}\) g cm\(^{-3}\) and \(\rho_0 = 10^{-26}\) g cm\(^{-3}\), we find the time-average from \(t = 0\) to \(2 \times 10^7\) yr. For models with \(\rho_0 = 10^{-22}\) g cm\(^{-3}\), we find the time-average from \(t = 1.2 \times 10^7\) to \(2.5 \times 10^8\) yr.

When \(M_{\text{BH}}/M_{\text{Edd}} < 3 \times 10^{-6}\), wind power dominates radiation power. When \(M_{\text{BH}}/M_{\text{Edd}} > 3 \times 10^{-6}\), radiation power is much larger than wind power. The interaction efficiency of wind and radiation with the accretion gas at large radii does not only depend on their powers. The reason is that the cross section of proton–particle and particle–particle interactions differs by several orders of magnitude (Yuan et al. 2018). The cross section of photon–particle interaction is the Thompson scattering cross section, \(\sigma_T = 6.65 \times 10^{-25}\) cm\(^2\). The cross section of Coulomb particle–particle interaction is \(\sigma_C \sim \pi e^4/kT^2\), where \(e\) is electron charge, and \(k\) is the Boltzmann constant. The distances taken for wind and photons to convert their energy and momentum to accretion gas at large radii can be quite different. Following Yuan et al. (2018), we define the “typical length scale of feedback” for wind \(l_{\text{wind}}\) (wind) and radiation \(l_{\text{rad}}\) (rad). They are the distances taken for winds and photons to convert a significant fraction of their energy and momentum to gas. The length scale of feedback is the mean free path of photons and wind particles. The length scale of feedback is the distance for optical depth \(\sim 1\). The typical length scale of radiation feedback is \(\sigma_T l_{\text{rad}}/\rho_0 = 1\). Therefore, we have

\[
l_{\text{rad}} = m_p/\rho_0 \sigma_T = 2.5 \times 10^{24} \rho_0^{-1} \text{ cm} \approx 10^9 \rho_0^{-1} \text{ pc},
\]

where \(\rho_0 = 10^8 M_\odot\). \(l_{\text{rad}} \sim 10^{11} \rho_0^{-1} T_{70}^{-1} r_s\). For wind feedback, the typical length scale of feedback is

\[
l_{\text{wind}} = m_p/\rho_0 \sigma_C = 1.7 \times 10^9 \rho_0^{-1} T_{70}^2 \text{ cm} \approx 5 \rho_0^{-1} T_{70}^2 \text{ pc},
\]

where \(T_7 = T/10^7\) K. For \(M_{\text{BH}} = 10^8 M_\odot\), we have \(l_{\text{wind}} = 5 \times 10^5 \rho_0^{-1} T_{70}^2 r_s\).

We list all the models in Table 2. The gas temperature at the Bondi radius for the sources collected in Pellegrini (2005) is in the range \(2 \times 10^6\) K \(-\) \(10^7\) K. In all the models, we set the initial gas temperature \(T_0 = 7 \times 10^6\) K.

#### 3.1. Models with \(\rho_0 = 10^{-24}\) g cm\(^{-3}\)

For models with \(\rho_0 = 10^{-24}\) g cm\(^{-3}\), the accretion rate is significantly smaller than \(M_{\text{Edd}}\). Bremsstrahlung radiative cooling is not important. When we calculate the Bondi accretion rate, we set \(\gamma = 5/3\). Figure 2 shows the time evolution of the mass accretion rate (in units of \(M_\odot\)) measured at the inner boundary. The horizontal solid line in each panel corresponds to the time-averaged value. From top to bottom, the panels correspond to models noFB24, radFB24, windFB24, and fullFB24, respectively.

For the no-feedback model (noFB24), one would expect the mass accretion rate to equal the Bondi accretion rate. However, we find that in this model, an outflow is present. Due to the presence of an outflow, the mass accretion rate is much smaller than the Bondi accretion rate. In our models, we inject gas with \(T = 7 \times 10^6\) K at the radial outer boundary. For \(T = 7 \times 10^6\) K, the Bondi radius is located at \(4.6 \times 10^5 r_s\). Therefore, the injected gas at the outer boundary \(10^5 r_s\) has a positive Bernoulli parameter. The mass accretion rate in this model is very low. The bremsstrahlung cooling timescale is much longer than the gas infall timescale \((r/v)\). Therefore, radiative cooling can be neglected. The gas has enough energy to form outflows. Proga & Begelman (2003) studied low-angular-momentum hot accretion flow without radiative cooling, and also found that an outflow can be produced.

