Simulations of radiation driven winds from Keplerian discs

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ABSTRACT

We study the ejection of winds from thin accretion discs around stellar mass black holes and the time evolution of these winds in presence of radiation field generated by the accretion disc. Winds are produced by radiation, thermal pressure and the centrifugal force of the disc. The winds are found to be mildly relativistic, with speeds reaching up to terminal speeds $0.1$ for accretion rate $4$ in Eddington units. We show that the ejected matter gets its rotation by transporting angular momentum from the disc to the wind. We also show that the radiation drag affects the accretion disc winds in a very significant manner. Not only that the terminal speeds are reduced by an order of magnitude due to radiation drag, but we also show that the non-linear effect of radiation drag, can mitigate the formation of the winds from the matter ejected by the accretion disc. As radiation drag reduces the velocity of the wind, the mass outflow rate is reduced in its presence as well.

Key words: Black Hole physics, accretion, accretion disc, jets and outflows, radiation dynamics

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1 INTRODUCTION

Outflows in the form of winds are commonly associated with various astrophysical sources like AGNs, X-ray binaries, YSOs etc. In radio quiet AGNs, blue-shifted iron lines are frequently reported. This blue shift is believed to be generated from resonance absorption of Fe-xxv or Fe-xxvi by propagating winds away from the source. The speeds of these winds are found to be relativistic and may reach up to 0.4c (Chartas et al. 2002, 2003; Markowitz et al. 2006; Dadina et al. 2005; Cappi et al. 2009; Reeves et al. 2009). Similarly this blue shift is observed in case of X-ray binaries as well (Miller et al. 2007; Trigo & Boirin 2016; Ponti et al. 2012).

These winds are observed in nearly half of these sources (Tombesi et al. 2010) indicating that the feature is quite general. Further, their short variability timescales (∼100ks) suggest that the winds might be outflowing from the central source from a region within 100 Schwarzschild radii (rs). In X-ray binaries, the winds are observed in soft state only where the observed spectra is mostly dominated by thermal emissions. In soft state, the accretion discs are well described by standard thin disc model, where the discs are optically thick but geometrically thin and emit thermally distributed radiation (Shakura & Sunyaev 1973).

Though, theoretically these discs are highly stable against most perturbations, but is susceptible to magneto-rotational instabilities (Balbus & Hawley 1991; Suzuki & Inutsuka 2009; Yuan et al. 2012), which apart from providing an origin of shear viscosity, may also contribute to outflows. Independent of such instabilities, magnetic field can remove energy and angular momentum from the accretion disc, such that centrifugally driven outflow along the magnetic field is possible (Blandford & Payne 1982).

Not only magnetic field can drive winds, but winds can also be generated by thermal and radiation pressure from the accretion discs (Begelman et al. 1983). It may be noted that outflows within sub-Eddington limit from optically thick discs were also studied by performing MHD simulations (Ohsuga et al. 2009; Ohsuga & Mineshige 2011). Lancová et al. (2019) also studied the MHD outflows from the accretion discs in general relativistic limit.

As the winds are found to be traveling up to mildly relativistic speeds, they need driving agents. The radiation driving of outflows (jets or winds) are studied by various authors through semi analytic works (Fukue 1996; Tajima & Fukue 1996; Chattopadhyay & Chakrabarti 2000a,b, 2002; Chattopadhyay 2005; Kumar et al. 2014; Vyas et al. 2015; Vyas & Chattopadhyay 2018, 2019) and radiation was shown to be an effective factor to accelerate jets and winds up to relativistic speeds. Similarly simulations were also carried out to study the effects of radiation on outflows Proga et al. (1997, 1998); Yang et al. (2018); Proga et al. (2000); Nomura & Ohsuga (2017); Proga (2003a); Proga (2003b) and Nomura & Ohsuga (2017) studied line driven winds. However, the line force may not be that effective when the temperature of the wind exceeds the ionization temperature significantly (∼10^5 K). Hence the winds driven by the radiation from inner region of the accretion disc especially in microquasars, where the temperatures are hotter, one may need other mechanisms. In that case, the radiation drives the winds directly by depositing the momentum and/or energy. Yang et al. (2018) studied winds driven from hot corona by radiation force of the underlying Keplerian disc (hereafter KD). It may be noted that, Yang et al. (2018) did not consider the role of radiation drag although they maintained the optically thin condition through out in their simulation. Moreover, Yang et al. (2018) considered the outflow from a hot corona. In most of the previous attempts mentioned above, the radiation drag was not part of their analysis. We would like to investigate whether continuum emission of a thin accretion disc can radiatively drive matter to form a wind, in presence of radiation drag. Apart from this, we investigate how much angular momentum of the accretion disc is transmitted to the winds above it. We would also like to study the effect of radiation drag on the wind solution, and will discuss the role of angular momentum removal in the winds due to radiation. As this is an exploratory study, we intend to study how accretion rate affects these aspects of wind generation.

