Large-scale Dynamics of Line-driven Winds with the Re-radiation Effect Postprint

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Full Text

Preamble

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Abstract

Previous simulations studying winds have focused only on the line force due to photons from central active galactic nuclei. What properties do winds exhibit when including the re-radiation force from scattered and reprocessed photons (i.e., the re-radiation effect)? We perform simulations to study the large-scale dynamics of accretion disk winds driven by radiation line force and re-radiation force. For the fiducial run, we find that the re-radiation force drives stronger outflows during the early stages. When the flows reach steady state, UV radiation due to spectral lines dominates the total radiation and the re-radiation effect becomes negligible. The opening angle of winds narrows as the initial gas density increases. The larger the gas density, the stronger the re-radiation effect.

For $M_{\rm BH} = 10^6 M_\odot$, $\epsilon = 0.3$, the outflows become much stronger with the re-radiation effect, yet the winds still cannot escape from the gravitational potential. We find that the detection probability of ultra-fast outflows and the properties of the winds are both consistent with observations.

Key words: accretion – accretion disks – black hole physics – galaxies: nuclei – stars: winds – outflows

1. Introduction

Observational evidence from low-luminosity active galactic nuclei (Crenshaw et al. 2003; Tombesi et al. 2010, 2014) and black hole X-ray binaries (Neilsen & Homan 2012; Homan et al. 2016) shows that winds are a common phenomenon. Winds are believed to play a momentous role in AGN feedback. Both winds and AGN radiation can interact with their host galaxies (Zhang et al. 2021; Lin et al. 2022). The radiation from AGNs can heat the interstellar medium (ISM) and affect its properties (Ciotti et al. 2009; Yuan & Narayan 2014). The winds can interact with the ISM effectively and result in their co-evolution (Ostriker et al. 2010; Weinberger et al. 2017; Yuan et al. 2018; Lin et al. 2022).

Accretion flows around a black hole can be divided into hot accretion flows and cold accretion flows. Hot accretion flows are highly hot and optically thin, found in systems with lower mass accretion rates. Winds from hot accretion flows have been directly detected in low-luminosity AGNs (Almeida et al. 2018; Ma et al. 2019; Shi et al. 2021) and black hole X-ray binaries (Homan et al. 2016; Munoz-Darias & Jimenez-Ibarra et al. 2019). Research has found that winds from hot accretion flows are emitted and accelerated under the combined action of centrifugal force, gas pressure gradient, and magnetic pressure gradient (Yuan et al. 2012; Yuan et al. 2015; Narayan et al. 2012; Bu & Gan 2018).

For the case of cold accretion mode, it is associated with relatively high mass accretion rates and comprised of cool, optically thick gas. Observational evidence of winds from luminous AGNs with cold thin disks has been reported (Crenshaw et al. 2003; Tombesi et al. 2010, 2014; Liu et al. 2013; Gofford et al. 2015; King & Pounds 2015; He et al. 2019) and for the soft state of black hole X-ray binaries (Neilsen & Homan 2012; Díaz Trigo & Boirin 2016; Homan et al. 2016; You et al. 2016).

Theoretically, three important mechanisms are believed to accelerate disk winds for a cold standard thin disk: thermal driving, magnetic driving, and radiation line force driving. The thermal driving mechanism can commendably understand the winds observed in some low-mass X-ray binaries (Begelman et al. 1983; Woods et al. 1996; Higginbottom et al. 2017). The magnetic driving mechanism can effectively explain winds in many astrophysical environments (Blandford & Payne 1982; Cao 2014). Radiation line force driving is a compelling mechanism to interpret the ionization state of the winds and understand fast outflows and ultra-fast outflows (UFOs) (Proga et al. 2000; Nomura et al. 2016; Nomura & Ohsuga 2017; Yang et al. 2021).

For the radiation line force driving mechanism, if the gas is moderately ionized and can interact with the UV continuum through many UV line transitions, the radiation pressure force due to spectral lines (i.e., line force) would accelerate the matter and launch cold winds. The line force can be 1000 times larger than the radiation pressure force due to Thomson scattering (Stevens & Kallman 1990; Liu et al. 2013), leading to high-velocity disk winds. Hydrodynamic simulations of winds driven by line force have been implemented (Proga et al. 2000; Proga & Kallman 2004; Nomura et al. 2016; Nomura & Ohsuga 2017; Nomura et al. 2020; Yang et al. 2021). It is found that the line force can effectively drive high-speed winds from the inner region of a cold thin accretion disk, and UFOs (Tombesi et al. 2010) are commendably explained by line-driven disk wind models. Yang (2021b) performed two-dimensional magnetohydrodynamic (MHD) simulations to understand the formation and acceleration of UFOs in radio-loud AGNs. Higher-velocity winds with a broader opening angle are produced in their MHD models, and UFOs in radio-loud AGNs may be driven by the combination of line force and magnetic field. Ajello et al. (2021) studied gamma-rays from fast black hole winds, finding that these outflows transfer 0.04% of their mechanical power to γ-rays and that the γ-ray emission originates from galaxies with UFOs.

