ON THE FEEDBACK EFFICIENCY OF ACTIVE GALACTIC NUCLEI

RYUICHI KUROSAWA1, DANIEL PROGA, AND KENTARO NAGAMINE
Department of Physics and Astronomy, University of Nevada, Las Vegas, Box 454002, 4505 Maryland Pkwy, Las Vegas, NV 89154-4002, USA; rk@physics.unlv.edu, dproga@physics.unlv.edu, kn@physics.unlv.edu
Received 2009 June 19; accepted 2009 October 27; published 2009 November 25

ABSTRACT

We measure and analyze the energy, momentum, and mass feedback efficiencies due to radiation from active galactic nuclei (AGNs) in relatively large-scale outflows (from ~0.01 to ~10 pc). Our measurements are based on the two-dimensional (axisymmetric) and time-dependent radiation–hydrodynamical simulations recently presented in Kurosawa & Proga. In that paper, we studied outflows from a slowly rotating (sub-Keplerian) infalling gas driven by the energy and pressure of the radiation emitted by the AGNs. These simulations follow the dynamics of gas under the influence of the gravity of the central 10^5 M⊙ black hole (BH) on scales from ~0.01 to ~10 pc. They self-consistently couple the accretion luminosity with the mass inflow rate at the smallest radius (our proxy for the mass-accretion rate, ˙M_a). Over 30 simulations have been performed to investigate how the results depend on the gas density at the outer radius, ρ_o. A key feature of these simulations is that the radiation field and consequently the gas dynamics are axisymmetric, but not spherically symmetric. Therefore, the gas inflow and outflow can occur at the same time. We compare our M_a–ρ_o relation with that predicted by the Bondi accretion model. For high luminosities comparable to the Eddington limit, the power-law fit (M_a ∝ ρ_o^q) to our models yields q ≈ 0.5 instead of q = 1.0, which is predicted by the Bondi model. This difference is caused by the outflows which are important for the overall mass budget at high luminosities. The maximum momentum and mass feedback efficiencies found in our models are ~10^{-2} and ~10^{-3}, respectively. However, the outflows are much less important energetically: the thermal and kinetic powers in units of the radiative luminosity are ~10^{-5} and ~10^{-4}, respectively. In addition, the efficiencies do not increase monotonically with the accretion luminosity but rather peak around the Eddington limit beyond which a steady-state disk–wind-like solution exists. Our energy feedback efficiencies are significantly lower than 0.05, which is required in some cosmological and galaxy merger simulations. The low feedback efficiencies found here could have significant implications on the mass growth of super massive BHs in the early universe. We stress, however, that we have not considered the innermost parts of the accretion and outflow where radiation and matter interact most strongly. The feedback from this region could have efficiencies significantly above the low values found here.

Key words: accretion, accretion disks – galaxies: evolution – galaxies: jets – galaxies: kinematics and dynamics – hydrodynamics

Online-only material: color figures

1. INTRODUCTION

The central location of active galactic nuclei (AGNs) in their host galaxies and the fact that they can produce a large amount of energy imply that AGNs can play a very important role in setting the physical conditions in their vicinity as well as on larger, galactic, and even intergalactic scales (e.g., Igumenshchev et al. 1993; Ciotti & Ostriker 1997, 2001, 2007; King 2003; Murray et al. 2005; Sazonov et al. 2005; Springel et al. 2005; Begelman & Nath 2005; Hopkins et al. 2005; Wang et al. 2006b; Thacker et al. 2006; Fabian et al. 2006, 2008; Pelupessy et al. 2007; Krolik 2007; Merloni & Heinz 2008; Booth & Schaye 2009, and references therein). There are many indications that support this idea. For example, the presence of broad and narrow emission lines and broad and narrow absorption lines in AGN spectra suggests that AGN continuum radiation affects the immediate environment of the AGN (see Krolik 1999 for an overview). In addition, the tight correlation between the mass (M_{BH}) of the central black hole (BH) in a galactic nucleus and the velocity dispersion σ of the galaxy’s bulge or spheroid, the so-called M_{BH}–σ relation (e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002), can be explained by the feedback between AGNs and the infalling material from large distances.

This feedback can quench both BH accretion and star formation in the galaxy when BH reaches a certain mass. AGNs could provide such feedback because they are very powerful sources of energy and momentum (e.g., Silk & Rees 1998; Blandford 1999; Sazonov et al. 2005; Fabian 1999; Fabian et al. 2002; King 2003; Scannapieco & Oh 2004; Murray et al. 2005; Springel et al. 2005; Di Matteo et al. 2005; Booth & Schaye 2009).

AGNs are powered by mass accretion onto a super massive BH (SMBH). To illustrate how the growth of SMBH can be self-regulated and how AGN feedback can be characterized, let us first express the radiation luminosity due to accretion as

\[ L_a = \epsilon_r c^2 M_a, \] (1)

where we invoke the simplest assumption such that the luminosity is proportional to the mass accretion rate (M_a) and a radiative (or the rest-mass conversion) efficiency (\epsilon_r). Both \epsilon_r and M_a are uncertain. For example, \epsilon_r ranges from \sim 10^{-1} in a standard, radiatively efficient thin disk to \sim 10^{-3} for spherically symmetric accretion from a low-density medium (e.g., Shakura & Sunyaev 1973; Shapiro 1973; Meszaros 1975; Soltan 1982; Yu & Tremaine 2002) while the mass accretion rate depends on poorly constrained physical conditions and geometry at large distances from the BH.

A common method to estimate M_a is to adopt the analytic formula by Bondi (1952), who considered spherically symmetric accretion from a non-rotating polytropic gas with uniform
density \( \rho_{\infty} \) and sound speed \( c_{\infty} \) at infinity. Under these assumptions, a steady-state solution to the equations of mass and momentum conservation exists with a mass accretion rate of

\[
M_B = \lambda \frac{4\pi r_B^2}{c^2} \rho_{\infty} c_{\infty},
\]

where \( \lambda \) is a dimensionless parameter that, for the Newtonian potential, depends only on the adiabatic index (cf. Bondi 1952; Shu 1992; Frank et al. 1992). The Bondi radius, \( r_B \), is defined as

\[
r_B = \frac{GM}{c^2},
\]

where \( G \) is the gravitational constant and \( M \) is the mass of the accretor.

One can quantify AGN feedback by measuring its efficiency in affecting the flow of energy, momentum, and mass. In this work, we consider only the energy and momentum carried out by matter. The total energy feedback efficiency \( \epsilon_t \) is defined as the ratio between the accretion luminosity of the system \( L_a \) (Equation (1)) and the sum of the kinetic power (kinetic energy flux) \( P_k \) and thermal energy power (thermal energy flux) \( P_{th} \), i.e.,

\[
\epsilon_t = \frac{P_k + P_{th}}{L_a}.
\]

Similarly, the kinetic energy and thermal energy feedback efficiencies (\( \epsilon_k \) and \( \epsilon_{th} \)) are defined as

\[
\epsilon_k = \frac{P_k}{L_a}
\]

and

\[
\epsilon_{th} = \frac{P_{th}}{L_a},
\]

respectively. From these definitions, it obviously follows that

\[
\epsilon_t = \epsilon_k + \epsilon_{th}.
\]

The momentum feedback efficiency (\( \epsilon_p \)) is defined as the ratio of the total wind momentum \( p_w \) to the total radiation momentum \( (L_a/c) \), i.e.,

\[
\epsilon_p = \frac{p_w}{(L_a/c)}.
\]