In section 2, we discuss the underlying assumptions, then we will show the set of governing equations and the radiation field in section 3. Afterwards we describe the simulation set up, initial and boundary conditions for the simulations, method of solving the equations, and numerical technique in section 4. We then proceed to results (section 5) and conclude the paper (section 6) with the significance of the analysis.

2 ASSUMPTIONS

We perform hydrodynamic simulation in cylindrical coordinate system r, φ, z. Axisymmetry in the system is assumed. In our simulation, the source of the wind is KD around a 10M⊙ black hole, which occupies the equatorial plane and winds are launched from the KD in the r − z plane. The radiation field above the KD interacts with the out-flowing wind through Thomson scattering, and drives the wind by depositing momentum onto the matter. We restrict ourselves to non relativistic regime and hence, while calculating the radiation field above the disc, relativistic transformations are ignored. However, to take care of strong gravity near the central source, we have assumed the Paczyński & Wiita potential (Paczyński & Wiita 1980) that mimics the general relativistic effects. In this paper, all ten independent components of the moments of radiation field are calculated, hence the effect of radiation drag is also incorporated. In this paper the distances are scaled and shown in Schwarzschild units.

3 GOVERNING EQUATIONS

The equations of motion for a fluid in the radiation-hydrodynamic regime (correct up to first order in v, see Mihalas & Mihalas 1984; Kato et al. 1998, for details) with density ρ, pressure p, propagating with velocity components v, vφ and vz, are given by

\[ \frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial (r \rho v_r)}{\partial r} + \frac{\partial (\rho v_z)}{\partial z} = 0 \]  

(1)

\[ \frac{\partial (\rho v_r)}{\partial t} + \frac{1}{r} \frac{\partial (r \rho v_r^2)}{\partial r} + \frac{\partial p}{\partial r} + \frac{\partial (\rho v_r v_z)}{\partial z} = \rho v_r^2 \hat{v}_φ + \rho f_{\delta} + \frac{\partial k}{\partial z} \]  

(2)
\[
\frac{\partial (\rho v_\phi)}{\partial t} + \frac{1}{r} \frac{\partial (\rho rv_r v_\phi)}{\partial r} + \frac{\partial (\rho v_z v_\phi)}{\partial z} = -\frac{\rho v_r}{r} + \frac{\rho k}{c^2} F_\phi
\]

\[
\frac{\partial (\rho v_z)}{\partial t} + \frac{1}{r} \frac{\partial (\rho rv_r v_z)}{\partial r} + \frac{\partial (\rho v_z^2 + P)}{\partial z} = -\rho \left( \frac{k}{c} v_i F_i + v_{fi,i} \right)
\]

(3)

(4)

In the above equations, \( E = \rho v^2/2 + \epsilon \) is the energy density of the fluid and \( \epsilon = p/(\Gamma - 1) \) is the thermal energy density, where \( \Gamma = 5/3 \) is the adiabatic index of the fluid. The local sound speed is defined as \( c_s = (\Gamma p/\rho)^{1/2} \). The fluid is being driven by the radiation field of the underlying thin accretion disc. The components of radiation terms are:

\[
F_i = F_\phi - E v_i - v_r P_\phi - v_p P_{\phi,j} - v_z P_{i,z},
\]

where \( i \equiv (r, \phi, z) \). Various moments of the radiation field are \( E, F_i, P \), and \( P_{\phi,j} \) (here, \( i, j \rightarrow r, \phi, z \)), which are basically the radiation energy density, various components of radiation flux and various components of radiation pressure, respectively. The scattering opacity is \( \kappa = \sigma_T/m_p \) with \( \sigma_T \) being Thomson scattering cross section and \( m_p \) is the proton mass. Moreover, \( f_{\text{gr}} \) and \( f_{\text{sz}} \) are \( r \) and \( z \) components of the gravitational force and are given by

\[
f_{\text{gr}} = \frac{GM}{r^2} \frac{z}{R(R/r_s - 1)^2},
\]

\[
f_{\text{sz}} = \frac{GM}{r^2} \frac{r}{R(R/r_s - 1)^2},
\]

(6)

(7)

(8)

where \( G \) and \( M \) are the universal constant of gravity and the mass of the black hole, respectively. The Schwarzschild radius of black hole defined as \( r_s = 2GM/c^2 \). All the lengths mentioned in the paper are in terms of \( r_s \) and we will refer to them in dimensionless form afterwards. Further, \( R \) is the radial distance from the centre of the black hole defined as

\[
R = \sqrt{r^2 + z^2}
\]

(9)

In the R.H.S of the components of momentum equations (2, 3 and 4), the components of radiative flux accelerates, while other velocity dependent terms with \( E \) and \( P_{\phi,j} \), have negative sign and therefore decelerates the flow. These are called radiation-drag terms and they show that radiation can also reduce the momentum of the flow. As the radiation drag depends upon various components of the fluid velocity, it becomes effective as the flow speed increases. The radiative acceleration and deceleration depend upon the relative strengths of various radiative moments and the components of flow speeds, therefore, the effect of radiation on the outflow can behave in a very nonlinear manner. We will show in section 5 that radiation acceleration drives the winds to the infinity. However, consideration of radiative drag term reduces the outflow speed, to the extent that it can even disrupt the ejected winds. Below we discuss the accretion disc and the radiative moments computed from its radiation field.