To understand the propagation and properties of winds at large scales (around parsec scale), Cui et al. (2020) and Cui & Yuan (2020b) studied the large-scale dynamics of winds through simulation and analytical methods. They found that when winds from a cold thin disk have a negative Bernoulli parameter, the winds will only propagate a short distance from their simulated injection inner boundary. However, they neglected radiation force in their simulations. Zhu et al. (2022) included both radiation force and radiative cooling/heating and performed numerical simulations to study the large-scale dynamics of winds. They indicated that the properties of the winds depend on the mass of the black hole and the luminosity of the accretion disk.

However, all the above-mentioned radiation-driven wind simulations only consider the radiation force due to electron scattering and UV line processes from first-order radiation coming from the central AGNs. They neglect scattered and reprocessed photons. In reality, locally generated photons through scattering, bremsstrahlung, and line radiation in the gas around parsec scale can also play an important role. The radiation force due to locally generated photons is called the re-radiation force, and the resulting impact corresponds to the re-radiation effect. Sim et al. (2010) studied multi-dimensional radiative transfer simulation to calculate the spectrum of the hydrodynamics simulation of line-driven accretion disk winds, finding that secondary photons ionize the wind material. Higginbottom et al. (2014) performed Monte Carlo simulations of radiative transfer, finding that scattered photons can also ionize gases, resulting in excessively high levels of ionization. However, the postprocess approach, which decouples radiative transfer and HD/MHD calculations, is implemented in their works. Liu et al. (2013) investigated the effect of re-radiation force on the dynamics of flows at parsec scale under irradiation from the central AGNs. They found that accretion flow properties change significantly due to the re-radiation effect, and outflows become stronger consequently. Mosallanezhad et al. (2019) improved the calculation of radiation force due to local processes and made comparisons between total radial forces and re-radiation forces. They found that the mass flux and velocity of outflows are significantly increased, and the outflows are mainly driven by the re-radiation force. Obviously, the re-radiation effect has an important impact on accretion flows at large scale. However, those simulations concentrate only on the large scale of accretion flows, and they do not consider the acceleration of matter in the inner scale due to line force. Substantial radiative accelerations occur within small scales and even lead to high-velocity (0.1–0.2c) disk winds (Proga et al. 2000; Proga & Kallman 2004; Nomura et al. 2016; Nomura & Ohsuga 2017). They will exchange momentum and energy with the gas. When the winds arrive at parsec scale, it is interesting to study the dynamics of winds driven by the combination of radiation line force and re-radiation force.

In this paper, we conduct numerical simulations to investigate the large-scale dynamics of winds driven by line force and re-radiation force. In our simulations, radiation line force, re-radiation force, and radiative cooling/heating are all included. We first simulate small-scale winds driven by radiation line force in a dynamical range of 30–1500 r_s and obtain the time-averaged properties of winds. Then, we perform our large-scale simulations in a dynamic range of 1500–$10^6 r_s$. We concentrate on the large-scale dynamics of winds driven by line force and re-radiation force. The aim of carrying out small-scale simulations is to derive internal boundary conditions for the large-scale simulations. Winds are injected into the inner boundary of large-scale simulations, with properties coming from time-averaged values of winds at the outer boundary of the small-scale simulations.

The paper is organized as follows: Section 2 describes our models and methods; Section 3 presents our results; Section 4 provides discussions; and Section 5 presents a summary.

2. Model and Method

We perform axisymmetric two-dimensional radiation hydrodynamic simulations using the PLUTO code, which solves systems of conservation laws using finite volume or finite difference approaches based on Godunov-type schemes (Mignone et al. 2007; Mignone et al. 2012; Yang et al. 2021; Yang 2021b; Zhu et al. 2022). The basic scenario and physical setup of our models are mostly the same as those used in Zhu et al. (2022).

2.1. Basic Equations

We carry out two-dimensional numerical hydrodynamic simulations using spherical coordinates (r, θ, ϕ). The equations solved are the standard hydrodynamic equations with radiation forces included. The disk scale height is assumed to be constant with radius ($z = 3.1\epsilon r_s$, with ϵ being the Eddington ratio; Nomura & Ohsuga 2017).