Lastly, the mass feedback efficiency \( \epsilon_m \) is defined as the ratio of the mass-outflow rate at the outer boundary \( M_{out} \) to the mass-inflow rate at the inner boundary \( M_{in} \), i.e.,

\[
\epsilon_m = \frac{M_{out}}{M_{in}}.
\]

The most advanced studies of feedback effects were carried out by Springel et al. (2005; SDH05 hereafter), Di Matteo et al. (2005), and Booth & Schaye (2009, BS09 hereafter). These studies used computer simulations of merging galaxies in which they linked local and global processes. This was possible because they adopted relatively crude phenomenological realizations of star formation, radiative cooling in a complex multi-phase medium, BH accretion and feedback, and because their spatial resolution is larger than \( r_B \). In particular, they assumed values of the above introduced efficiencies instead of directly computing them. A main result of these simulations is that the \( M_{BH} - \sigma \) relation can be reproduced remarkably well and that the relation is insensitive to the gas fraction in the model galaxies. In addition, the BH mass appears to be little affected by the details of star formation and supernova feedback.

Begelman & Nath (2005) argued that the results from simulations of merging galaxies suggest that the feedback regulating BH accretion operates on local scales, comparable to \( r_B \) or closer in, rather than solely on the global scales usually considered (see also Murray et al. 2005). They also presumed that the insensitivity to gas fraction occurs in the galaxy merger simulations because the gas mass is somehow “maximized” on the scales where the accretion rate is determined. Thus, on these scales, BH feedback can be much more important than that due to stars. If this is correct then for state-of-the-art models, the key feedback processes represent “subgrid” physics. This is a limitation of current models of AGN feedback in large-scale cosmological and galaxy merger simulations because they cannot be directly related to AGN physics.

On the other hand, simulations that aim to provide insights into AGN physics do not include galaxy but rather focus on \( r_B \) or even smaller scales (e.g., Proga 2007; Proga et al. 2008; Kurosawa & Proga 2008; Kurosawa & Proga 2009a, 2009b). Thus, they cannot be directly related to AGN feedback on large scales. However, these smaller scale simulations can be used directly to measure the feedback efficiencies listed above. Consequently, they can be used to quantify the effects that are assumed or parameterized in large-scale simulations.

The goal of this paper is to present measurements of the mass accretion rate, and various feedback efficiencies based on direct simulations of inflows and outflows in AGN, on sub-parsec and parsec scales performed by Kurosawa & Proga (2009a, KP09 hereafter). In other words, we wish to determine if AGN can supply energy in the form and amount required by the cosmological and galaxy merger simulations. In this work, we do not attempt to provide a definitive answer to the problem of AGN feedback efficiency as our simulations do not include the smallest scales (the BH radius) and the very large scales (>10 pc), and also do not include all physical processes operating in AGNs (e.g., dust, magnetic fields, and star formation). Here, we simply report the AGN feedback efficiencies found in the simulations previously presented by KP09 who focused on relatively large-scale inflow and outflow (~0.01 to ~10 pc).

2. AGN MODELS IN CURRENT COSMOLOGICAL SIMULATIONS

2.1. Mass Accretion Rates

In recent cosmological and galaxy merger simulations (e.g., SDH05: Robertson et al. 2006; Sijacki et al. 2007; Khalatyan et al. 2008; Di Matteo et al. 2008; Johansson et al. 2009; BS09), the actual physical process of the mass-accretion onto the BH is not explicitly modeled because of a relatively poor resolution. Often, these simulations rely on a separate analytical model to describe the small-scale physical processes. The unresolved accretion process is usually described by a Bondi–Hoyle–Little formulation (Hoyle & Lyttleton 1939; Bondi & Hoyle 1944; Bondi 1952). Here, we consider the case in which the accreting BH does not move with respect to the surrounding gas. This reduces the process to a simpler Bondi spherical accretion problem. Then, the mass-accretion rate can be written as Equation (2). The dimensionless constant \( \lambda \) (in Equation (2)) depends on the adiabatic index \( \gamma \). For the gas with \( \gamma = 5/3, \lambda = 1/4 \) (see, e.g., Frank et al. 1992). The Bondi accretion formula relates the mass-accretion rate of a BH located at the center to the gas density and the sound speed (or equivalently the temperature) of the gas at a large scale.

On the other hand, in the Bondi accretion prescription used by, e.g., SDH05 and BS09, the mass-accretion rate is written as

\[
\dot{M}_S = 4\pi G^2 M_{BH}^2 \rho \frac{c^3}{c_s^3},
\]
where $\rho$ and $c_s$ are the density and the sound speed estimated near the BH using the surrounding smoothed particle hydrodynamics (SPH; Gingold & Monaghan 1977; Lucy 1977) gas particles. Note that the expression contains the “dimensionless parameter” $\alpha$, which is different from $\lambda$ in Equation (2). SDH05 introduced $\alpha$ to overcome the gap in the scale sizes between the numerical resolution and the Bondi accretion regime. In a typical cosmological or galaxy merger SPH simulation, the smoothing length ($\sim 10^3$ pc) is much larger than the gravitational radius of influence or the Bondi radius, $r_B$, which is $\sim 2\rho$. If we assume that the gas located at a large distance, heated by the AGN radiation, is “Comptonized” ($T \approx 2 \times 10^7$ K), the corresponding speed of sound ($\approx 5/3$) is relatively high ($\sim 500$ km s$^{-1}$).

SDH05, BS09, and others (e.g., Robertson et al. 2006; Sijacki et al. 2007; Khalatyan et al. 2008; Di Matteo et al. 2008; Johansson et al. 2009) find that a very large factor of $\alpha$ is required for low-mass BHs to grow their masses; hence, the problem is not strictly a Bondi accretion problem. Most of the AGN feedback model in the cosmological simulations mentioned above assume a constant value of $\alpha = 100$ (see also Table 2 in BS09) except for BS09, who allow $\alpha$ to depend on the value of local gas density. The assumption of a very large value of $\alpha$ becomes inadequate when the local gas density is higher than that required by the formation of a cold interstellar gas phase, and when the cosmological simulation does resolve the Jeans length and the Bondi radius (BS09).

By noting these, BS09 abandoned the assumption of constant $\alpha$ in Equation (9), and introduced the following parameterization of $\alpha$:

$$\alpha = \begin{cases} 
1 & \text{for } n_H < n_H^*, \\
(n_H/n_H^*)^{\beta} & \text{for } n_H \geq n_H^*,
\end{cases}$$

where $n_H$ and $n_H^*$ are the number density of hydrogen and the critical hydrogen number density above which the gas is expected to become multi-phase and star formation is expected to begin via contraction of gas due to thermo-gravitational instability (cf. Schaye 2004; Schaye & Dalla Vecchia 2008). The critical density is chosen as $n_H^* = 0.1$ cm$^{-3}$, i.e., the corresponding critical hydrogen density is $\rho_H^* = 1.7 \times 10^{-25}$ g cm$^{-3}$. The best-fit models of BS09 to some observations (e.g., the $M_{ BH} - \sigma$ relation) gives $\beta = 2.0$. Note that the new parameterization of $\alpha$ in Equation (10) provides an additional density dependency of the mass-accretion rate in Equation (9). In the formulation of BS09, the mass-accretion rate steeply depends on the density of the surrounding gas, i.e., $M \propto \rho^5$, for $\rho > \rho_H^*$ while the formulation of SDH05 and the original Bondi accretion model (Equation (2)) always give a linear dependency, i.e., $M \propto \rho$. In most of the AGN accretion models in the cosmological simulations (e.g., SDH05; BS09), the highest mass-accretion rate is limited to the Eddington rate, i.e.,

$$M_{\text{Edd}} = \frac{4\pi G M_{BH} m_p}{\epsilon_f c \sigma_T c},$$

where $m_p$, $\epsilon_f$, $\sigma_T$, and $c$ are the proton mass, the radiative efficiency (the rest mass to radiation conversion efficiency), the Thomson cross section, and the speed of light, respectively. The Eddington ratio ($\Gamma$) is defined as the ratio of a system mass-accretion rate to the Eddington rate, i.e., $\Gamma = \dot{M}/M_{\text{Edd}}$.