3.1 Accretion disc properties

An accretion disc around a black hole, on one hand, supplies matter to the black hole, on the other hand also supplies matter flowing out as outflow. In the present case, the outflow is driven by the disc radiation. Since the KD is defined on the equatorial plane so the dynamical coordinates of the KD is represented by \( R_d \equiv (r_d, \phi, 0) \). From the mass conservation equation, we have the expression of accretion rate to be

\[
\dot{M} = 2\pi r_d \rho v_{r,K}(2H),
\]

(10)

where, \( H \) is the height of the disc from equatorial plane. \( v_{r,K} \) is the radial inflow speed due to accretion. The KD rotation velocity is \( (\text{Paczynski } & \text{Wiita 1980; Kato et. al. 1998}) \)

\[
v_{r,K} = \sqrt{\frac{GM \rho_d}{(r_d - r_s)^2}}
\]

(11)

In KD \( v_{r,K} >> v_{r,K} \), and the radial velocity distribution is given by \( \text{(Kato et. al. 1998)} \)

\[
v_{r,K} = 3.1 \times 10^6 \alpha x^{-4/3} \mathcal{M}^{-1} m^{-1} x^{-3} \left( 1 - \sqrt{\frac{3}{x}} \right)^{2/3},
\]

(12)

where \( x = r_d/r_s \) and \( \alpha \) is the viscosity parameter. Now, the distribution of the equatorial density along \( r_d \) is obtained to be \( \text{(Shakura & Sunyaev 1973)} \)

\[
\rho = 4.423 \times 10^4 m^{-1} \mathcal{M}^{-1} v_{r,K}^{-1}
\]

(13)

The distribution of density along \( z \) is \( \tilde{\rho} = \rho e^{-z/(z/r_s)} \) \( \text{(Shakura & Sunyaev 1973)} \). It may be noted that at high accretion rates the inner part of the disc may become radiation pressure dominated and in such cases the disc thickness is controlled by vertical radiative pressure rather than by gas pressure. The density profile would change and instability might set in. However, we assume that since radiation pressure is driving winds from the inner region, so the density profile of the disc may not depart significantly from equation 13. For a KD, viscosity is required for angular momentum transport in a manner such that the matter occupies subsequent Keplerian orbits. Viscosity heats up the matter, the dissipated heat is locally radiated as blackbody emission at each radius of the disc. Assuming the surface temperature \( T_{\text{disc}} \) as the temperature of each annulus, its radial distribution is given by

\[
\sigma T_{\text{disc}}^4 = \frac{3GM \dot{M}}{8\pi r_d^3} \left( 1 - \frac{T_\infty}{T_{r_d}} \right),
\]

(14)

where \( \sigma \) is Stefan-Boltzmann’s constant, \( r_\infty = 3 \) (in units of \( r_s \)) is the inner radius of the disc, and the disc extends up to an outer boundary \( r_o = 512 \). Expressing accretion rate and mass of the black hole in units of Eddington accretion rate, the previous equation becomes:

\[
T_{\text{disc}} = 4.35 \times 10^7 \mathcal{M}^{-1} m^{-1/3} x^{-2/3} \left( 1 - \sqrt{\frac{3}{x}} \right)^{1/4},
\]

(15)

where, \( \dot{m} = \dot{M}/\dot{M}_{\text{Edd}} \) and \( M = m M_\odot \), moreover, the Eddington accretion rate is \( \dot{M}_{\text{Edd}} = 1.44 \times 10^{37} \text{m} \) (gm s\(^{-1}\)) and \( M_\odot = 2 \times 10^{30}\text{gm} \).
Figure 1. Contours of radiative moments computed at each point in $r-z$ plane around the black hole which resides at the origin and the disc on the equatorial plane. Radiation energy density (a); radiative flux terms, $F_r$, $F_z$, and $F_\phi$ (b)-(d) respectively; and the components of radiation pressure tensor, $P_{rr}$, $P_{r\phi}$, $P_{rz}$, $P_{\phi\phi}$, $P_{\phi z}$, $P_{zz}$ from (e) to (j), respectively. Only the inner $51.2r_s \times 51.2r_s$ region is shown.
3.2 Radiation field above a thin accretion disc

In the following we present the expression of various radiative moments. For the convenience of representation, we define the radiative moments in the following form,

\[ \frac{kE}{c} = E_0 \varepsilon; \quad \frac{kF_i}{c} = F_0 f_i \quad \text{and} \quad \frac{kP_{ij}}{c} = P_0 p_{ij} \]

with,

\[ E_0 = F_0 = P_0 = \frac{3GM_B M_K \sigma_T}{8\pi r_d^2 m_p c} \]