The line force and the force multiplier M depend on the ionization of the winds and the spectral energy distribution of the radiation field. For more details of the calculations, readers are referred to Proga et al. (1998) and Proga et al. (2000).

Here, ρ, v, P, e, ζ, and Φ represent density, velocity, gas pressure, internal energy, the net cooling/heating rate, and gravitational potential, respectively. $F_{\rm rad}$ is the radiation force per unit mass including Compton scattering, line force, and re-radiation force. We apply an equation of state for ideal gas $P = (\gamma - 1)e$ with $\gamma = 5/3$. In this work, we consider the gravitational potential of both the central black hole $\Phi_{\rm BH} = -GM_{\rm BH}/(r - r_s)$ (Paczyński & Wiita 1980) and the host galaxy (Dye et al. 2008; Bu et al. 2016; Cui et al. 2020), where $M_{\rm BH}$, G, r_s, r, C, and σ_v are the black hole mass, gravitational constant, Schwarzschild radius, distance from a point to the black hole, constant, and velocity dispersion, respectively. We adopt $\sigma_v = 2 \times 10^7$ cm s^{-1}.

2.2. Model Setup

We assume a geometrically thin and optically thick disk around the central black hole for luminous AGNs. The thin disk is responsible for UV emissions and the hot corona for X-ray emissions. The hot corona can irradiate the thin disk, and the radiation intensity from the surface of the accretion disk is written as:

$$F_D(r_D) = \frac{3GM_{\rm BH}\dot{M}}{8\pi r_D^3}\left[1 - \left(\frac{r_*}{r_D}\right)^{1/2}\right]$$

where r_D, r_*, and $\dot{M}$ denote the radial position on the disk surface measured from the central black hole, the inner edge of the disk, and the mass accretion rate of the accretion disk, respectively. f_X is the ratio of X-ray luminosity L_X

from the corona to disk luminosity L_D ($f_X = L_X/L_D$). We refer to Yang et al. (2021) for detailed calculation of f_X.

The effective temperature of the disk surface is determined by $T_{\text{eff}}^4 = F_D/\sigma$, with σ being the Stefan-Boltzmann constant. We consider radiation from the high-temperature (> 3000 K) region of the accretion disk as contributing to the line force.

The gas above the accretion disk is irradiated by UV photons from the disk surface and X-ray photons from the corona. Our simulations are implemented in spherical coordinates (r, θ, ϕ). We place the surface of the accretion disk on the plane $\theta = \pi/2$, corresponding to the disk scale height z. For simplicity, we assume the disk scale height is constant.

We assume initially that the gas above the thin disk is in hydrostatic equilibrium and locally isothermal in small-scale simulations. The density at the surface of the accretion disk is set according to the standard thin disk model (Shakura & Sunyaev 1973; Nomura & Ohsuga 2017). For large-scale simulations, we do not consider an accretion disk at the midplane. Our computational domain covers from $1500 r_s$ to $1.5 \times 10^6 r_s$. We employ non-uniform grids to discretize the computational domain with resolution 300×160. Initially, low-density gas ρ_0 is placed in the computational domain. Various values of ρ_0, ϵ, and M_{BH} are adopted. Model details are listed in Table 1 . We employ axis-of-symmetry boundary conditions at $\theta = 0^\circ$ and equator-of-symmetry boundary conditions at $\theta = 90^\circ$. Refer to Zhu et al. (2022) for more details on the computational domain and boundary conditions.

2.3. Radiative Cooling/Heating

The radiative processes and interactions between radiation and gas include Compton heating/cooling, X-ray photoionization and recombination, bremsstrahlung, and line cooling (Blondin 1994; Proga et al. 2000). The net cooling rate ζ is expressed as:

$$\zeta = \zeta_{\text{Compton}} + \zeta_X + \zeta_{b,l}$$

where n is number density, G_{Compton} is the Compton heating/cooling rate, G_X is the net X-ray photoionization heating-recombination cooling rate, and $L_{b,l}$ is the bremsstrahlung and line cooling rate. In the above equations, $\mu = 1$ denotes the mean molecular weight, m_p is proton mass, and $T_X = 10^8$ K is the characteristic temperature of X-ray radiation. The parameter δ controls line cooling, and we set $\delta = 1$, representing optically thin cooling.