Figure 1 illustrates how the mass-accretion rate depends on the density ($\rho$) in the models by Bondi (1952), SDH05, and BS09. The mass of the BH is assumed to be $M_{BH} = 10^6 M_{\odot}$. In all three models, the speed of sound $c_s$ is set to 520 km s$^{-2}$, which corresponds to that of Comptonized gas temperature $T \approx 2 \times 10^7$ K with the adiabatic index of gas $\gamma = 5/3$. The mass of the BH is set to $M_{BH} = 10^6 M_{\odot}$. While $\alpha = 100$ is adopted in the model of SDH05, $\beta = 2.0$ is adopted in the model of BS09. In the modified Bondi accretion models of SDH05 and BS09, the mass-accretion rates are limited to the Eddington rate (Equation (11)).

$$\dot{M} \sim 10^{-20} g cm^{-3}$$

which corresponds to that of Comptonized gas temperature $T \approx 2 \times 10^7$ K with the adiabatic index of gas $\gamma = 5/3$. In the modified Bondi accretion models of SDH05 and BS09, the mass-accretion rates are limited to the Eddington rate (Equation (11)), and the radiative efficiency $\epsilon_f$ is set to 0.1. The dimensionless parameter $\alpha = 100$ is adopted for the model of SDH05, and $\beta = 2.0$ is adopted in the model of BS09. The figure shows that the mass-accretion rate of SDH05 is larger than the Bondi accretion rate for $\rho \lesssim 10^{-20}$ g cm$^{-3}$. On the other hand, the mass-accretion rate by BS09 is similar to that of the Bondi accretion rate (off by a factor of $\lambda = 1/4$ in Equation (2)) in the low-density regime ($\rho \lesssim 10^{-25}$ g cm$^{-3}$), but it is significantly larger than the Bondi accretion rate for the density range of $10^{-25}$ g cm$^{-3} \lesssim \rho \lesssim 10^{-20}$ g cm$^{-3}$. The densities above which the accretion proceeds at the Eddington rate are $\sim 9.5 \times 10^{-23}$ g cm$^{-3}$ and $\sim 6.3 \times 10^{-24}$ g cm$^{-3}$ for the models of SDH05 and BS09, respectively. However, these values change depending on the adopted value of $\epsilon_f$. In the Bondi accretion model, the mass-accretion rates reach the Eddington rate at much higher density ($\rho \sim 10^{-20}$ g cm$^{-3}$). We note that adding a rotation to the gas can reduce the mass-accretion rate. As shown by Proga & Begelman (2003) and Ryu et al. (1995), the reduction of $M$ can be significant, i.e., by an order of magnitude or more, compared to $M_B$.

2.2. AGN Feedback Models

In SDH05 and BS09 (also in many others; cf. Table 2 in BS09), $\epsilon_f = 0.1$ (e.g., Shakura & Sunyaev 1973; see also Soltan 1982) is assumed and is fixed. A higher value of $\epsilon_f$ ($\sim 0.2$) can be achieved in an accretion model with a thin disk and a rapidly rotating BH (e.g., Thorne 1974). Recent observations suggest a wide range of $\epsilon_f$: 0.07 (Martínez-Sansigre & Taylor 2009), 0.30–0.35 (Wang et al. 2006a), 0.16 (Yu & Lu 2008), 0.15 (Elvis et al. 2007).
hand, Cao & Li (2008) find that the AGN radiation is dominated by the disk radiation (95% UV accretion disk and a spherical X-ray corona. We assumed that the AGN radiation is isotropically emitted to the surrounding. Using Equation (1), the rate of energy deposition to the surrounding (the AGN feedback rate) in SDH05 is written as

\[ E_\text{f} = \epsilon_\text{f} L_\text{a} = \epsilon_\text{f} \epsilon_\text{cc} M_{\text{BH}} c^2, \]

where \( \epsilon_\text{f} \) is the efficiency of the AGN energy deposition to the surrounding gas, and is a free parameter which is to be constrained by observations. BS09 find that the models with \( \epsilon_\text{f} = 0.15 \) matches observations (e.g., the Magorrian relation and the \( M_{\text{BH}}-\sigma \) relations) very well, and similarly SDH05 find that \( \epsilon_\text{f} = 0.05 \) matches observations well (see also Di Matteo et al. 2005). In the study of BS09, they find that the global BH number density at the current era (zero redshift) and the BH scaling relations are very sensitive to a choice of \( \epsilon_\text{f} \), and the former is nearly inversely proportional to the value of \( \epsilon_\text{f} \).

3. OUR MODEL

Our approach is to use physical two-dimensional (axisymmetric) and time-dependent hydrodynamical (HD) simulations of AGN flows to investigate the dependency of the BH mass-accretion rate on the surrounding gas density, and to find the AGN feedback efficiencies in converting the accretion luminosity into the outward fluxes of energy, momentum, and mass. Here, we simply analyze the simulation results previously published in KP09 for this purpose. KP09 used a modified version of the ZEUS-MP code (cf. Hayes et al. 2006) for their numerical simulations. In the following, we briefly summarize their main model assumptions and results.

In KP09, we studied axisymmetric hydrodynamical simulations of a slowly rotating gas that is under the influence of the gravity of a \( 10^8 M_\odot \) BH and is irradiated by a geometrically thin UV accretion disk and a spherical X-ray corona. We assumed that the AGN radiation is dominated by the disk radiation (95% of the total luminosity). Further, we account for the fact that the radiation from the disk depends on the polar angle \( \theta \), i.e., proportional to \( \cos \theta \) due to the geometrical foreshortening. We ran a set of simulations for various values of the gas density \( \rho_0 \) at the outer radius of the computational domain, \( r_o \approx 7 \) pc. After the initial transient stage, this density determines the key characteristics of our solutions such as the accretion luminosity and the outflow properties. We compute the accretion luminosity of a system based on the accretion-rate, which is assumed to be equal to the mass-supply rate at the inner radius of the computational domain \( r_i \approx 10^{-2} \) pc (i.e., we used Equation (1), where we assumed \( \epsilon_\text{cc} = 1/12 \) and \( M_a = M_{\text{in}}[r_i] \)). See Section 5.3 for more details on this assumption.

For the models with high-temperature gas at large radii and with high luminosities, we found a strong correlation between \( M_{\text{out}} \) and \( L_a \) (see Figure 1 in KP09). The power-law index describing the correlation is very similar to that for radiation-driven stellar and disk–wind models (e.g., Castor et al. 1975; Proga et al. 1998; Proga 1999). More surprisingly, for the models with high density at large radii, we found steady-state solutions with \( L_a \) exceeding the Eddington limit. The super-Eddington accretion proceeds in the equatorial region and is possible because the radiation flux from the disk is significantly reduced in the equatorial direction due to the geometrical foreshortening effect.