The dimensionless radiation energy density (\( \varepsilon \)), the three components of radiative flux (\( f_i \)), as well as the six components of pressure tensor (\( p_{ij} \)) are given by Chattopadhyay (2005);

\[ \varepsilon = \int_{r_{in}}^{r_{out}} \int_0^{2\pi} \frac{z(r_d^{-2} - \sqrt{3}r_d^{-5/2})d\phi}{(r^2 + z^2 + r_d^2 - 2rr_d\cos\phi)^{3/2}(1 - v_i l_i)^d} dr_d \]

\[ f_i = \int_{r_{in}}^{r_{out}} \int_0^{2\pi} \frac{z(r_d^{-2} - \sqrt{3}r_d^{-5/2}) l_i d\phi}{(r^2 + z^2 + r_d^2 - 2rr_d\cos\phi)^{3/2}(1 - v_i l_i)^d} dr_d \]

\[ p_{ij} = \int_{r_{in}}^{r_{out}} \int_0^{2\pi} \frac{z(r_d^{-2} - \sqrt{3}r_d^{-5/2}) l_i l_j d\phi}{(r^2 + z^2 + r_d^2 - 2rr_d\cos\phi)^{3/2}(1 - v_i l_i)^d} dr_d, \]

where \( l_i \)s are the direction cosines from the disc to the field point.

Since the accretion disc is not a static radiator, but the disc matter is in motion, therefore the radiation field is Doppler beamed by this disc motion. It can be shown that the frequency integrated radiation intensity measured by the comoving observer (\( I_0 \)) has the following transformation relation with that measured by an inertial observer (\( I \)) (Kato et al. 1998)

\[ \frac{I_0}{I} = \gamma^4 (1 - v_i l_i)^4 \approx (1 - v_i l_i)^4 \]

\[ \frac{E}{F_0} \]

The Lorentz factor \( \gamma \approx 1 \) for KD. This factor appears in the expression of the moment equations and affects the radiation field. In particular the disc motion along \( \phi \) direction generates non-zero \( f_\phi \) and also various components of \( p_{\phi\phi} \). The coordinates of the thin Keplerian disc are \( (r_d, \phi) \) and the integration limits of accretion disc are \( r_{in} = 3 \) and \( r_{out} = 512 \).

We plot the dimensionless radiation moments i.e. \( E \) (Figure 1a), radiative fluxes \( F_r \) (Figure 1b), \( F_\phi \) (Figure 1c), \( F_\theta \) (Figure 1d) and the 6 independent components of radiative pressure \( P_{rr} \) (Figure 1e), \( P_{\phi\phi} \) (Figure 1f), \( P_{zz} \) (Figure 1g), \( P_{\phi\phi} \) (Figure 1h), \( P_{\phi z} \) (Figure 1i) and \( P_{zz} \) (Figure 1j). The moments are plotted in \( r - z \) plane. Each panel zooms the inner 51.2 \times 51.2 in order to resolve the contours of the radiative moments. The radiative moments are distinctly anisotropic, especially close to the black hole. Since the KD only extends up to 3, and the KD flux maximizes at \( r \approx 4 \), so the radiative moments maximizes at around 4 – 5. \( E \) or the radiative energy density is by far the most dominant of all the moments. Close to the axis \( F_r \approx F_\theta \approx 0 \), while \( F_\phi \) is very important. In general, \( |F_r| \geq |F_\theta| \) and dominates \( F_\theta \). In addition, \( P_{\phi\phi} \) is quite strong, hence the azimuthal velocity gained by the wind due to \( F_\phi \) will also be reduced due to the radiation drag along \( \phi \) direction. Moreover, none of the components of the radiative pressure is greater than all the radiative flux components. This would confine the effect of radiative drag. This augurs well for the wind, so that it can be driven away from the KD, but would not be spread by a very large angle due to the gain in angular momentum from the radiation field. We have plotted the radiative moments in a region very close to the horizon (\( \leq 51.2 \)), and in that region, the radiation field is from an extended source (KD), and therefore the moments show a complicated space dependence. At large distances, the space dependence of radiation field follows \( \sim R^{-2} \), although not in the computational domain we have chosen.