The net cooling rate ζ depends on density ρ, characteristic X-ray temperature T, radiation temperature T_X, and ionization parameter ξ. The ionization parameter ξ is expressed as:

$$\xi = \frac{L_X}{nr^2} e^{-\tau_X}$$

where τ_X is the optical depth for X-rays from the corona. For large-scale simulations, we calculate optical depths for X-ray τ_X and UV radiation $\tau_{\rm UV}$ from the accretion disk as:

$$\tau_X = \tau_{0,X} + \int_{1500r_s}^{r} \rho\sigma_X dr$$

$$\tau_{\rm UV} = \tau_{0,\rm UV} + \int_{1500r_s}^{r} \rho\sigma_e dr$$

where $\tau_{0,X}$ and $\tau_{0,\rm UV}$ are optical depths across the entire small-scale simulation domain, σ_e is the mass-scattering coefficient for free electrons set to 0.4 $\rm g^{-1}cm^2$. We set $\sigma_X = \sigma_e$ for $\xi \geq 10^5$ erg cm $\rm s^{-1}$ and $\sigma_X = 100\sigma_e$ for $\xi < 10^5$ erg cm $\rm s^{-1}$ (Proga et al. 2000; Yang et al. 2021).

2.4. The Radiation Force

Liu et al. (2013) and Mosallanezhad et al. (2019) indicate that the re-radiation effect can significantly affect the properties of accretion flows around parsec scale. Therefore, the re-radiation force can play an important role in driving winds when they spread to large scales, launching from inside hundreds of Schwarzschild radii.

The total radiation force includes radiation force from the central AGN and re-radiation force from locally produced photons:

$$\mathbf{F}_{\rm rad} = \mathbf{F}_r^c + \mathbf{F}_z^{\rm re}$$

where the re-radiation force $\mathbf{F}_z^{\rm re}$ is in the z-direction and is described by:

$$\mathbf{F}_z^{\rm re} = \frac{\sigma_e}{c} \int (F_D + F_X)\rho dz$$

where the source term denotes first-order scattered photons from central AGN radiation (Liu et al. 2013). F_D and F_X are the accretion disk flux and X-ray flux, respectively.

The radiation force $\mathbf{F}_r^c$ from the central AGN is expressed as a vector-valued integral, which is more accurate and reliable in our simulations. In this paper, F_D and F_X are obtained through specific integrals over the solid angle Ω subtended by the disk and central object.

3. Results

We perform simulations with different values of initial gas density ρ_0 and accretion disk luminosity $L_D = \epsilon L_{\rm Edd}$ ($L_{\rm Edd}$ being Eddington luminosity) to explore the re-radiation effect of these parameters. We also study the influence of galactic potential on wind dynamics. Model parameters and general results are summarized in Table 1. Wind properties in Table 1 are obtained by time-averaging values at the outer radial boundary. We provide time-averaged values over the interval $0.5T_{\rm ob}$–$1.0T_{\rm ob}$, where $T_{\rm ob}$ denotes the orbital time at the outer radial boundary.

3.1. The Effect of the Host Galaxy Potential

Model 1 and Model 2 show winds without and with galaxy potential for $M_{\rm BH} = 10^8 M_\odot$, $\epsilon = 0.6$, respectively. In Figure 1 [Figure 1: see original paper], we plot time-averaged mass fluxes, momentum fluxes, and kinetic power of the winds for Models 1 and 2. Mass outflow flux, momentum flux, and kinetic energy flux are calculated as:

$$\dot{M}_w = \int_0^{\pi/2} \rho v_r r^2 \sin\theta d\theta$$

$$\dot{P}_w = \int_0^{\pi/2} \rho v_r^2 r^2 \sin\theta d\theta$$

$$\dot{E}_w = \int_0^{\pi/2} \frac{1}{2}\rho v_r^3 r^2 \sin\theta d\theta$$

In both models, mass fluxes remain almost unchanged with radius, while momentum fluxes and kinetic power increase due to acceleration by line force. The winds do not stop at the outer radial boundary of our simulations and can move out of the AGNs to interact with the interstellar medium of their host galaxies. The kinetic power of the winds is significantly higher than $0.5\% L_{\rm Edd}$, so the winds can provide sufficient feedback to their host galaxies (Di Matteo et al. 2005; Hopkins & Elvis 2010; Bu & Yang 2021). The curves for mass flux, momentum flux, and kinetic power are almost identical for Models 1 and 2, indicating that including the gravitational potential of the host galaxy has little impact on the large-scale dynamics of the winds.