Comparing models noFB24 and radFB24 shown in Figure 2, we see that the evolution patterns of the accretion rate are roughly the same. Also, both the magnitude of fluctuation and the time-averaged values of mass accretion rate are also the same. Therefore, radiation feedback plays a negligible role. The reasons are as follows. For radiation feedback, we consider both the radiation pressure due to Thompson scattering and Compton heating/cooling. The luminosity in model radFB24 is significantly smaller than the Eddington value (see Table 1). Therefore, the radiation pressure is negligibly small compared to gravity. We have calculated the time and \(\theta\) averaged value for density in model radFB24, and found that the averaged density decreases with increasing radius. The averaged value of density is in the range \(10^{-22}\) to \(10^{-20}\) g cm\(^{-3}\). According to
deposit its energy into the accretion flow. We have also calculated the optical depth of Thompson scattering using the time-averaged density and found that the scattering optical depth is $\tau \sim 1.4 \times 10^{-4}$. Therefore, radiation can only deposit $\sim 10^{-4}$ of its energy into the accretion flow. We have also compared the Compton heating timescale ($\tau_{\text{fi}}$) to the gas infall timescale ($r/v_{\text{f}}$). We find that the Compton heating timescale is several orders of magnitude longer than the gas infall timescale. Therefore, radiation feedback is not important.

In model windFB24, the time-averaged mass accretion rate is 3.2 times smaller than that in model noFB24. Wind can push away the gas surrounding the LLAGN, which will decrease the mass accretion rate. In model windFB24, the maximum accretion rate can be two orders of magnitude higher than the minimum accretion rate. In model noFB24, the maximum accretion rate is just one order of magnitude higher than the minimum accretion rate. After considering wind feedback, the fluctuation magnitude of the mass accretion rate is significantly enhanced. The reason for the fluctuation is as follows. When the accretion rate is high, the wind is strong. Strong wind will push the gas surrounding the LLAGN away, which will decrease the mass supply rate for the LLAGN. The LLAGN will enter into a low-accretion-rate stage. Then, when wind becomes weak, the gas will fall onto the central region again. Then, the accretion rate becomes higher again.

In order to study the detailed effects of wind feedback, we plot Figure 3. The top panel shows radial profiles of time-averaged (from $t = 0$ to $2 \times 10^5$ yr) mass inflow rate (solid lines) and outflow rate (dashed lines) for models noFB24 (black lines) and windFB24 (red lines). In model noFB24, outflow is only strong outside $2 \times 10^5 r_\odot$. Inside $2 \times 10^5 r_\odot$, the mass outflow rate is significantly smaller than the mass inflow rate. In model windFB24, outflow is strong in the whole computational domain. Also, the outflow rate is almost equal to the mass inflow rate. Therefore, in model windFB24, the mass inflow rate keeps decreasing from the outer boundary to the inner boundary. The mass accretion rate at the inner boundary in model windFB24 is smaller than that in model noFB24. Due to the stronger outflow, the gas density in model windFB24 is much smaller than that in model noFB24 (see middle panel of Figure 3). The wind feedback can also convert some energy of the wind to internal energy of accretion flow. Therefore, the gas temperature in model windFB24 is higher than that in model noFB24 (see the bottom panel of Figure 3).

In order to see the geometry of the outflow, we plot Figures 4 and 5. In Figure 4, we plot two-dimensional time-averaged (from $t = 0$ to $2 \times 10^5$ yr) properties of models noFB24 (left panel) and windFB24 (right panel). The colors show logarithm temperature in units of virial temperature; the vectors show unit velocity vector. Figure 5 is a zoomed-in view of the right panel of Figure 4. From these figures, we see that the time-averaged flow is very ordered. However, we note that the snapshot of the accretion flows is very disordered. For the model noFB24, an outflow is clearly present outside $2 \times 10^5 r_\odot$, which is consistent with what we introduced above (see top panel of Figure 3). From the right panel of Figures 4 and 5, we see that in model windFB24, an outflow is present from the inner boundary to the outer boundary. Wind is injected in the region $30^\circ < \theta < 70^\circ$.  