In all simulations performed by KP09, an outflow is driven from an inflow with sub-Keplerian rotation. For the models with high temperatures at large radii, the inflow occurs over a wide range of the polar angles, whereas the outflow occurs in a relatively narrow polar angle range (see the left panel in Figure 2). However, for the super-Eddington cases with low temperature at large radii, the inflow persists only very close to the equatorial plane, resembling a thin accretion disk, while the outflow arises in a wide range of radii and polar angles (see the right panel in Figure 2). The geometry of this extreme inflow–outflow solution is very similar to a radiation-driven wind from a luminous Keplerian accretion disk (e.g., Woods et al. 1996; Proga et al. 1998; Proga & Kallman 2002). For the cold super-Eddington solutions, \( M_{\text{out}} \) is only very weakly correlated. The weaker correlation is mainly caused by a mismatch between the direction of escaping photons and the inflowing gas. In other words, the radiation is emitted mostly in the polar directions whereas the inflowing gas occurs mainly in the equatorial region.

As it has been discussed and shown in the past, we find that self-consistently determined preheating/cooling from the quasar radiation can significantly reduce the rate at which the central BH is fed with matter. However, our results also emphasize a little-appreciated feature. Namely, quasar radiation does drive a non-spherical, multi-temperature, and very dynamic flow.

In the following, we present the mass-accretion rates and various (energy, momentum, and mass) AGN feedback efficiencies computed from the simulations. For this purpose, we use a subset of the models in KP09. Here, we concentrate on the models in which the outer boundary temperature is not fixed at a constant value, but it is self-consistently determined from the radiative and adiabatic heating (Models 28–34 in KP09). Note that the flow solutions for these models are, in general, very similar to those with the fixed outer boundary temperature at \( 2 \times 10^6 \) K (the low temperature models, i.e., Models 1–9 in KP09).

4. RESULTS

We analyze the dependency of the mass-accretion rate on the gas density at a large distance from a BH and AGN feedback efficiencies based on the axisymmetric hydrodynamical simulations presented in KP09. The main results of the models along with the input outer boundary density \( \rho_0 \) are summarized in Table 1.

4.1. Mass-accretion Rates

The mass-inflow rates at the inner boundary \( M_{\text{in}}(r_i) \) and those at outer boundary \( M_{\text{in}}(r_o) \) from the HD simulations are plotted as a function of the outer boundary density \( \rho_0 \) in Figure 3 (see Table 1 for the numerical values). For a given value of \( \rho_0 \), \( M_{\text{in}}(r_i) \) and \( M_{\text{in}}(r_o) \) are not equal to each other, but rather \( M_{\text{in}}(r_i) < M_{\text{in}}(r_o) \) because of an outflow. The lowest density model (Model 35) is an exception since no outflow is formed in this model. For the higher density models, an outflow forms, and not all the material entering from the outer boundary reaches the inner boundary. A fraction of gas experiences a strong radiation pressure and radiative heating, and the direction of flow changes, forming an outflow.

The figure also shows the mass-accretion rates predicted by the Bondi accretion model (Equation (2)) and those computed from the formulations of SDH05 and BS09 (Equations (9)
The density (in logarithmic scale) is overplotted with the directions of poloidal velocity as arrows for Models 36 (left panel), 29 (middle panel), and 34 (right panel). See Table 1 for the corresponding model numbers. The figures are placed in order of increasing density at the outer boundaries ($\rho_o$) from the left to right (cf. Table 1). Their corresponding accretion luminosities in the unit of the Eddington luminosity, i.e., the Eddington ratio, are $\Gamma = 0.32, 0.71,$ and 4.3, from the left to right panels. For the low-density ($\rho_o$) and low-accretion luminosity model (Model 36 in the left panel), the outflow is very narrow ($0^\circ \leq \theta \leq 30^\circ$), and the inflow is very wide ($30^\circ \leq \theta \leq 90^\circ$). As the density ($\rho_o$) and accretion luminosity increase (Model 29 in the middle panel), the outflow becomes wider ($0^\circ \leq \theta \leq 50^\circ$), whereas the inflow becomes narrower ($50^\circ \leq \theta \leq 90^\circ$). For the very high density and accretion model (Model 34 in the right panel), the outflow occurs over a very wide range of the polar angle ($0^\circ \leq \theta \leq 58^\circ$), and the accretion region is now confined to a thin equatorial wedge (the disk–wind-like solution).

Table 1

| Model | $\rho_o$ ($10^{-21}$ g cm$^{-3}$) | $T_i$ ($10^7$ K) | $M_{in}$ ($r_i$) ($10^{25}$ g s$^{-1}$) | $\Gamma$ | $M_{out}$ ($r_o$) ($10^{25}$ g s$^{-1}$) | $M_{in}$ ($r_o$) ($10^{25}$ g s$^{-1}$) |
|-------|-----------------|--------------|-----------------|--------|-----------------|-----------------|
| 35    | 2               | 0.02         | 3.4 (0.1)       | 0.20   | 0.0 (0.0)       | 3.4 (0.1)       |
| 36    | 4               | 0.07         | 5.5 (0.6)       | 0.32   | 0.11 (0.02)     | 5.4 (0.2)       |
| 28    | 10              | 0.14         | 8.9 (0.68)      | 0.52   | 1.0 (0.032)     | 9.4 (0.1)       |
| 29    | 20              | 0.14         | 12 (0.58)       | 0.71   | 3.5 (0.52)      | 15 (0.3)        |
| 30    | 40              | 0.36         | 18 (1.1)        | 1.1    | 7.1 (1.4)       | 25 (0.2)        |
| 31    | 80              | 0.80         | 25 (2.6)        | 1.4    | 10 (2.3)        | 35 (2.1)        |
| 32    | 160             | 0.98         | 36 (4.9)        | 2.1    | 9.9 (2.6)       | 49 (5.3)        |
| 33    | 320             | 0.85         | 52 (2.6)        | 3.1    | 11 (0.48)       | 63 (1.1)        |
| 34    | 640             | 1.30         | 72 (0.56)       | 4.3    | 9.5 (0.19)      | 82 (0.9)        |

Notes.

a The model numbers are identical to those in Kurosawa & Proga (2009a), except for Models 35 and 36, which are additional models presented here for the first time.

b Self-consistently determined temperature at the outer boundary.

c Values in brackets are the standard deviations of the time series values.

The figure clearly shows that our models have a weaker dependency of the mass-inflow rates on the density than that of the Bondi model. However, the figure shows the mass-inflow rates from our models are very similar to those of the Bondi rates, i.e., the rates are of the same order of magnitude. Interestingly, our $M_{in}$ ($r_i$) and the Bondi mass-accretion rate matches around $\rho_o = 4 \times 10^{-20}$ g cm$^{-3}$, which coincidentally corresponds to $\Gamma \approx 1$. Since the accretion rates from SDH05 and BS09 are the Eddington rates (the rates corresponding to $\Gamma = 1$) in this density range, their lines also cross at the same point.