The left panel of Figure 2 [Figure 2: see original paper] shows the radial dependence of specific gravitational force. Black hole gravitational force dominates for $r < 1.1 \times 10^6 r_s$, while host galaxy gravitational force dominates for $r > 1.1 \times 10^6 r_s$. The total gravitational force equals the black hole gravitational force when $r < 10^5 r_s$. The right panel of Figure 2 shows time-averaged kinetic energy of winds along $\theta = 71^\circ$ (where winds move almost radially), galaxy gravitational energy, and black hole gravitational energy. The kinetic energy of the winds is significantly larger than both galaxy and black hole gravitational energy, especially when $r > 10^5 r_s$. Therefore, galaxy and black hole gravitational energy are negligible compared to kinetic energy, showing little effect on large-scale wind dynamics from including the host galaxy potential.

We also study the effect of host galaxy potential for various accretion disk luminosities. From Table 1, compared to Model 8, Model 9 shows the mass flux at the outer boundary slightly decreases, and momentum flux and kinetic energy flux reduce to about 90% for $M_{\rm BH} = 10^6 M_\odot$, $\epsilon = 0.3$. This indicates that the host galaxy potential works to restrain outflows. The reasons are as follows: the kinetic energy of the winds is rather small, and the winds cannot reach the outer boundary for $M_{\rm BH} = 10^6 M_\odot$, $\epsilon = 0.3$. Moreover, the black hole gravitational energy decreases compared to Models 1 and 2, making the effect of galaxy potential more obvious. However, those fluxes measured at the outer boundary are significantly small, and the winds cannot escape from the gravitational potential.

3.2. The Fiducial Run

We choose Model 3 as the fiducial model and compare it with Model 2. The fiducial model parameters are $M_{\rm BH} = 10^8 M_\odot$, $\epsilon = 0.6$, including host galaxy potential and re-radiation force. The only difference between Models 3 and 2 is whether the re-radiation force is included.

In Figure 3 [Figure 3: see original paper], we plot snapshots of density (color) and velocity (arrows) for Models 2 and 3. Upper panels correspond to $t = 0.1T_{\rm ob}$ and bottom panels to $t = 0.5T_{\rm ob}$. Right panels show Model 2, while left panels show Model 3. Winds propagate at $\theta = 71^\circ$. From $t = 0.1T_{\rm ob}$ to $t = 0.5T_{\rm ob}$, winds spread to the outer boundary and radial velocity continuously increases, meaning accretion disk winds driven by radiation mechanisms move outward and can even reach beyond $1.5 \times 10^6 r_s$. Comparing upper panels, wind velocity in Model 3 is slightly larger than in Model 2, so propagation distance is further. Gas density near the equatorial plane decreases. Comparing bottom panels, velocity and density of winds in Model 3 are almost identical to those in Model 2, indicating that re-radiation force drives stronger outflows initially but becomes negligible after some time.

To show this more clearly, we plot wind properties from 0 to $0.5T_{\rm ob}$ for Models 2 and 3 in Figure 4 [Figure 4: see original paper]. The left panel shows mass outflow fluxes at $1.5 \times 10^6 r_s$ (solid black for Model 2, solid red for Model 3) and mass flux ratio K (dashed line). Mass flux for Model 3 exceeds that for Model 2 from 0 to $0.12T_{\rm ob}$, becoming equal after about $0.15T_{\rm ob}$. The mass flux ratio K exceeds 1 from 0 to $0.16T_{\rm ob}$ and equals approximately 1 from $0.2T_{\rm ob}$ to $0.5T_{\rm ob}$.

The right panel shows time dependence of radial velocity (solid lines) and density (dashed lines) at $r = 1.5 \times 10^6 r_s$, $\theta = 71^\circ$. Velocity and density show sharp increases at $0.13T_{\rm ob}$. For Model 3, velocity and density become steady at $0.23T_{\rm ob}$, while Model 2 reaches quasi-steady state at $0.34T_{\rm ob}$. When quasi-steady state forms, outflow properties are identical for both models. As Mosallanezhad et al. (2019) found, outflow rates at the outer boundary are enhanced under central AGN irradiation when including re-radiation force. The re-radiation force works importantly in early stages, making mass flux for Model 3 larger than Model 2 from 0 to $0.16T_{\rm ob}$, even two orders of magnitude larger at $0.12T_{\rm ob}$. However, mass flux values are extremely small during this period.