Equation (16), the length scale of radiation feedback is $\sim 10^3 - 10^4 r_\odot$, which is significantly larger than the outer boundary of our simulation. Radiation cannot effectively

Figure 2. Time evolution of the mass accretion rate (in unit of Bondi accretion rate $\dot{M}_B$) measured at the inner boundary. The Bondi accretion rate is calculated by setting $\gamma = 5/3$. The horizontal solid line corresponds to the time-averaged (from $t = 0$ to $2 \times 10^5$ yr) value. From top to bottom, the panels correspond to models noFB24, radFB24, windFB24, and fullFB24, respectively.
When it moves outward, it changes its direction to $0^\circ < \theta < 45^\circ$. When wind moves outward, more and more gas from inflowing region joins the wind. Therefore, the outflow mass flux increases with increasing radius.

Comparing models windFB24 and fullFB24 (see Figure 2), we can see that the magnitude of mass accretion rate fluctuation in these two models is roughly the same. This indicates that the fluctuation is mainly due to the effect of wind feedback. The averaged mass accretion rate in model fullFB24 is $\sim$2 times smaller than that in model windFB24. Radiation plays some role in reducing the mass accretion rate in model fullFB24. We note that the two-dimensional geometry of outflow in model fullFB24 is quite similar to that in model windFB24 shown in Figure 4. Therefore, we do not show it here.

The black hole luminosity listed in Table 2 is calculated using the radiative efficiency shown in Equation (11). The radiative efficiency decreases with the decrease of mass accretion rate. Comparing model noFB24 to model fullFB24, we see that when feedback is taken into account, the mass accretion rate can be decreased by a factor $\sim$6.4. However, with the decrease of accretion rate, radiative efficiency is also decreased. Therefore, the black hole luminosity in model fullFB24 is 16 times smaller than that in model noFB24. If the black hole accretes at the Bondi rate $\dot{M}(r_{\text{in}}) = M_\text{B}$, we will have a black hole luminosity $L = 10^{-5} L_{\text{Edd}}$. In the model without feedback (noFB24), due to the presence of outflow, the accretion rate is much smaller than the Bondi value. Correspondingly, the luminosity is decreased by a factor of 25. When feedback is considered, the luminosity is decreased by another factor of $\sim$16. The black hole luminosity in model fullFB24 is $\sim$400 times smaller than that predicted by the Bondi formula.

The mechanical energy flux of outflow is an important parameter in the study of AGN feedback. The mechanical energy flux of outflow is calculated as follows:

$$P_K(r) = 2\pi r^2 \int_0^{90^\circ} \rho \max(v_r^2, 0) \sin \theta d\theta. \quad (18)$$

The mechanical energy flux of outflow measured at the outer boundary for all of our models is summarized in column 7 of Table 2.

We also perform simulations with lower density ($\rho_0 = 10^{-26} \text{ g cm}^{-3}$); they are models of noFB26, radFB26, windFB26, and fullFB26. We find that the results are quite similar to those in models with $\rho_0 = 10^{-24} \text{ g cm}^{-3}$. The reason for this is as follows. In all models with $\rho_0 = 10^{-26} \text{ g cm}^{-3}$ and $\rho_0 = 10^{-24} \text{ g cm}^{-3}$, the mass accretion rate is significantly smaller than the Eddington rate. Therefore, in these models, the bremsstrahlung radiative cooling rate is all negligibly small. As mentioned above, radiation feedback is not important in models with $\rho = 10^{-24} \text{ g cm}^{-3}$. According to Equation (16), the length scale of radiation feedback in models radFB26 and fullFB26 is even longer than that in models radFB24 and fullFB24. Therefore, radiation feedback in all models with $\rho_0 = 10^{-26} \text{ g cm}^{-3}$ and $\rho_0 = 10^{-24} \text{ g cm}^{-3}$ is also not important. The accretion flows in these models are all evolving adiabatically. Therefore, from Figures 2 and 6, we see that time-averaged value of accretion rate (in units of Bondi rate) and the magnitude of accretion rate fluctuations are all quite similar in models noFB24, radFB24, noFB26, and radFB26. The results of model windFB26 are quite similar to those of model fullFB26. Other properties of accretion flow (e.g., velocity field, density, and temperature profiles) in models with $\rho_0 = 10^{-26} \text{ g cm}^{-3}$ are all quite similar to those in their counterpart models with $\rho_0 = 10^{-24} \text{ g cm}^{-3}$.