4 NUMERICAL APPROACH

4.1 The numerical scheme and simulation set up

The hydrodynamic equations (1-5) are solved in this paper using Total Variation Diminishing (TVD) scheme, introduced and developed by Harten (1983). The scheme (or, the modified version of it) is applicable to hydrodynamic problems and has been used extensively in relevant astrophysical applications (Ryu 1993; Ryu et al. 1995a,b; Lee et al. 2011; Chattopadhyay et al. 2012; Lee et al. 2016). TVD scheme is an Eulerian, second order accurate, nonlinear, finite difference scheme, which accurately captures shock. The temporal and spatial evolution of the conserved quantities \( \rho, p, v, \) and \( \varepsilon \) is computed using approximate Roe type Riemann solver to solve the differential equations, followed by application of a non-oscillatory first order accurate scheme to the modified flux functions to achieve second order accuracy (see, Roe 1981; Ryu 1993; Harten 1983). Equations of motion (1-5) are similar to those solved in Chattopadhyay et al. (2012). In Chattopadhyay et al. (2012) the galactic outflow was powered by the radiation from the galactic disc, while being decelerated by the gravity of the galactic disc, the halo and the bulge matter. In contrast, in this paper, the accretion disc outflow is powered by the radiative fluxes and the centrifugal force from the KD, and is decelerated by the radiative drag terms as well as, the gravity of the central black hole. To solve the equations of motion (1-5), we considered the TVD scheme (see, Chattopadhyay et al. 2012, for details) for the resolution 512 \times 512. A schematic representation of the computational arrangement is presented in Figure 2, which marks the ghost cells where the boundary conditions are implemented and also the computational domain. We employed continuous boundary condition at \( z = 0 \) boundary, and outflow boundary condition at the outer \( r \) and \( z \) boundaries (i.e., no inflow but continuous if \( v > 0 \)). At \( r = 0 \), or the axis of symmetry, reflection boundary condition has been employed. The type of boundary conditions employed, are also mentioned in Figure (2). We simulate a region of 512 from the black hole, each in \( r \) and \( z \) direction, therefore the dimension of each cell is equivalent to 1. The gravity of the black hole is described by Paczyński & Wiita potential (Paczynski & Wiita 1980). In order to avoid the coordinate singularity on the horizon, the black hole is covered by a sink region of radius 3 around the origin, which do not affect the physics since the inner edge of KD is 3.

The KD is on the equatorial plane, ranging from 3 – 512, the density, pressure and the components of velocity distribution given by equations (10 –15) are maintained in a region described by \( r \rightarrow 3 – 512 \) and \( z \rightarrow 0--3 \). We supply the dynamical variables of the KD at every time step within a
5 RESULTS

5.1 Wind propagation above the disc: density and velocity evolution

In Figure 3(a)-(f), we overplot velocity vectors \( (v_\phi \equiv \sqrt{v_r^2 + v_z^2}) \) on the density contours of radiatively driven winds from a KD, for \( \dot{m}_i = 3 \) and at different time steps \( t = 2 \) (a), \( t = 6 \) (b), \( t = 62 \) (c), \( t = 72 \) (d), \( t = 82 \) (e), and \( t = 92 \) (f). Arrows represent velocity vectors in \( r-z \) plane, where the magnitude of the velocity \( (v_\phi) \) is proportional to the length of the arrows. All densities in this paper are scaled to \( \rho_{\text{ref}} \). The KD is hotter and denser near the inner edge, and the radiative flux maximizes at around 4. Therefore, both the thermal gradient force and the radiative force drive matter in the form of wind from the inner parts of the disc. Very little matter is ejected from the region \( r_d > 100 \), even if the simulation is run for a longer time.

As the wind emerges from the inner regions of the disc, the general direction of motion is away from the axis of symmetry [Figure 3(b)]. However, at a later time, a part of the wind moves towards the axis of symmetry [Figure 3(d)], but the wind again moves away from the axis. The entire wind-fan oscillates as a whole, somewhat dancing like a flame in a breeze. All the matter that is being ejected, does not flow out, but a tiny fraction of it falls back, and hits the wind base, which causes a perturbation propagating along the wind. Moreover, \( F_r \) near the wind base is directed towards the axis, but higher up it is directed away from the axis. The inner radius of KD is \( r = 3 \), so there is no source of radiation for \( r < 3 \). Hence, close to the axis of symmetry and just above the disc, \( r \) component of the radiative flux points inward i.e. \( F_r < 0 \). The centrifugal force is always directed away from the axis. \( F_\phi \) which is weaker than the fluxes in the other two directions, will spin up the wind, but stronger pressure components boosts the drag in the \( \phi \) direction. Additionally the radiative force along \( z \) powers the wind upwards. And finally gravity attracts every part of the wind towards the black hole. All these factors together interact with the ejected matter and generates a wind which originates from the inner region of the KD, but fans out in the \( r-z \) plane. This effect is quite clearly presented in various panels (Figure 3c-f). It may also be noted that all the matter coming out of the KD do not become a wind but sits above the KD.