After quasi-steady state formation, winds are driven by the combination of line force and re-radiation force, but UV radiation due to spectral lines dominates total radiation. Therefore, mass flux, velocity, and density of Models 2 and 3 are almost identical. To prove this, we plot the structure of time-averaged radiation fluxes in Figure 5 [Figure 5: see original paper]. Comparing panels, the time-averaged radiation flux $F_r^{c,\rm line}$ due to UV radiation from the AGNs in the radial direction is much greater than $F_r^{c,\rm phx}$ due to photoionization heating-recombination cooling and X-ray radiation. Specifically, $F_r^{c,\rm line}$ is almost eight orders of magnitude larger than $F_r^{c,\rm phx}$ along $\theta = 71^\circ$, indicating that radiation flux from photoionization heating-recombination cooling and X-ray radiation can be neglected, and UV radiation dominates in the radial direction when flows reach steady state.

Similarly, the time-averaged radiation flux $F_z^{\rm line}$ due to UV radiation from the central AGNs in the vertical direction is much greater than $F_z^{\rm re}$ from local radiative processes and scattered photons. $F_z^{\rm line}$ is almost nine orders of magnitude larger than $F_z^{\rm re}$ along $\theta = 71^\circ$. Thus, radiation flux from local processes and scattered photons can be ignored, and the re-radiation effect is negligible for $M_{\rm BH} = 10^8 M_\odot$, $\epsilon = 0.6$ when quasi-steady state forms. Therefore, wind properties are almost identical. The kinetic power of winds is significantly higher than $0.5\% L_{\rm Edd}$, providing sufficient feedback to host galaxies. Deep red areas within $10^5 r_s$ in middle panels and bulges within $3\times10^4 r_s$ in bottom panels show sharp increases due to the line force multiplier M. As Zhu et al. (2022) found, winds accelerate when moving from small to large radii inside $10^5 r_s$, and the line force multiplier M becomes negligibly small outside $\sim 10^5 r_s$. Compared with Mosallanezhad et al. (2019), the re-radiation force seems unimportant due to low initial gas density.

3.3. Initial Gas Density Dependence

We study the effect of initial gas density (ρ_0) in this section. Figure 6 [Figure 6: see original paper] compares wind properties for Models 3, 5, and 7. Densities in the region $\theta < 45^\circ$ increase from top left to bottom left panels, while densities and velocities in $\theta > 60^\circ$ remain the same. Additionally, wind velocities in $45^\circ < \theta < 60^\circ$ decrease. This means the opening angle of winds becomes narrower.

The bottom right panel of Figure 6 shows angular distribution of wind densities and velocities at the outer boundary. Densities for Models 3, 5, and 7 in $\theta < 45^\circ$ remain at about 10^{-26} g cm^{-3}, 10^{-25} g cm^{-3}, and 10^{-23} g cm^{-3}, respectively, corresponding to their initial densities. In $45^\circ < \theta < 60^\circ$, densities and velocities change with angle and eventually converge. In $60^\circ < \theta < 80^\circ$, density and velocity curves are identical.

The reasons are as follows: winds propagate at angles $45^\circ < \theta < 80^\circ$ for $M_{\rm BH} = 10^8 M_\odot$, $\epsilon = 0.6$. Models 3, 5, and 7 have few velocities in $\theta < 45^\circ$, with densities almost equal to initial values. Initially, low-density gas for Models 3, 5, and 7 is placed in the computational domain with $\rho_0 = 10^{-25}$ g cm^{-3} and $\rho_0 = 10^{-23}$ g cm^{-3}, respectively. Injected winds have limited power in $45^\circ < \theta < 60^\circ$. Greater initial density leads to greater optical depth and wind resistance, narrowing the opening angle. In the wind region $60^\circ < \theta < 80^\circ$, winds propagate at $\theta = 71^\circ$ with most kinetic energy flux. Injected winds have sufficient kinetic power to overcome resistance, so densities and velocities are identical.

From Table 1, the significance of re-radiative effect depends on initial gas density. For $M_{\rm BH} = 10^8 M_\odot$, $\epsilon = 0.6$, when $\rho_0 = 10^{-25}$ g cm^{-3}, mass flux at the outer boundary for Model 4 is approximately the same as Model 5. But when $\rho_0 = 10^{-23}$ g cm^{-3}, mass flux increases by a factor of about 1.5 from Model 6 to Model 7. For $M_{\rm BH} = 10^6 M_\odot$, $\epsilon = 0.3$, when $\rho_0 = 10^{-25}$ g cm^{-3}, mass flux increases by a factor of about 2.6 from Model 11 to Model 12. But when $\rho_0 = 10^{-23}$ g cm^{-3}, mass flux increases by a factor of about 14 with the re-radiation effect. The larger the gas density, the stronger the re-radiation effect. Liu et al. (2013) also found that larger density produces stronger re-radiation force because re-radiation force is proportional to density squared, while gravitational force and gas pressure gradient are proportional to density (refer to Equation 14).