### 3.2. Models with $\rho_0 = 10^{-22} \text{ g cm}^{-3}$

If radiative cooling is not important, when gas falls inward, gas temperature will increase. For two models with $\rho_0 = 10^{-22} \text{ g cm}^{-3}$, we note that...
$10^{-22}$ g cm$^{-3}$ (noFB22, radFB22), we find that at the region around the outer boundary ($5 \times 10^3 - 10^5 r_c$), the bremsstrahlung radiative cooling timescale can be shorter than the gas infall timescale. Radiative cooling is important in this region. Gas temperature does not increase inward. Gas temperature in this region is almost a constant with radius. Therefore, when we calculate the Bondi accretion rate in the models in this subsection, we set $\gamma = 1$.

Figure 7 shows the time evolution of the mass accretion rate. For model noFB22, the mass accretion rate quickly increases from $t = 0$ to $5 \times 10^4$ yr. When $t > 1.2 \times 10^7$ yr, the flow achieves a quasi-steady state. The mass accretion rate approximately equals the Bondi rate. In this model, outflow does not exist. The Bernoulli parameter of the injected gas at the outer boundary is positive. When gas falls toward the center, bremsstrahlung radiation cools the gas. The Bernoulli parameter decreases inward. We find that when $r < 1.4 \times 10^5 r_c$, the Bernoulli parameter becomes negative. The gas does not have enough energy to form an outflow. The time-averaged luminosity is $1.5\%L_{Edd}$. A hot accretion flow can only be present when $L < 2\%L_{Edd}$ (Yuan & Narayan 2014). We find that when $\rho_0 > 10^{-22}$ g cm$^{-3}$, if no feedback is considered, the luminosity of the black hole will exceed $2\%L_{Edd}$. Therefore, in this paper, we do not consider accretion flow with $\rho_0 > 10^{-22}$ g cm$^{-3}$. The reason for the oscillation of the mass accretion rate is as follows. In this model, the gas has a rotational velocity. Also, bremsstrahlung radiative cooling is present. The flow is not in exact equilibrium. Compared with models with wind feedback, the magnitude of oscillation of the mass accretion rate is very small.

For model radFB22, we also find that the mass accretion rate quickly increases from $t = 0$ to $5 \times 10^4$ yr. When $t > 10^5$ yr, the flow achieves a quasi-steady state. We find that when $t > 10^7$ yr, the mass accretion rate oscillates around its mean value. The oscillation is due to the episodic generation of outflow outside $10^5 r_c$. We introduced the properties of Compton-heating-launched outflow in Bu & Yang (2018). For convenience, we also briefly introduce it here. In the region $r > 10^5 r_c$, the gas temperature is lower than the Compton temperature of the photons emitted by the LLAGN. Therefore, gas in this region can be Compton-heated. We also calculate the radiative cooling $(e/Br)$ and gas infall $(r/v_r)$ timescales in this region. We find that the Compton heating timescale $(e/Sc)$ is shorter than both the radiative cooling and gas infall timescales. Therefore, the gas temperature in the region $r > 10^5 r_c$ can be Compton-heated to be above local virial temperature. An outflow can form in this region. We note that the outflow is present episodically. The reason for this is as follows. When the accretion rate is high, the black hole luminosity is high. Therefore, the Compton heating rate is high and an outflow can form. When an outflow forms, gas will be taken away. The black hole accretion rate will become low. Then the Compton heating will become unimportant due to the decrease of luminosity (or accretion rate). The outflow will disappear. The gas will cool and fall to the center again. The black hole accretion rate will become high again. Comparing this model with noFB22, we find that the time-averaged accretion rate is reduced by a factor of 2. Correspondingly, the black luminosity also decreased by a factor of $\sim 2$.

Compared to the models with $\rho_0 = 10^{-24}$ g cm$^{-3}$, radiation feedback in models with $\rho_0 = 10^{-22}$ g cm$^{-3}$ is more efficient. This is because that the length scale for radiation feedback decreases with the increase of gas density (Equation (16)). However, the effects of radiation feedback are still less important than those of wind feedback when $\rho_0 = 10^{-22}$ g cm$^{-3}$ (see the next paragraph).