5.2 Angular momentum transport

Due to high rotational speed of the inner region of the disc, winds produced from this region propagate with a fraction of the rotational speed of the disc. Hence matter ejected from the KD carry a part of the disc angular momentum along with them. This can be seen as one of the ways through which the disc removes its angular momentum. In Figure 4, we plot \( v_\phi \) as a function of \( r \) at a height of \( z = 6 \) from the equatorial plane, measured in three different runtimes \( t = 30 \) (solid), 50 (dashed) and 80 (dashed-dotted). The disc \( v_\phi \) is also included for comparison. It can be seen that near the disc inner edge, almost 64% of the azimuthal component of velocity is effectively removed by the wind which therefore would reduce angular momentum too. All the terms with negative sign in the last term of Equation(3) resist rotation, thereby remove angular momentum (and \( v_\phi \)) from the wind. The rotational speed of the wind can be as high as 0.3 near the axis of symmetry but are much less than the disc rotational velocity. Since the radiative moments are weak above the outer part of the disc, the rotation velocity just above the disc is similar to that on the disc at the same \( r \). Since all the curves (solid, dashed, dash-dotted) almost overlap each other in Figure 4, we conclude that the \( v_\phi \) distribution close to the disc is almost steady. Further, we plot the contours of \( \dot{v}_\phi \) of winds generated from accretion discs with accretion rates \( \dot{m}_i = 3 \) and 4 (Figures 5a & 5b, respectively). As the winds are stronger for higher accretion rates, the outflowing matter driven by radiation from a disc with higher \( \dot{m}_i \), matter with higher \( v_\phi \) are injected. Winds from an accretion disc with \( \dot{m}_i = 4 \), possess higher values of azimuthal velocities in a larger region above the accretion disc, compared to the winds from a disc of lower \( \dot{m}_i \). It may be noted that, a fraction of outflowing matter near the axis of symmetry fall back, and at some height above the disc interacts with the outflowing wind and makes it to bend away. For KDs with higher \( \dot{m}_i \) which are
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Figure 3. Contours of Density $\log_{10}(\rho)$ over plotted with respective net velocity vector arrows. These profiles are for $\dot{m} = 3$. Panels correspond to the snapshots at run time $t = 2, 6, 62, 72, 82$ and $92$ from (a) to (f).

Figure 4. Radial variation of $v_\phi$ at a height $z = 6$ from the equatorial plane, for three run times $30, 50$ and $80$ as shown in legends for $\dot{m} = 3$. The disc $v_\phi$ is plotted for comparison.

Ejecting fast matter and with higher rotation, traps these relatively higher rotating matter in the region where the inner boundary of the wind bend away. And as the matter further move away, $v_\phi$ is reduced by radiation drag.

5.3 Effect of radiation drag

In section (3) the expression of the radiation term (equation 6) contains both positive and negative terms. The flux terms ($F_i$) are positive and therefore would accelerate the flow along its direction. However, the terms having radiation energy density and pressure components, appear with a negative sign and are also proportional to various velocity components. The negative terms causes deceleration and would reduce relevant components of momentum density. These negative terms are called radiative drag terms. For example, the radial component of momentum density equation (2) will be increased by $F_r$, but will be reduced provided any or all the terms containing $E, P_{rr}, P_{r\phi}, P_{rz}$ are dominant. It may be noted that, the radiative drag terms are highly non-linear, for example, $P_{\phi r}$ will couple with $v_r$ and hinder the growth of azimuthal momentum density ($\rho v_\phi$), but will also couple with $v_\phi$ and oppose the growth of $\rho v_r$ (refer to, equation(6) for radiative terms and the equations of motion 2-3).
To show the impact of radiation drag on the dynamics of the winds, we compare solutions with and without drag terms. We plot the density contours and velocity field of wind solutions with drag terms in the left panels (a, c, e) of Figure (6), while solutions without drag terms are plotted in the right panels (b, d, f) of the same figure. The accretion rates for each pair of comparable panels are $\dot{m} = 1.3$ (Figures 6a & b), $\dot{m} = 2.5$ (Figures 6c & d) and $\dot{m} = 3$ (Figures 6e & f). All the plots obtained are at run time $t = 72$. For lower $\dot{m}$ the wind is launched, but as it accelerates to higher velocities the drag terms suppress the wind. However, in absence of radiation drag the wind freely propagates outwards. For a slightly higher $\dot{m} (= 2.5)$, a weaker wind is generated in presence of drag terms (Figure 6c) however, without drag terms the wind is relatively stronger (Figure 6d). Similar effect can be seen for $\dot{m} = 3$ in which the wind in presence of drag terms (Figure 6e) is weaker than the the one in absence of drag term (i.e. Figure 6f). It may be noted, in absence of radiation drag term, a lower luminosity disc will produce stronger winds than that above a luminous disc in which drag terms are considered (compare Figures 6d & 6e). Here Figure 6(e) is identical to Figure 3(d). Radiation driving ($F_r, F_z$) is weaker above low luminosity accretion discs. As the wind is launched from such a disc, it has low poloidal velocity ($v_p = \sqrt{v_r^2 + v_z^2}$) to start with, but high $v_\phi$. It means radiation drag is not important along $r, z$ directions, but, $v_\phi$ being high, it boosts the drag terms in all the three direction. Therefore, matter ejected from the disc will not flow out as wind but will be smothered down by the drag term. Above a luminous disc, however, jets are strongly driven in $r, z$ direction and can overcome the radiation drag due to high $v_\phi$. At larger distances, where poloidal velocity increases, drag becomes more effective and limits the terminal speed of the outflow. This figure illustrates the effect of radiative drag.

5.4 Terminal speeds of the winds

Once the winds leave the computational domain and escape to infinity, the maximum speeds they acquire while escaping is what we call terminal speed ($v_T$). These are the speeds that correspond to the observed blue shift in the spectra from these sources. In this paper, we consider the the maximum speed at the outer boundary as the $v_T$ (i.e. $v_T = v_p(512)$). In Figure (7), we plot the terminal speeds as a function of $\dot{m}$ at run time $t = 100$. The dashed curve corresponds to $v_T$ when all the radiative terms are effective (including drag terms). To show the effect of radiation drag, we over plot corresponding terminal speeds without considering the radiation drag terms (solid). The winds are faster for higher accretion rates and safely reach mildly relativistic values. In absence of radiation drag, the terminal speeds are overestimated by about an order of magnitude.