3.4. Accretion Disk Luminosity Dependence

Zhu et al. (2022) found that for $M_{\rm BH} = 10^6 M_\odot$, $\epsilon = 0.3$, winds cannot escape black hole potential. In this paper, we also study large-scale dynamics of winds driven by line force and re-radiation force for $M_{\rm BH} = 10^6 M_\odot$, $\epsilon = 0.3$. Corresponding models are presented in Table 1. The mass flux of injected winds (measured at the inner boundary) equals $0.028370 L_{\rm Edd}/c^2$. From Table 1, mass flux at the outer boundary increases by a factor of about 1.5 from Model 9 to Model 10, but these fluxes are much smaller than at the inner boundary. This indicates that outflows become much stronger with the re-radiation effect, yet winds still cannot escape gravitational potential.

3.5. Comparison to Observations

Outflows from AGNs are fundamental mechanisms for interaction between central supermassive black holes and host galaxies. Observational evidence indicates UFO absorbers are found in hard X-ray bands (6–9 keV) in $\sim 40\%$ of nearby AGNs (Pounds et al. 2003; Tombesi et al. 2010, 2011, 2012; Gofford et al. 2013, 2015; Laha et al. 2021). We define UFOs as outflows with velocities $v \sim 0.03$–$0.3c$, ionization parameter $\xi \sim 10^3$–10^6 erg cm s^{-1}, and column density 10^{22} cm^{-2} $\leq N_H \leq 10^{24}$ cm^{-2}. UFOs may be driven from accretion disks by line force (Nomura et al. 2016; Nomura & Ohsuga 2017; Yang et al. 2021;

Zhu et al. 2022). In our large-scale simulations, we also find UFOs are present.

Figure 7 [Figure 7: see original paper] shows viewing angle (θ) dependence of column density and wind velocity. Outflows over 44°–66° satisfy UFO properties in our fiducial model. The detection probability of UFOs is around 36%, defined as $\Omega_{\rm UFO}/4\pi$ (Nomura et al. 2016).

Gofford et al. (2015) performed systematic analysis of outflow properties in 51 Suzaku-observed AGNs, finding mass flux and kinetic power of UFOs follow power-law relationships. Nomura & Ohsuga (2017) and Zhu et al. (2022) performed two-dimensional simulations of line-driven disk winds, finding power-law indexes almost identical to observations. Typically, detected UFOs have mass outflow rates $\sim 10^{24}$–10^{26} g s^{-1} and kinetic luminosity constrained between $\sim 10^{43}$–10^{45} erg s^{-1}. In our simulations, winds are driven by both line force and re-radiation force, with mass outflow rate between 1.58×10^{25} and 1.35×10^{26} g s^{-1}, and kinetic luminosity between 2.72×10^{44} and 9.96×10^{44} erg s^{-1}. These properties are consistent with observations. Therefore, UFOs are quite probably driven by the combination of radiation line force and re-radiation force.

4. Discussions

In this paper, we time-average simulation results at the outer boundary of small-scale simulations and inject winds into the inner boundary of large-scale simulations. Using this time-averaged method, properties of high-ionization winds can be erased due to their low density. Therefore, at the inner radial boundary of large-scale simulations, we mainly inject low-ionization winds, exploring mostly the dynamics of low-ionization winds. It is computationally too expensive to perfectly study large-scale wind dynamics with inner boundary close to the black hole and outer boundary beyond parsec scale.

In our simulations, we set $\sigma_X = 100\sigma_e$ for $\xi < 10^5$ erg cm s^{-1} and $\sigma_X = \sigma_e$ for $\xi \geq 10^5$ erg cm s^{-1} (Proga et al. 2000; Nomura & Ohsuga 2017; Yang et al. 2021; Zhu et al. 2022), which is an inherent limitation in current hydrodynamics setups for line-driven disk wind simulations. The abrupt switch due to this step function is arbitrary. For example, X-rays are heavily attenuated below $\xi = 10^5$ erg cm s^{-1} when switching from $\sigma_X = \sigma_e$ to $\sigma_X = 100\sigma_e$, resulting in very effective shielding. For UV radiation, $\sigma_{\rm UV} = \sigma_e$ across the entire range of ξ. This processing method is physically inconsistent with absorption of ultraviolet radiation by wind material through bound transitions. Proga & Kallman (2004) also explored the situation of $\sigma_X = \sigma_e$ for all ξ. Nomura et al. (2020) compared these two methods and found wind mass fluxes differ by roughly a factor of 2. However, both treatments are arbitrary. In future work, we plan to study more realistic physical models of X-ray and UV opacities.