From the third panel of Figure 7 we see that in the model windFB22, wind can effectively interact with the accretion flow. Due to the presence of wind feedback, the time-averaged
accretion rate is significantly decreased. The time-averaged mass accretion rate in model windFB22 is $\sim 100$ times smaller than that in model noFB22. For the models with $\rho_0 = 10^{-24} \text{ g cm}^{-3}$, wind feedback can only decrease the mass accretion rate by a factor of $\sim 3$ (see Table 1). In model windFB22, the wind power is significantly higher than that in model windFB24 (see Figure 1). Also, the length scale of wind feedback in model windFB22 is much smaller than that in model windFB24. Therefore, compared to models with $\rho_0 = 10^{-24} \text{ g cm}^{-3}$, the
In order to study the individual effects of radiation and wind feedback, we plot Figure 8. The top panel shows the radial profiles of time-averaged (from \( t = 1.2 \times 10^5 \) to \( 2.5 \times 10^5 \) yr) mass inflow rate (solid lines) and outflow rate (dashed lines) for models radFB22 (black lines) and windFB22 (red lines). As mentioned above, in model radFB22, outflow can be driven by Compton heating outside \( 10^5 r_\odot \). Inside \( 10^5 r_\odot \), Compton heating is not important because the Compton heating timescale is much longer than the gas infall timescale. Inside \( 10^5 r_\odot \), Compton scattering even plays a cooling role, because in this region, gas temperature is much higher than the Compton temperature. In model windFB22, the outflow is strong in the whole computational domain, and the mass inflow rate keeps decreasing from the outer boundary to the inner boundary. Due to the strong outflow in model windFB22, the mass accretion rate at the inner boundary is significantly reduced. Also, the gas density in model windFB22 is much smaller than that in model radFB22 (see middle panel of Figure 8). As mentioned above, the wind feedback can also convert some energy of wind to the internal energy of accretion flow. Therefore, the gas temperature in model windFB22 is higher than that in model radFB22 (see the bottom panel of Figure 8).

We showed in our previous paper that the outflow in model radFB22 is spherically distributed (see Figure 1 in Bu & Yang 2018). This is because that in this model, the outflow is launched due to Compton heating. The Compton heating rate is spherically distributed. Here, we study, in the case of wind feedback, what is the geometry of the outflow. This is explored in Figures 9 and 10. In the left panel of Figure 9, we plot time-averaged (from \( t = 1.2 \times 10^5 \) to \( 2.5 \times 10^5 \) yr) logarithm density (colors); the vectors show time-averaged (from \( t = 1.2 \times 10^5 \) to \( 2.5 \times 10^5 \) yr) velocity vector. We see that in the region \( 30^\circ < \theta < 80^\circ \), the gas flows inward. Outflows are present close to the rotational axis (\( \theta < 30^\circ \)) and around the midplane. The outflow velocity around the rotational axis is much higher than that around the midplane. The outflow density around the midplane is much higher than that in the region close to the rotational axis. In the right panel of Figure 9, the colors show the time-averaged (from \( t = 1.2 \times 10^5 \) to \( 2.5 \times 10^5 \) yr) logarithm temperature in units of virial temperature; the vectors show time-averaged (from \( t = 1.2 \times 10^5 \) to \( 2.5 \times 10^5 \) yr) unit velocity vector. It is clear that in the outflow region, the gas temperature is higher than the virial temperature. Outflows are pushed out by the gas pressure gradient force. In the inflow region, the gas temperature is much lower than the virial temperature. Figure 10 is zoomed-in view of the right panel of Figure 9. One portion of the injected wind moves outward in the region \( \theta > 45^\circ \). The other portion collides with the infall gas. The infall gas becomes outflow after colliding and moves outward around the midplane. The time-averaged flow is very ordered. However, we note that the snapshot of the velocity field is very tangled. Figure 11 shows the distribution of time-averaged (from \( t = 1.2 \times 10^5 \) to \( 2.5 \times 10^5 \) yr) mass outflow rate with \( \theta \) at the outer radial boundary. It is clear that the outflow mass flux in the region close to the midplane is comparable to that around the rotational axis.