Our models include the effects of radiative heating and radiation force. Therefore, we do not, in general, expect our solution to reproduce an exactly same density dependency of the mass-inflow rate as that of the Bondi model. However, the figure shows the mass-inflow rates from our models are very similar to those of the Bondi rates, i.e., the rates are of the same order of magnitude. Interestingly, our $M_{in}$ ($r_i$) and the Bondi mass-accretion rate matches around $\rho_o = 4 \times 10^{-20}$ g cm$^{-3}$, which coincidentally corresponds to $\Gamma \approx 1$. Since the accretion rates from SDH05 and BS09 are the Eddington rates (the rates corresponding to $\Gamma = 1$) in this density range, their lines also cross at the same point.
Comparison of the mass-inflow rates found in the HD simulations (Table 1) with those predicted by the Bondi accretion model (Bondi 1952; solid line) and with those adopted by SDH05 and BS09 (dashed line). In the density range of the models considered here, the mass-accretion rates adopted by SDH05 and BS09 are limited by the Eddington rate (Equation (11)); hence, the line is a function of the outer boundary density $\rho_o$ (squares) of the computational domain are shown as a function of the outer boundary temperature $T$ (circles) and with the Comptonized temperature $T = 2 \times 10^4 \text{K}$ and with the adiabatic index $\gamma = 5/3$. (A color version of this figure is available in the online journal.)

4.2. Feedback Efficiencies

Next, we compute AGN feedback efficiencies in energy, momentum and mass using the simulation results, as defined in Equations (4)-(8). Since the models used here show some degree of variability (typically $\sim 10$% level, cf. Table 1), the physical quantities used to compute the feedback efficiencies are based on the time averaged values.

4.2.1. Energy Feedback Efficiency

Figure 4 shows the energy feedback efficiencies, $\epsilon_k$, $\epsilon_e$, and $\epsilon_{th}$, computed based on our models (Table 1), as a function of the Eddington ratio ($\Gamma$). The numerical values of the efficiencies are listed in Table 2. For systems with relatively low Eddington ratio ($\Gamma \lesssim 0.4$), the thermal feedback efficiency is higher than the kinetic feedback efficiency ($\epsilon_{th} > \epsilon_k$). On the other hand, for systems with relatively high Eddington ratio ($\Gamma \gtrsim 0.6$), the kinetic feedback dominates the thermal feedback by a factor of $\sim 10$ to $\sim 100$. The model with $\Gamma = 0.2$ does not form an outflow, indicating an approximate $\Gamma$ value below which no outflow forms (with our system setup).

The energy feedback efficiencies increase as $\Gamma$ increases, but the efficiencies saturate for $\Gamma \gtrsim 1$. The total energy feedback efficiency peaks at $\Gamma \approx 1$ with $\epsilon_k \sim 10^{-4}$. The flattening of the efficiencies for $\Gamma \gtrsim 1$ is caused by the transition of the inflow-outflow morphology to a “disk–wind” like configuration (cf. Figure 2) for the higher $\Gamma$ models (KP09). As briefly mentioned in Section 3, because of the mismatch between the direction in which most of the radiation escapes (in polar direction) and the direction in which the most of the accretion occurs in the system (the equatorial direction), the radiatively driven outflows in the disk–wind-like configuration cannot increase the outflow efficiency by increasing the accretion luminosity or equivalently, $\Gamma$. A similar behavior is found in the $M_{out}(r_o)–\Gamma$ relation of KP09 (see their Figure 7).

4.2.2. Momentum Feedback Efficiency

Figure 5 shows the momentum feedback efficiency $\epsilon_p$ as a function $\Gamma$. The numerical values of $\epsilon_p$ for each model are listed in Table 2. The dependency of $\epsilon_p$ on $\Gamma$ is similar to that of the energy feedback efficiency. For $\Gamma \lesssim 1$, $\epsilon_p$ increases as $\Gamma$ increases, but it decreases as $\Gamma$ increases for $\Gamma \gtrsim 1$. No outflow is formed for the models with $\Gamma = 0.2$ and below. The cause of the peaking of $\epsilon_p$ at $\Gamma \approx 1$ (and the declining for $\Gamma \gtrsim 1$) is again due to the change in the inflow-outflow morphology to a disk–wind-like configuration for the higher $\Gamma$ models (KP09; see also Figure 2). The momentum deposition of the photons becomes less efficient once the flow has the disk–wind-like
configuration since a major fraction of the radiation escapes in the polar direction, but gas is not present in that direction since it has been already blown away by the strong radiation. The maximum momentum feedback efficiency is $\epsilon_p \approx 0.03$, which is about 2 orders of magnitude larger than the total energy feedback efficiency found in Section 4.2.1.

### 4.2.3. Mass Feedback Efficiency

Figure 6 shows the mass feedback efficiency ($\epsilon_m$) plotted as a function $\Gamma$. The dependency of $\epsilon_m$ on $\Gamma$ is very similar to that of the momentum feedback efficiency (Figure 5). The numerical values of $\epsilon_m$ are listed in Table 2. For $\Gamma \lesssim 1$, the mass feedback efficiency $\epsilon_m$ increases as $\Gamma$ increases, but it starts to decrease slightly beyond $\Gamma \approx 1$. The efficiency peaks around $\Gamma \approx 1$ with the maximum efficiency value $\sim 0.4$. In other words, about 40% of the total infalling mass is redirected to an outflow. The turnaround of $\epsilon_m$ values is caused by the transition of the outflow morphology to a disk–wind-like configuration (cf. Figure 2) for the larger $\Gamma$ models, as in the cases for the energy and momentum feedback efficiencies (Sections 4.2.1 and 4.2.2).

The accretion process in our model is fundamentally different from that of the Bondi accretion model and those adopted in the cosmological simulations (e.g., SDH05; BS09) because in our model an outflow and an inflow can simultaneously be formed while the Bondi accretion model can only form an inflow. The model of SDH05 and others can form either an inflow or an accretion (but not both simultaneously).

## 5. DISCUSSION

### 5.1. Comparisons with Other Studies

The main purpose of this study is to measure the efficiency of the AGN feedback in our radiation hydrodynamical simulations of accretion flows irradiated by an AGN. We are especially interested in the energy feedback efficiency ($\epsilon_f$) as this is an important parameter to determine the BH growth rate and the BH number density at the current epoch (redshift zero) in the cosmological simulations (e.g., SDH05; BS09). BS09 find that the BH growth rate is nearly inversely proportional to the value of $\epsilon_f$, which is important for the self-regulation of a BH growth (e.g., Silk & Rees 1998; Fabian 1999).

The approximate ratios of the maximum feedback efficiencies in energy, momentum, and mass using the results from Section 4.2 are

$$
\epsilon_m : \epsilon_p : \epsilon_k = 1000 : 100 : 1 : 1 : 0.1,
$$

where the total energy feedback efficiency $\epsilon_t \sim 10^{-4}$. Compared to the mass feedback efficiency, the thermal energy feedback efficiency is $10^4$ times smaller. Thus, the coupling between the radiation and the thermal energy of the gas, on scales between $10^{-2}$ and a few parsecs, is relatively inefficient.