Sim et al. (2010) and Higginbottom et al. (2014) indicate that scattered X-ray photons also contribute to gas ionization in postprocessed radiation transfer calculations. However, radiative transfer and hydrodynamics are decoupled in those studies. Realistic flow simulations require coupling radiation transfer and

HD/MHD calculations, which remains impractical due to large computational costs.

In this paper, we perform hydrodynamics simulations of line-driven winds with the re-radiation effect, including radiation force from scattered and reprocessed photons in the momentum equation. Although scattered and reprocessed photons are included, our treatments for calculating wind photoionization structure and radiation interactions are oversimplified. The next generation of HD/MHD formalism is urgently needed, which can handle radiative transfer in a more realistic and detailed manner.

Additionally, magnetic fields are always present. Including magnetic fields will enhance outflows and produce winds with broader opening angles (Kuncic & Bicknell 2007; Cui & Yuan 2020b; Yang et al. 2021). The standard magnetorotational instability (SMRI) has been directly observed in a Taylor-Couette cell with independently rotating, electrically conducting end caps and is responsible for angular momentum transfer (Balbus & Hawley 1991; Wang et al. 2022a, 2022b). It will be interesting to study large-scale wind dynamics driven by the combination of radiation and magnetic fields in the future.

5. Summary

We carry out two-dimensional simulations to study the large-scale dynamics of accretion disk winds driven by radiation line force and re-radiation force. We investigate wind properties with the re-radiation effect around parsec scale. Currently, it is impossible to perform simulations with inner boundary close to the black hole and outer boundary around parsec scale. Therefore, we divide the spatial scale into small and large scales. For small-scale simulations, the computational domain is $30r_s \leq r \leq 1500r_s$, where winds are driven by radiation line force. For large-scale simulations, the domain covers $1500r_s \leq r \leq 1.5 \times 10^6 r_s$. Locally generated photons through scattering, bremsstrahlung, and line radiation in the gas can also play important roles. Large-scale wind dynamics are driven by the combination of radiation line force and re-radiation force. We inject winds at the inner radial boundary ($1500r_s$) obtained from time-averaged small-scale simulations.

Including the gravitational potential of the host galaxy has little impact on large-scale wind dynamics. For $M_{\rm BH} = 10^8 M_\odot$, $\epsilon = 0.6$, wind properties are identical. For $M_{\rm BH} = 10^6 M_\odot$, $\epsilon = 0.3$, mass flux at the outer boundary slightly decreases, and momentum and kinetic energy fluxes reduce to about 90% with galaxy potential. However, those fluxes measured at the outer boundary are too small, and winds cannot escape gravitational potential.

Using the fiducial model as an example, we find that re-radiation force drives stronger outflows initially. As Mosallanezhad et al. (2019) found, outflow rates at the outer boundary are enhanced. However, when flows reach steady state, radiation flux from photoionization heating-recombination cooling, X-ray radiation, and local photons from local processes and scattered photons can be neglected, and UV radiation due to spectral lines dominates. Thus, wind properties are almost identical when quasi-steady state forms. The kinetic power of winds is significantly higher than $0.5\% L_{\mathrm{Edd}}$, providing sufficient feedback to host galaxies (Di Matteo et al. 2005; Hopkins & Elvis 2010; Bu & Yang 2021).

We find that initial gas density affects wind properties driven by radiation line force and re-radiation force. In our models, low-density gas is placed in the computational domain with $\rho_0 = 10^{-25}$ g cm^{-3} and $\rho_0 = 10^{-23}$ g cm^{-3}. The opening angle of winds narrows with increasing initial density. Moreover, the significance of re-radiative effect depends on initial gas density: the larger the gas density, the stronger the re-radiation effect. We also study accretion disk luminosity dependence. For $M_{\mathrm{BH}} = 10^6 M_{\odot}$, $\epsilon = 0.3$, the magnitude of mass flux is comparable to the increase due to re-radiation effect, producing more visible results. The kinetic power of winds is much lower than $0.5\% L_{\mathrm{Edd}}$, so winds might not affect host galaxy evolution.

We compare our simulation results to observations. The observed dependence of kinetic power and mass flux on accretion disk luminosity can be well reproduced (Gofford et al. 2015; Nomura & Ohsuga 2017; Zhu et al. 2022). For UFOs found in hard X-ray bands, the detection probability of UFOs and wind properties in our fiducial model are both consistent with observations. Therefore, UFOs are quite probably driven by the combination of radiation line force and re-radiation force.

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Note: Figure translations are in progress. See original paper for figures.