5.5 Mass outflow properties

As the matter is ejected from the upper disc surface, the mass flux due to the emission can be represented in differential form as

$$d\dot{M}_{\text{out}}(r) = 2\pi r \rho v_z dr \quad (20)$$

The total integrated value of $\dot{M}_{\text{out}}$ along radial direction can be written as

$$\dot{M}_{\text{out}} = \int_{r_i}^{r_o} 2\pi r \rho v_z dr \quad (21)$$

Here we have spatial resolution of $dr = 1$. We calculate the radial variation of outflow at a certain height, $z$ from the disc, as well as the net integrated outflow along $r$ at that specific $z$, for a particular time step. In Figure 8(a), we plot $d\dot{M}_{\text{out}}$ (in Eddington units) with $r$, calculated just above the disc for $\dot{m} = 2.5, 3$ & 4 at run time $t = 100$, signifying the outflow from the launching point of the wind. Further, in Figure (8b), we estimate the radial variation of the outflow rate at the outer $z$ boundary of the computational domain. The outflow at the ejection base mostly comes out from the inner regions of the accretion disc and with time it gradually covers the entire numerical domain diagonally leaving the domain through the outer boundaries. Further, the outflow rates at
Figure 6. Density distribution for $\dot{m} \approx 1.3$ (a & b), $\dot{m} \approx 2.5$ (c & d) and $\dot{m} \approx 3$ (e & f), snapshots are at run time $t = 72$; frames in the left column are generated considering the radiation drag and the right panel frames are without the drag effect. It is evident that for low mass accretion rate (here, $\dot{m} \approx 1.3$), the winds cannot be driven away due to the presence of the radiation drag.
the outer boundary are significantly less than the outflow at the launching, indicating that all the matter ejected from the disc does not leave the domain but only a fraction of it escapes. In Fig. 8(c), we show the integrated outflow rates \( \dot{M}_{\text{out}} \) (black dashed) from the disc calculated at outer \( z \) boundary (\( z = 512 \)). These values are obtained by integrating the outflow rates along \( r \), at run time \( t = 100 \). For comparison, we show the outflow rates without drag (blue solid) and observed that, as expected, the radiation drag has significant effect in suppressing the matter ejection in form of the winds. Furthermore, very small magnitudes of the outflow rates compared to the accretion rates justify our assumption that the disc can remain mostly in steady state and is not affected by the matter ejection. In other words, the accretion rates remain time-independent.

The computational domain in this paper is just \( 512 \times 512 \), so it is intriguing to wonder what fraction of the computed outflow will actually escape the gravity of the black hole. Since the wind is also a fluid, therefore if the wind is transonic then it will definitely escape the the black hole gravity. In Fig. 9 we plot the percentage of the calculated mass outflow rate at \( z = 512 \) which are transonic or \( v_T(r,512)/c_s(r,512) > 1 \), and is measured as

\[
\hat{R}_{\text{out}} = \frac{\dot{M}_{\text{out}}\,\text{(trans)}}{\dot{M}_{\text{out}}\,\text{(total)}},
\]

where both \( \dot{M}_{\text{out}}\,\text{(trans)} \) and \( \dot{M}_{\text{out}}\,\text{(total)} \) are measured at \( z = 512 \) or the upper boundary of the computational box. Figure 9 shows that of all the matter which is ejected from the computational domain, only a fraction of it is transonic and therefore actually can leave the gravitational attraction of the central black hole. For \( \dot{m} = 3 \) (dotted, blue) the transonic mass outflow rate is about 10% of the total mass leaving the computational domain as winds. For \( \dot{m} = 3.5 \) (solid, red) it varies between 30-70% of the total outflow. We compute the wind flowing out of the computational domain only through upper \( z \) boundary, because mass-outflow rate through outer \( r \) boundary is about an order of magnitude less compared to that through the upper \( z \). Moreover, the mass flowing out through the outer \( r \)-boundary is subsonic and would not contribute significantly in the net outflow rate. The wind outflow rate is also variable.

Figure 7. Terminal speeds as a function of \( \dot{m} \) for winds with radiation drag terms (solid curve) and without radiation drag terms (dashed) at run time \( t = 100 \).