The efficiency of the AGN energy deposition to the surrounding gas $\epsilon_f$ is usually treated as a free parameter and is somewhat constrained by observations, e.g., by fits to the Magorrian relation and the $M_{\text{BH}}-\sigma$ relations. SDH05, Robertson et al. (2006), Sijacki et al. (2007), Di Matteo et al. (2008), and Johansson et al. (2009) find that their numerical simulations with $\epsilon_f = 0.05$ match observations. BS09, who adopted a slightly different BH accretion model (Section 2.1), find that a larger value of $\epsilon_f = 0.15$ produces a good match with observations. In their models, the energy is assumed to be released only in the form of thermal energy; hence, their $\epsilon_f$ is equivalent to our $\epsilon_{\text{th}}$. Our thermal energy feedback efficiency $\epsilon_{\text{th}}$ is about $5 \times 10^{-3}$ times smaller than their $\epsilon_f$. Even when we compare it with our total energy feedback efficiency $\epsilon_t$, their $\epsilon_f$ is still about $5 \times 10^{-2}$ times larger.

The relatively small value of the kinetic energy feedback efficiency $\epsilon_k$ found here ($\sim 10^{-4}$) is consistent with those found in Chelouche (2008), who analyzed the X-ray spectra...
(Chandra/HETGS) of five AGNs (type I) with $M_{\text{BH}} \sim 10^7 M_\odot$. He found $\varepsilon_k$ ranges between $10^{-5}$ and $10^{-3}$. Our models also agree with the relatively low energy and mass feedback efficiencies found by Krongold et al. (2007) and Stoll et al. (2009), who studied X-ray and UV absorbing outflows in Seyfert galaxies. On the other hand, the AGN evolution and the BH growth synthesis model of Merloni & Heinz (2008), combined with the observed star formation rate history of the universe, suggests that $\varepsilon_k = (3-5) \times 10^{-3}$, which is about an order of magnitude larger than the value found in our models.

While SDH05 and BS09 assumed that the energy feedback efficiency is constant (independent of accretion luminosity), recent studies by Ciotti et al. (2009) and Shin et al. (2009), who performed one-dimensional hydrodynamical simulations of co-evolution of SMBH and elliptical galaxy, include the dependency of the AGN feedback efficiency (in a form of kinetic energy) on the accretion luminosity or more precisely on the Eddington ratio ($\Gamma$) of the system. Their parameterization of $\varepsilon_k$ with $\Gamma$ somewhat resembles our result (Figure 4), in a sense that $\varepsilon_k$ monotonously increases for $\Gamma \lesssim 1$. Ciotti et al. (2009) find that models with varying $\varepsilon_k$ are in general more consistent with observations than those with a constant $\varepsilon_k$. Interestingly, $\varepsilon_k$ values found by Shin et al. (2009) are only about 5 to 10 times larger than our values. This is a much better agreement than that with the models of SDH05 and BS09, as mentioned above. In summary, Ciotti et al. (2009) and Shin et al. (2009) concluded that the models need both radiation and mechanical feedback mechanisms included at the same time to account for observations such as the ratio of the central BH mass to the stellar mass ratio ($M_{\text{BH}}/M_*$), and the X-ray luminosity of hot diffused gas.

5.2. Causes of Low Feedback Efficiencies

Relatively low feedback efficiencies found in our models (Section 4.2) are mainly caused by the combinations of the following: (1) the axisymmetric nature of the assumed underlying accretion luminosity (the disk radiation), (2) axisymmetric nature of the inflow–outflow geometry, and (3) the relatively low optical depth in the outflow. When the Eddington ratio ($\Gamma$) of the system is small, the inflow is nearly spherical. However, when the accretion rate is increased and $\Gamma$ becomes close to 1, the flow becomes very aspherical (cf. Figure 2). The inflow occurs only near the equator and the outflow occurs in the polar direction. Despite a rather large value of $\Gamma$, the accretion can proceed in the equatorial region. This is because of the angular distribution of the radiation: in our model, most of the radiation is emitted by a flat disk. Consequently, the disk radiation has $\cos \theta$ dependency due to the geometrical foreshortening, i.e., the flux peaks in the polar direction and decreases toward the equator. The Eddington ratio, $\Gamma$, is a global property of a system. The ratio ($Q$) between the radiation force ($f_r$) and the gravitational force ($f_g$), i.e., $Q = f_r/f_g$, does not depend on the polar angle ($\theta$) for a spherically symmetric case; however, it does depend on $\theta$ for a case in which radiation is emitted from a flatter source. In the spherical case, when $\Gamma > 1$, $Q$ is always greater than 1 and an outflow forms in all directions ($\theta$). N.B. For the argument here, we consider the radiation force due to electron scattering only, but not including the force due to line processes (which is included in our simulations). For the disk radiation case, $Q$ depends on $\theta$, and $Q$ can be less than 1 (inflow can occur) near the equator even if the global parameter $\Gamma$ is greater than 1. In our simulations, $Q > 1$ in the polar direction (forming outflow) and $Q < 1$ in the equatorial direction (forming inflow) for all the models presented here, except for Model 35, which does not form an outflow.

Once the inflow–outflow geometry becomes very aspherical (i.e., equatorial) as in the middle and right panels of Figure 2, the coupling between the matter and radiation in the polar funnel is reduced. Most of the (high-density) gas accretes near the equator where the radiation is weakest, whereas most of the radiation escapes (without interacting with gas) in the polar directions where there is very little accreting matter. The electron optical depth in the outflow in our models is rather small ($\tau_\text{es} < 1$) even in the highest mass-accretion rate model. This mismatch between the preferred direction of the disk radiation and the direction of accretion is a main cause of the relatively low feedback efficiencies found in our simulations. This occurs in an equatorial system, but not in a spherically symmetric system.

In our models, the outflow is formed from initially inflowing gas. In other words, some fraction of the inflowing gas is turned around by the radiation force and becomes an outflow. The turn-around points or wind launching points can occur at a large distance from the center, i.e., near the outer boundary (cf. Figure 2). When the wind is launched from a larger radius, the gas does not have time or space to accelerate to a terminal velocity before escaping from the outer boundary. This may result in slightly smaller momentum and energy feedback efficiencies than those obtained from larger scale simulations. The efficiencies reported here is strictly on $\sim 0.01$ to $\sim 10$ pc scale. Finally, in the simulations presented by KP09, only gas dynamics and its microphysics are considered. Including the effect of dust would be very important in a larger scale simulation ($\sim 10$ pc). If dust dynamics is included in the model and the size of the computational domain is increased, the energy and momentum feedback efficiencies could be larger than the values reported in this paper.

5.3. Assumption on Mass Accretion Rate

To compute the total luminosity of the system (Equation 1), we need to have the information of the total mass accretion rate ($\dot{M}_\text{in}$) onto the BH. Since the inner radius ($r_1 \sim 0.01$ pc) of the computational domain in the simulations in KP09 is much larger than the inner radius of the accretion disk (which is on the order of the Schwarzschild radius), we assumed that $\dot{M}_\text{in}$ is equal to the mass-inflow rate at the inner radius of the computational domain ($\dot{M}_\text{in} [r_1]$). In other words, we assumed that all the gas which crosses the inner boundary will eventually reach the central BH. We also assumed that no material can enter the computational domain from the inner boundary, whereas energy and momentum in the form of the radiation can. These assumptions had to be made for numerical reasons. We simply do not know how much gas would enter from the inner boundary without explicitly modeling the accretion disk and its wind consistently with the larger scale flow. Unfortunately, the current computer speeds and resources would not allow us to include such small-scale and large-scale ($\sim 10$ pc) flows at the same time in this type of numerical simulations. However, in reality, some gas would enter the computational domain from the inner boundary, perhaps due to a disk–wind (e.g., Proga et al. 2000) or a jet produced in the immediate vicinity of the BH. We simply do not know how much and in what form of material enter from the inner boundary; hence, we made the simplest assumption:

---

2 The feedback efficiency defined by Ciotti et al. (2009) and Shin et al. (2009) is equivalent to our $\varepsilon_i \times \varepsilon_k$, where $\varepsilon_i \approx 0.1$ used in our model.
no gas enters into the computational domain from the inner boundary.

