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# The relationship between black hole accretion rate and gas properties at the Bondi radius

**De-Fu Bu**

Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China
email: dfbu@shao.ac.cn

**Abstract.** The mass accretion rate determines the black hole accretion mode and the corresponding efficiency of active galactic nuclei (AGNs) feedback. In large-scale simulations studying galaxy formation and evolution, the Bondi radius can be at most marginally resolved. In these simulations, the Bondi accretion formula is always used to estimate the black hole accretion rate. The Bondi solution can not represent the real accretion process. We perform 77 simulations with varying density and temperature at Bondi radius. We find a formula to calculate the black hole accretion rate based on gas density and temperature at Bondi radius. We find that the formula can accurately predict the luminosity of observed low-luminosity AGNs. This formula can be used in sub-grid models in large-scale simulations with AGNs feedback.

**Keywords.** accretion, accretion discs, black hole physics, hydrodynamics, galaxies:active, galaxies:nuclei

## 1. Introduction

Mass accretion rate is a key parameter in black hole accretion physics. It determines the accretion mode and the spectrum of a black hole system. AGN feedback plays an important role in the evolution of their host galaxy (Fabian 2012). AGNs outputs including wind (Li & Begelman 2014), radiation (Giotti & Ostriker 2001) and jet (Guo 2016) depend on accretion mode of the black hole. Different accretion modes can have very different AGNs feedbacks.

In large-scale simulations studying galaxy formation and evolution, the Bondi radius can be at most marginally resolved (e.g. Springel *et al.* 2005; Yuan *et al.* 2018). In these simulations, the Bondi formula is usually used to estimate the black hole accretion rate. The black hole growth and accretion mode are determined by the Bondi solution. The Bondi accretion model is simple but has some problems (Waters *et al.* 2019). For example, in the Bondi solution, it is assumed that the accretion rate is constant with radius in the region between black hole horizon and Bondi radius. In reality, due to the presence of wind, the accretion rate decreases from the Bondi radius towards the black hole. Some previous works (e.g. Igumenshchev & Narayan 2002; Moscibrodzka 2006; Gaspari *et al.* 2013) have shown that the Bondi formula is not a good estimate when calculating the black hole accretion rate.

We aim to find an analytical formula to calculate the real accretion rate onto the black hole as a function of density and temperature at the Bondi radius (see Bu & Yang 2019). We focus on low luminosity active galactic nuclei (LLAGNs), which has a luminosity lower than 2% Eddington luminosity. The accretion mode for LLAGNs is hot accretion flow (see Yuan & Narayan 2014 for reviews). Although radiation and wind of a LLAGN

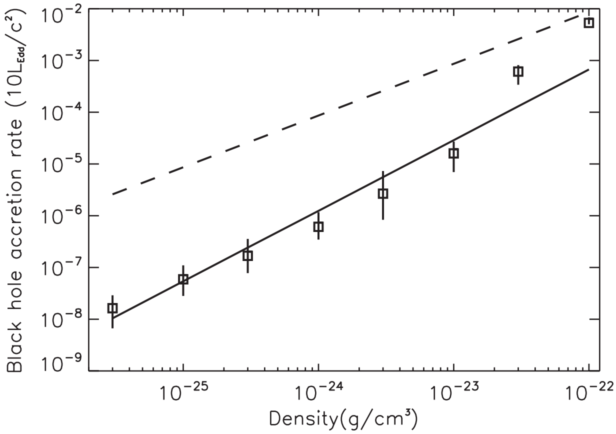


**Figure 1.** Black hole accretion rate in unit of Eddington rate versus gas density at Boundi radius, with gas temperature at Bondi radius fixed to be $10^7$K. The solid line is from Equation (3.1). Squares correspond to time-averaged values of each simulation. The error bars over-plotted represent the change range of simulations owing to fluctuations. The dashed line is calculated by using Bondi formula, assuming adiabatic index $\gamma = 5/3$.

are not as strong as those for luminous AGNs, the AGNs spend most of its time in the LLAGN phase. Therefore, the cumulative effects of LLAGN (or hot accretion mode) feedback should be important (Yuan *et al.* 2018).

## 2. Numerical method

We set the black hole mass to be $10^8$ solar mass. We consider slowly rotating accretion flows in the region $500r_s$–$10^6r_s$ ($r_s$ is the Schwarzschild radius). The accretion flow is irradiated by the photons from the region very close to the black hole. Because we focus on LLAGN, we assume that the photons from the region very close to the black hole are all X-ray photons. The gas can be Compton heated/cooled by the X-ray photons. The Compton temperature of the X-ray photons is set to be $10^8$K (Xie *et al.* 2017). We can calculate the mass accretion rate at the inner radial boundary of the simulations. According to the simulation results of hot accretion flow (Yuan *et al.* 2012), we can know how the accretion rate changes with radius inside our inner radial boundary ($500r_s$). Then the black hole accretion rate can be calculated. The luminosity of the accretion flow can also be calculated by combining accretion rate and radiative efficiency (Xie & Yuan 2012).