The magnitude of fluctuation of the accretion rate in model fullFB22 is larger than that in model windFB22 (Figure 7). This is because in model fullFB22, both radiation and wind feedbacks exist. In windFB22, only wind feedback is included. The time-averaged mass accretion rate in model fullFB22 is larger than that in model windFB22 by a factor of \( \sim 4 \). This is a
surprising result, because one would expect that with the help of radiation feedback, the mass accretion rate should be much smaller in model fullFB22 than that in model windFB22. The reason for a higher mass accretion rate in model fullFB22 is as follows. We find that in model fullFB22, in the region \( r < 3 \times 10^4 r_s \), the gas temperature is higher than \( 10^8 \) K. Therefore, in the region \( r < 3 \times 10^4 r_s \), Compton scattering plays a cooling role. We find that in the region \( r < 3 \times 10^4 r_s \), the gas temperature in model fullFB22 is lower than that of model windFB22. Correspondingly, in this region, the gas density in model fullFB22 is higher than that in model windFB22. The radial infall velocities in these two models are roughly the same. Therefore, the black hole mass accretion rate in model fullFB22 is higher than that in model windFB22. The black hole luminosity in model fullFB22 is \( \sim 33 \) times smaller than that in model noFB22. The time-averaged outflow geometry in model fullFB22 is quite similar to that in model windFB22 shown in Figure 9. This is because in model fullFB22, outflow is mainly launched due to wind feedback.

Figure 9. Two-dimensional properties of model windFB22. Left panel: the colors show time-averaged (from \( t = 1.2 \times 10^5 \) to \( 2.5 \times 10^5 \) yr) logarithm density; the vectors show time-averaged (from \( t = 1.2 \times 10^5 \) to \( 2.5 \times 10^5 \) yr) velocity vector. The lengths of the vectors show the velocity magnitude. Right panel: the colors show time-averaged (from \( t = 1.2 \times 10^5 \) to \( 2.5 \times 10^5 \) yr) logarithm temperature in unit of virial temperature; the vectors show time-averaged (from \( t = 1.2 \times 10^5 \) to \( 2.5 \times 10^5 \) yr) unit velocity vector.

Figure 10. Zoomed-in view of the right panel of Figure 9.

Figure 11. Distribution of time-averaged (from \( t = 1.2 \times 10^5 \) to \( 2.5 \times 10^5 \) yr) mass outflow rate with \( \theta \) at the outer radial boundary. Mass flux is in units of Bondi accretion rate.

4. Summary and Discussion

We perform two-dimensional simulations to study slowly rotating low-luminosity hot accretion flow at parsec and subparsec scales. The feedback effects of radiation and wind from the central LLAGN are taken into account. We set the black hole mass \( M = 10^8 M_\odot \).

We set the gas density at the outer boundary to be \( \rho_0 = 10^{-20} \) g cm\(^{-3}\) and \( \rho_0 = 10^{-22} \) g cm\(^{-3}\). Due to the low gas density, the accretion flow is in hot accretion mode. Due to the low gas density, the length scale of radiation feedback (see Equation (16)) is very large. In other words, the Thompson scattering optical depth of the accretion flow is very small. Radiation cannot effectively deposit its energy to the accretion flow. Radiation feedback plays a very minor role in quenching the black hole accretion.

The typical length scale of wind feedback is very small. Wind can effectively interact with the accretion flow. Due to the wind feedback, the accretion rate strongly oscillates with time. In the accretion flows with \( \rho_0 = 10^{-24} \) g cm\(^{-3}\), we find that outflow can be present even without feedback from the central LLAGN.
If we consider the wind feedback of the central LLAGN, the mass accretion rate can be decreased by a factor of \(~3\) compared to models without wind feedback. The luminosity in the model with both radiation and wind feedback can be smaller than that predicted by the Bondi accretion rate by a factor of 400.

In the accretion flows with higher density ($\rho_0 = 10^{-22}$ g cm$^{-3}$), wind power is significantly higher. Therefore, wind feedback is more efficient at suppressing the black hole mass accretion rate. Wind feedback can decrease the black hole mass accretion rate by a factor of 100. We find that in the model with full feedback (fullFB2), the black hole luminosity is smaller than that predicted by the Bondi formula by a factor of 33.

Pellegrini (2005) calculated the luminosity for many local universe dim galactic nuclei. In her calculation, the black hole accretion rate is assumed to be equal to the Bondi accretion rate. The radiative efficiency used in that paper is $\eta \propto M$, which is given by the ADAF model (Narayan & Yi 1995). In that paper, it was found that the calculated black hole luminosity is significantly higher than observations of many local universe galactic nuclei. In this paper, we find that for the accretion flow, self-consistently taking into account wind and radiation feedback, the black hole luminosity can be significantly lower than that predicted by the Bondi formula. The results in this paper may be useful for explaining the low-luminosity of galactic nuclei in the local universe.

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