Figure 8. Radial variation of mass outflow rate \( d\dot{M}_{\text{out}}(r) \), (a) just above the accretion disc and (b) at outer \( z \) boundary. (c) Variation of mass outflow \( \dot{M} \) at the outer \( z \) boundary, w.r.t \( \dot{m} \), with and without considering the effect of radiation drag on the outflows. All the outflows are measured in Eddington unit, at run time \( t = 100 \).
6 CONCLUSIONS

In this paper, we have studied the generation mechanism and properties of the winds around black hole accretion discs. The winds are generated by a Shakura - Sunyaev Keplerian accretion disc which is steady in nature and act as a source of wind and the radiation field which drives them. The radiation field is controlled by $\dot{m}$. We computed all components of radiative moments numerically. The radiation field generated by the steady KD are also steady. It may be noted that, our assumption of optically thin nature of the medium above the KD is justified since the cumulative optical depth along the $z$-direction is much less than 1 (see appendix A). Although we keep our analysis in non relativistic regime, we have used pseudo-Newtonian gravitational potential to take care of strong gravity near the black hole.

We show that the radiation pressure inside the disc along with the thermal pressure is able to push the matter out of the disc. The winds are mostly generated from inner region of the accretion disc ($r < 30$). The matter emitted out not only carries matter with it but also removes angular momentum from the disc. Highly rotating winds are driven by a combined effect of thermal pressure, radiation field and centrifugal force and typically for $\dot{m} > 1.8$ the winds escape to infinity. While for smaller accretion rates we showed that the winds fall back to the disc as they don’t have sufficient radiation drive to push them to escape. One curious fact which these simulations showed is that a part of the matter ejected does not become wind but may accumulate above the disc.

We showed that the radiation drag limits the jet speed. In fact below a certain luminosity, the wind is destroyed by the drag term. Only for a luminous disc, radiation can generate a wind against gravity and its own drag. So radiation drag is a significant factor in determining the dynamical properties of the winds. The $\phi$ component of the radiation drag is also capable to reduce the angular momentum of the wind. The work of Yang et. al. (2018) is similar to ours, except that they considered outflows from a corona and they did not consider radiation drag. These authors considered more luminous disc (up to 0.75 Eddington luminosity) while we considered only up to 0.66 Eddington luminosity ($\equiv 4M_{\text{Edd}}$). However, the maximum terminal speeds are somewhat similar for luminous disc, although we predict a lower cutoff of disc luminosity to drive a wind from KD.

We analyzed the terminal properties of the winds and found that the terminal velocities of the disc winds are sub relativistic and higher accretion rate leads to higher magnitudes of the wind speed. The wind speeds are found to be mildly relativistic which is consistent with observations. We show that if radiation drag is ignored, the terminal speeds are overestimated significantly.Detailed study of mass outflow rate shows that the mass loss from the disc is indeed a very small fraction of the disc mass and hence we may conclude that the radiative property of the KD will not be significantly affected by radiatively driven winds. Inclusion of radiation drag sufficiently suppresses the mass outflow rates at outer boundary of our computational domain. So one needs to take care of radiation drag effects while carrying out the analysis of radiation driving in the winds. It is a non relativistic study of the disc wind dynamics under impact of radiation field in Thomson scattering regime. In upcoming works, we would examine the role of Compton scattering in driving such winds.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

REFERENCES

Ballesteros S. A., Hawley J. F., 1991, ApJ, 376, 214
Blandford R. D., Payne D. R., 1982, MNRAS, 277, 1327
Begelman M. C., McKee C. F., Shields G. A., 1983, ApJ, 271, 70
Cappi M., et. al., 2009, A&A, 504, 401
Chartas G., Brandt W. N., Gallagher S. C., Garmire G. P., 2002, ApJ, 579, 169
Chartas G., Brandt W. N., Gallagher S. C., 2003, ApJ, 595, 85
Chattopadhyay I., Chakrabarti S. K., 2000a, Int. Journ. Journ. Mod. D, 9, 57
Chattopadhyay I., Chakrabarti S. K., 2000b, Int. Journ. Journ. Mod. D, 9, 717
Chattopadhyay I., Chakrabarti S. K., 2002, MNRAS, 333, 454
Chattopadhyay I., 2005, MNRAS, 356, 145
Chattopadhyay et. al., 2012, MNRAS, 423, 2153

Figure 9. The percentage of the total outflow which are transonic $R_{\text{out}}$ as a function of time, for two accretion rates $\dot{m} = 3.0$ (dotted, blue) and $\dot{m} = 3.5$ (solid, red).
The radiative moments in this paper are computed assuming that the medium above the disc is optically thin. In this appendix, we calculate the optical depths above the accretion disc to check the justification to this assumption. The optical depth is calculated by integrating the differential optical depth along z direction, above the disc, in the computational domain as

$$\tau = \int_z \frac{\sigma T \rho(z)}{m_p} dz \quad (A1)$$

It is calculated at a fixed radial distance $r$ from the black hole. In Figure (A1) we plot the estimated optical depths above the disc for various values of $\dot{m}$ calculated at different but fixed values of $r$. Since, $\tau < 1$ at every $r$ throughout the computational domain, the assumption of tenuous winds above the disc plane is justified. For high $\dot{m}$, the optical depth reach up to $<0.7$ at the top of the computational domain at higher values of $r$, while it remains sufficiently low at smaller $r$ even for high $\dot{m}$. It is worth mentioning that all the radiative effects are mainly applicable to small $r$. At larger distances from black hole, the radiation field is not very effective.