## 3. Results

We perform 77 simulations with different gas densities and temperatures at the Bondi radius. We use power-law function of density and temperature at Bondi radius to fit the simulation results. We find that the black hole accretion rate can be described as follows,

$$\frac{\dot{\mathrm{M}}_{\mathrm{BH}}}{\dot{\mathrm{M}}_{\mathrm{Edd}}} = 10^{-3.11}\left(\frac{\rho_0}{10^{-22}\mathrm{g}\cdot\mathrm{cm}^{-3}}\right)^{1.36}\left(\frac{T_0}{10^7\mathrm{K}}\right)^{-1.9} \tag{3.1}$$

where $\dot{\mathrm{M}}_{\mathrm{BH}}$ and $\dot{\mathrm{M}}_{\mathrm{Edd}}$ are black hole mass accretion rate and Eddington accretion rate, respectively. $\rho_0$ and $T_0$ are gas density and temperature at Bondi radius.

We compare the results with the Bondi solution. Figure 1 shows the black hole accretion rate as a function of gas density at the Bondi radius. In order to plot Figure 1, we set $T_0 = 10^7$K. It is clear that the Bondi formula can over estimate the accretion rate by almost two orders of magnitude. We find that the reason for the significantly lower

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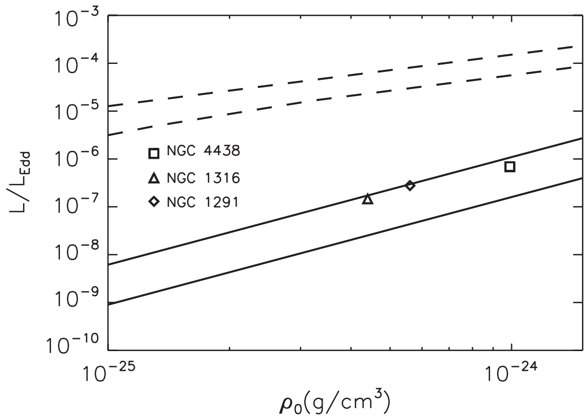


**Figure 2.** Luminosity of the accretion flow in unit of Eddington luminosity versus gas density at Boundi radius. The two solid lines are calculated using the formula Equation (3.1). The upper and lower solid lines correspond to $T_0 = 3.9 \times 10^6$ K and $7.2 \times 10^6$ K, respectively. The upper and lower dashed lines are calculated according to the adiabatic Bondi formula, assuming $T_0 = 3.9 \times 10^6$ K and $7.2 \times 10^6$ K, respectively. The square, triangle and diamond represent NGC 4438, 1316 and 1291, respectively.

accretion rate given by Equation (3.1) is that strong wind is present. Winds take away gas, which makes the black hole accretion rate significantly lower than that predicted by the Bondi formula. The mechanisms for driving wind depend on the accretion rate. We find that if $\dot{M}_{BH}/\dot{M}_{Edd} < 10^{-3}$, both radiative cooling and Compton heating/cooling are not important, wind is driven by gas pressure gradient force. If $\dot{M}_{BH}/\dot{M}_{Edd} > 10^{-3}$, wind is episodically driven by Compton heating. In this case, X-ray photons from the central region can heat gas, which makes gas temperature to be higher than virial temperature. Consequently, winds are launched. In AGNs, the winds driven by Compton heating have also been studied by Giotti & Ostriker (2001). Recently, it is found that Compton heating can also drive winds from a thin disk in a black hole X-ray binary system (Higginbottom *et al.* 2019).

We also do comparison with observations. In order to make the comparison, we need to look for observations of LLAGNs. The LLAGNs must satisfy three conditions. First, the black hole mass is $\sim 10^8$ solar mass; second, the gas density and temperature around the Bondi radius of these LLAGNs are known; finally, the luminosity of these LLAGNs is given by observations. There are three LLAGNs (Pellegrini 2005), namely NGC 4438, NGC 1316 and NGC 1291. The temperature of gas around the Bondi radius of these three LLAGNs is in the range $3.9 - 7.2 \times 10^6$ K. The results are shown in Figure 2. From this figure, we can see that the Bondi formula overestimates the luminosity of these three LLAGNs by two orders of magnitude. The fitting formula (Equation (3.1)) accurately predicts the luminosity of these three LLAGNs.

## 4. Implications

Two-dimensional simulations were performed to investigate slowly rotating accretion flows irradiated by a LLAGN at parsec and sub-parsec scales. We obtained a formula to calculate the black hole accretion rate based on the density and temperature of gas at Bondi radius. The formula can well predict the luminosity of LLAGNs. This formula can be used in subgrid models in large-scale simulations studying galaxy formation and evolution with AGNs feedback.

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