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On the possibilities of mass loss from an advective accretion disc around stationary black holes

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Abstract. We study the coupled disc-jet system around the black hole where the outflow solutions are obtained in terms of the inflow parameters. We observe that an advective accretion disc can eject outflows/jets for wide range of viscosity parameter. However, such possibility is reduced if the cooling is active as the energy dissipative process inside the disc. For mass outflow, we obtain the parameter space spanned by the inflow angular momentum and the viscosity in terms of cooling and quantify the limits of viscosity parameter.

Keywords : black hole physics – accretion, accretion discs – methods: numerical

1. Introduction

Outflows/jets are commonly observed from black hole systems. They seem to originate from the accreting matter as black hole does not have any intrinsic atmosphere. In rotating accreting matter, centrifugal force at the vicinity of the black hole acts as a barrier to the faster supersonic matter following it and eventually slows it down. If the barrier is strong enough then it triggers the formation of shock waves (Chakrabarti 1996; Das et al. 2001; Chakrabarti & Das 2004; Das 2007; Chattopadhyay 2008; Chattopadhyay & Chakrabarti 2011). This centrifugally supported post-shock matter is hot and piles up in the form of a torus around the black hole called CENtrifugal pressure supported BOundary Layer (CENBOL) (Chakrabarti 1999). In the post-shock region, accreting matter is compressed and becomes hot. Consequently, excess thermal gradient force develops in the post-shock disc, which ultimately deflects a part of the accreting matter to

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form bidirectional outflows/jets. This was shown via Lagrangian, as well as, Eulerian numerical simulation codes (Molteni et al. 1994, 1996; Lee et al. 2011). Theoretically, Chakrabarti (1999) computed the mass outflow rate for very simplistic flow configurations, in terms of inflow parameters. In the same spirit, but considering rotating accretion flow, Das et al. (2001) computed the mass outflow rates from input parameters of inviscid flow where the accretion is rotating but jet was assumed to be radial. Later, Chattopadhyay & Das (2007); Das & Chattopadhyay (2008) calculated mass loss from dissipative accretion disc considering rotating outflow. Subsequently, mass outflows have been computed for variety of shocks (Becker et al. 2008; Das et al. 2009), various types of acceleration mechanisms (Kumar & Chattopadhyay 2013; Kumar et al. 2014), and even for variable adiabatic index (Kumar et al. 2013), using an equation of state of the flow designed to handle multi-species fluid (Chattopadhyay & Ryu 2009). Recently, Das et al. (2014) showed that a part of the inflowing matter is periodically ejected from the disc when the viscosity parameter is chosen beyond its critical values. Already, Chattopadhyay & Das (2007) and Das & Chattopadhyay (2008) studied the outflow properties in terms of the disc viscosity and cooling processes. The outflow rate computed from the appropriate choice of the inflow parameters is consistent with the jet kinematic luminosity estimated from the radio luminosity of the jets (Heinz & Sunyeav 2003). Here, we mean outflows as jets and not winds. Jets differ from winds as they are usually fast, supersonic and collimated outflows. It is well known that the increase of accretion rate demonstrates the transition of the black hole sources from hard to softer spectral states (Chakrabarti & Titarchuk 1995; Chakrabarti 1997) which suggests an underlying connection between outflow properties and the spectral states. The outflow rate also depends on viscosity, which indicates that there exists a range of viscosity that allows mass loss from the disc for a given accretion rate. Such critical limits of the viscosity is not studied so far and for the first time, we identify the range of viscosity for the formation of mass outflow from the accretion disc.

In the next Section, we present the basic assumptions and governing equations. In Section 3, we discuss the results and finally present the conclusions.

2. Assumptions and model equations

We consider a steady, viscous, axisymmetric accretion flow on to a Schwarzschild black hole. We adopt Paczyński & Wiita (1980) potential to describe space-time geometry around the black hole. Also, the flow is assumed to be in hydrostatic equilibrium in the vertical direction (Matsumoto et al. 1984). In our model, jets are tenuous, and have negligible shear and therefore can be assumed to be inviscid (Chattopadhyay & Das 2007) and have low angular momentum compared to the outer edge of the disc. In this work, we use $2G = M_{\rm BH} = c = 1$ unit system, where G, $M_{\rm BH}$, and c are the gravitational constant, the mass of the black hole, and the velocity of light, respectively.