We recognize that the feedback from the innermost part of the accretion flow may be very important, and may influence the result of larger scale simulations such as the ones presented in this paper. Once again, we remind readers that the feedback efficiencies reported here are those of large scales (specifically $\sim 0.01 \sim 10$ pc scales) but not in the AGN as a whole (including the accretion disk–wind/jet). On the small scale, different forms of feedback mechanism (e.g., disk–wind and jet) may be important, but this is beyond the scope of the current investigation.

6. CONCLUSIONS

We have presented and analyzed the AGN feedback efficiencies of energy, momentum, and mass based on our axisymmetric and time-dependent hydrodynamical simulations (see Table 1) presented in Kurosawa & Proga (2009a). The simulations capture the radiation-driven outflows formed from a slowly rotating (sub-Keplerian) infalling gas under the influence of the gravity of the central SMBH. The accretion luminosity and the outer boundary temperature are self-consistently determined in these models. The radial range of the simulations spans from $\sim 10^{-2}$ to $\sim 10$ pc.

The dependency of the mass accretion rate on the density of the surrounding gas (or the outer boundary density $\rho_o$) has been examined (Figure 3). The result is compared with the Bondi mass accretion rate (Equation (2)), and with those adopted in the cosmological simulations of SDH05 and BS09 (see also Figure 1). The density dependency of the mass accretion rate in our models is somewhat similar to that of the Bondi accretion model. For the density range of $10^{-21}$ g cm$^{-3}$ $\lesssim \rho_o \lesssim 10^{-18}$ g cm$^{-3}$ (or correspondingly, $0.2 \lesssim \Gamma \lesssim 5$), the differences between the two models are within a factor of 10. At $\Gamma \approx 1$ ($\rho_o \approx 4 \times 10^{-20}$ g cm$^{-3}$), the accretion rate of our model and that of the Bondi accretion model agree with each other. An important difference between the two models is the steepness of the dependency on the density. The power-law fit ($M_\dot{\alpha} \propto \rho^p$) of our models results yields $q \approx 0.5$ instead of $q = 1.0$ which is predicted by the Bondi accretion model. This difference is due to outflows in our model. We note that in this density range, the mass accretion rates adopted by SDH05 and BS09 have no density dependency because their accretion rates are limited by the Eddington rate. The accretion rates of SDH05 are artificially boosted up ($\alpha$ factor in Equation (9)) by a factor of 100 in comparison with the Bondi mass accretion rates. Consequently, their rates reach the Eddington limit at much smaller $\rho_o$ than in our simulations (see Figure 1).

We find the energy feedback efficiency of our models depends on the accretion luminosity of the system (Figure 4). For $\Gamma \lesssim 1$, the dependency is similar to the parameterization of the feedback efficiency adopted by Ciotti et al. (2009). Both kinetic and thermal energy efficiencies ($\epsilon_k$ and $\epsilon_{th}$) peak at around $\Gamma = 1$. The maximum efficiency values are $\epsilon_k \approx 10^{-4}$ and $\epsilon_{th} \approx 10^{-5}$, respectively (see Table 2). For systems with relatively low Eddington ratio ($\Gamma \lesssim 0.4$), the thermal feedback efficiency is higher than the kinetic feedback efficiency ($\epsilon_{th} > \epsilon_k$). On the other hand, for systems with relatively high Eddington ratio ($\Gamma \gtrsim 0.6$), the kinetic feedback dominates the thermal feedback by a factor of $\sim 100$.

The dependency of the momentum feedback efficiency $\epsilon_p$ on $\Gamma$ is similar to that of the energy feedback efficiency (Figure 5). The maximum efficiency is $\epsilon_p \approx 10^{-2}$, which is about $\sim 100$ times larger than that of the total energy feedback efficiency. The dependency of the mass feedback efficiency $\epsilon_m$ on $\Gamma$ is also similar to that of $\epsilon_p$ (Figure 6). The maximum value of $\epsilon_m$ found is $\sim 0.4$ at around $\Gamma = 1$, i.e., about 40% of the total mass that moves inward at large radii does not reach the inner boundary of our computational domain, but rather is turned into outflows.

Compared to the energy (thermal only) feedback efficiencies ($\epsilon_{th} = 0.05$) required in the recent cosmological and galaxy mergers simulations (e.g., SDH05; Robertson et al. 2006, Sijacki et al. 2007, Di Matteo et al. 2008 and Johansson et al. 2009), our thermal energy feedback efficiency $\epsilon_{th}$ at the peak value is about $5 \times 10^3$ times smaller than their $\epsilon_{th}$. Our total and kinetic energy efficiencies are about $5 \times 10^2$ times smaller than their values. These large discrepancies would suggest a few things. For example, our models are missing important elements. In particular, we do not include effects of dust, which could make the outflows stronger. In addition, we focus here on axisymmetric models, which could differ from fully three-dimensional (3D) models. Our preliminary 3D simulations show that in 3D, the wind kinetic energy is smaller than in two-dimensional while the opposite is true for the thermal energy (Kurosawa & Proga 2009b). Although these changes are small (less than a factor of 2) in one of the cases studied by Kurosawa & Proga (2009b), they could be more significant in other cases (i.e., for the luminosity higher and lower than $\Gamma = 0.6$ assumed by Kurosawa & Proga 2009b).

It is also possible that the AGN feedback may not be as effective as one might have had expected. Instead, other forms of feedback may be more significant than the AGN feedback via radiation on scales between $10^{-2}$ and a few parsecs. They include the supernova feedback, the radiative feedback from star formation, the strong stellar wind from massive stars, and strong accretion disk winds or jets from the AGN. The last two forms will introduce magnetic fields, which may carry outward fluxes of energy and momentum. It is also possible that the AGN feedback efficiencies are indeed low and the AGNs take a long time to influence their environment. We note that in our models, the AGNs do not shut off the mass supply completely even at very high luminosities. This indicates that the AGNs could operate on a very long timescale over which their impact on the environment can accumulate and eventually become significant.

Finally, we conclude by noting that AGN feedback has two distinct modes: (1) radiation-driven (quasar) mode and (2) magnetic driven (radio jet) mode. In the current cosmological simulations, it is particularly difficult to deal with the latter, as it requires a full magnetohydrodynamical (MHD) treatment, and we do not have an adequate resolution and more importantly the full understanding of the jet mechanism. Nevertheless, Sijacki et al. (2007) extended the original implementation of the quasar mode feedback in SDH05 by injecting energy at random positions within a sphere centered around a BH to emulate the hot gas bubbles created by AGN jets. The radio mode could be very important in certain situations, such as the cooling flows in clusters of galaxies where channeling the energy within a very narrow jet helps to transport the energy outside a galaxy. However, this occurs in the low accretion rate regime, and it is subdominant in terms of the total BH mass growth. On the other hand, our simulations do not include the MHD treatment of the collimated jet; hence, the focus of this paper is on the physical mechanism of the quasar mode feedback. Since the quasar mode is the dominant process for the total BH mass growth, our results of low feedback efficiencies would have significant implications on the mass growth of SMBHs in the early universe. In the near
future, we plan to further investigate the implications of our results by taking the boundary conditions of our simulations from full cosmological hydrodynamic simulations, thereby making more direct connections with the physical conditions in a cosmological context.

Authors thank the anonymous referee for constructive comments and suggestions for improving the clarity of the manuscript. We thank J. M. Stone for suggesting to carry out this study. We also thank J. Ostriker, J.-H. Choi, and L. Ciotti for useful discussions. This work was supported by NASA through grant HST-AR-11276 from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. We acknowledge support from NSF (grant AST-0807491) and the National Aeronautics and Space Administration under grant/Cooperative Agreement No. NNX08AE57A issued by the Nevada NASA EPSCoR program.

REFERENCES

Begelman, M. C., & Nath, B. B. 2005, MNRAS, 361, 1387
Blandford, R. D. 1999, in ASP Conf. Ser. 182, Galaxy Dynamics, ed. D. R. Merritt, M. Valluri, & J. A. Sellwood (San Francisco, CA: ASP), 87
Bondi, H. 1952, MNRAS, 112, 195
Bondi, H., & Hoyle, F. 1944, MNRAS, 104, 273
Castor, J. I., Abbott, D. C., & Klein, R. I. 1975, ApJ, 195, 157
Ciotti, L., & Ostriker, J. P. 1997, ApJ, 487, L105
Ciotti, L., & Ostriker, J. P. 2001, ApJ, 551, 131
Di Matteo, T., Colberg, J., Springel, V., Hernquist, L., & Sijacki, D. 2008, ApJ, 676, 33
Di Matteo, T., Springel, V., & Hernquist, L. 2005, Nature, 433, 604
Elvis, M., Risaliti, G., & Zamorani, G. 2002, ApJ, 565, L75
Fabian, A. C. 1999, MNRAS, 308, L39
Fabian, A. C., Celotti, A., & Elvis, M. C. 2006, MNRAS, 373, L16
Fabian, A. C., Vasudevan, R. V., & Gandhi, P. 2008, MNRAS, 385, L43
Fabian, A. C., Wilman, R. J., & Crawford, C. S. 2002, MNRAS, 329, L18
Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9
Frank, J., King, A., & Raine, D. 1992, Accretion Power in Astrophysics (Cambridge: Cambridge Univ. Press)
Gebhardt, K., et al. 2000, ApJ, 539, L13
Gingold, R. A., & Monaghan, J. J. 1977, MNRAS, 181, 375
Hayes, J. C., Norman, M. L., Fiedler, R. A., Bordner, J. O., Li, P. S., Clark, S. E., ud-Doula, A., & Mac Low, M.-M. 2008, ApJ, 685, 188
Hopkins, P. F., Hernquist, L., Cox, T. J., Di Matteo, T., Martini, P., Robertson, B., & Springel, V. 2005, ApJ, 630, 705
Hoyle, F., & Lyttleton, R. A. 1939, Proc. Camb. Phil. Soc., 35, 405
Igumenshchev, I., Illarionov, A. F., & Kompaneets, D. A. 1993, MNRAS, 260, 727
Janiuk, A., Proga, D., & Kurosawa, R. 2008, ApJ, 681, 58
Johansson, P. H., Naab, T., & Burkert, A. 2009, ApJ, 690, 802
Khlatyana, C., Castanea, A., Schramm, M., Gottlöber, S., Steinmetz, M., & Wisotzki, L. 2008, MNRAS, 387, 13
King, A. 2003, ApJ, 596, L27
Krolik, J. H. 1999, Active Galactic Nuclei: From the Central Black Hole to the Galactic Environment (Princeton, NJ: Princeton Univ. Press)
Krolik, J. H. 2007, ApJ, 661, 52
Krongold, Y., Nicastro, F., Elvis, M., Brickhouse, N., Binette, L., Mathur, S., & Jiménez-Bailón, E. 2007, ApJ, 659, 1022
Kurosawa, R., & Proga, D. 2008, ApJ, 674, 97
Kurosawa, R., & Proga, D. 2009, MNRAS, 397, 1791 (KP09)
Lucy, L. B. 1977, AJ, 82, 1013
Martínez-Sansigre, A., & Taylor, A. M. 2009, ApJ, 692, 964
Merloni, A., & Heinz, S. 2008, MNRAS, 388, 1011
Meszaros, P. 1975, A&A, 44, 59
Murray, N., Quataert, E., & Thompson, T. A. 2005, ApJ, 618, 569
Pelupessy, F. I., Di Matteo, T., & Ciardi, B. 2007, ApJ, 665, 107
Proga, D. 1999, MNRAS, 304, 938
Proga, D. 2007, ApJ, 661, 693
Proga, D., & Begelman, M. C. 2003, ApJ, 582, 69
Proga, D., & Kallman, T. R. 2002, ApJ, 565, 455
Proga, D., Ostriker, J. P., & Kurosawa, R. 2008, ApJ, 676, 101
Proga, D., Stone, J. M., & Drew, J. E. 1998, MNRAS, 295, 595
Proga, D., Stone, J. M., & Kallman, T. R. 2000, ApJ, 543, 686
Robertson, B., Hernquist, L., Cox, T. J., Di Matteo, T., Hopkins, P. F., Martini, P., & Springel, V. 2006, ApJ, 641, 90
Ryu, D., Brown, G. L., Ostriker, J. P., & Loeb, A. 1995, ApJ, 452, 364
Sazonov, S. Y., Ostriker, J. P., Ciotti, L., & Sunyaev, R. A. 2005, MNRAS, 358, 168
Scannapieco, E., & Oh, S. P. 2004, ApJ, 608, 62
Schaye, J. 2004, ApJ, 609, 667
Schaye, J., & Dalla Vecchia, C. 2008, MNRAS, 383, 1210
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Shapiro, S. L. 1973, ApJ, 180, 531
Shin, M.-S., Ostriker, J. P., & Ciotti, L. 2009, arXiv:0903.5310
Shu, F. 1992, The Physics of Astrophysics, Vol. II: Gas Dynamics (Sausalito: Univ. Science Books)
Sijacki, D., Springel, V., di Matteo, T., & Hernquist, L. 2007, MNRAS, 380, 877
Silk, J., & Rees, M. J. 1998, A&A, 331, L1
Solotan, A. 1982, MNRAS, 200, 115
Springel, V., Di Matteo, T., & Hernquist, L. 2005, MNRAS, 361, 776 (SDH05)
Stoll, R., Mathur, S., Krongold, Y., & Nicastro, F. 2009, arXiv:0903.5310
Thacker, R. J., Scannapieco, E., & Couchman, H. M. P. 2006, ApJ, 653, 86
Thorne, K. S. 1974, ApJ, 191, 507
Tremaine, S., et al. 2002, ApJ, 577, 740
Wang, J.-M., Chen, Y.-M., & Hu, C. 2006b, ApJ, 642, L111
Wang, J.-M., Chen, Y.-M., & Hu, C. 2006a, ApJ, 637, L85
Woods, D. T., Klein, R. I., Castor, J. I., McKee, C. F., & Bell, J. B. 1996, ApJ, 461, 767
Yu, Q., & Lu, Y. 2008, ApJ, 689, 732
Yu, Q., & Tremaine, S. 2002, MNRAS, 335, 965