2.1 Equations for accretion

The dimensionless governing equations for accretion are (Chakrabarti 1996),

(a) the radial momentum equation:

$$u\frac{du}{dx} + \frac{1}{\rho}\frac{dP}{dx} - \frac{\lambda^2(x)}{x^3} + \frac{1}{2(x-1)^2} = 0, \tag{1a}$$

(b) the mass conservation equation:

$$\dot{M} = 2\pi\Sigma u x, \tag{1b}$$

(c) the angular momentum conservation equation:

$$u\frac{d\lambda(x)}{dx} + \frac{1}{\Sigma x}\frac{d}{dx}\left(x^2 W_{x\phi}\right) = 0, \tag{1c}$$

and (d) the entropy equation:

$$uT\frac{ds}{dx} = Q^+ - Q^- \tag{1d}$$

where, x, u, ρ, P and $\lambda(x)$ are the radial distance, radial velocity, density, isotropic pressure and specific angular momentum of the flow, respectively. Here, Σ is vertically integrated density, s is the specific entropy of the flow, and T is the local temperature. The viscous stress is represented by $W_{x\phi}$ ($= -\alpha\Pi$, $\Pi = [W + \Sigma u^2]$ is the vertically integrated total pressure, α is the viscosity parameter, W is vertically integrated thermal pressure). Heat gained by the flow are given by (Chakrabarti 1996; Das & Chattopadhyay 2008),

$$Q^+ = -\frac{\alpha}{\gamma}x(ga^2 + \gamma u^2)\frac{d\Omega}{dx}, \tag{2a}$$

where, γ is the adiabatic index, $g = I_{n+1}/I_n$, $n = 1/(\gamma - 1)$, $I_n = (2^n n!)^2/(2n+1)!$ (Matsumoto et al. 1984). In this work, Bremsstrahlung cooling process is ignored as it is inefficient and only synchrotron cooling is considered which is given by (Das & Chattopadhyay 2008),

$$Q^- = \frac{Sa^5}{ux^{3/2}(x-1)}, \tag{2b}$$

where,

$$S = \frac{32\eta\mu^2 e^4 \times 1.44 \times 10^{17}}{3\sqrt{2}m_e^3\gamma^{5/2}}\frac{\dot{m}_i}{2GM_\odot c^3}. \tag{2c}$$

Here, e is the electron charge, m_e is electron mass, $M_\odot$ is solar mass, and $\mu = 0.5$ for fully ionized plasma. The accretion rate $\dot{m}_i$ is measured in units of Eddington accretion rate adopting $10M_\odot$ black hole. We use η (≤ 1) which is the ratio between the magnetic pressure to the gas pressure to estimate the magnetic field for synchrotron cooling. In this work, $\gamma = 4/3$ and $\eta = 0.1$ are used throughout the paper.

2.2 Equations of motion for outflows

The conserved energy equation for jet is given by (Chattopadhyay & Das 2007),

$$\mathcal{E}_j = \frac{1}{2}v_j^2 + na_j^2 + \frac{\lambda_j^2}{2x_j^2} - \frac{1}{2(r_j - 1)}, \tag{3a}$$

where, $\mathcal{E}_j$ and λ_j are the specific energy and the angular momentum of the jet, respectively. The integrated continuity equation for jet is,

$$\dot{M}_{\rm out} = \rho_j v_j \mathcal{A}, \tag{3b}$$

where, $\dot{M}_{\rm out}$ is the outflow rate, ρ_j is the jet density, v_j is the jet velocity and $\mathcal{A}$ denote the area function of the jet (Chattopadhyay & Das 2007).

3. Method

Since a part of the accreting matter is deflected at the CENBOL surface to form bidirectional outflows (Das et al. 2013, 2014), therefore, our focus would be on such accretion solutions that contain stationary shocks. For shock, accreting flow must possess two saddle type sonic points, namely inner sonic point (x_{ci}) and outer sonic point (x_{co}). Interestingly, the range of x_{ci} is usually restricted within $2 - 4$ r_g ($r_g \equiv$ Schwarzschild radius) (Chakrabarti & Das 2004; Das 2007) and we choose x_{ci} as one of the input parameters to obtain the accretion solution that includes shock wave. Other input parameters are angular momentum λ_i at x_{ci}, viscosity (α) and accretion rate $\dot{m}_i$, respectively. We calculate the accretion solution by integrating the governing equations (Eqs. 1a-d) once from x_{ci} inwards and then outwards (Chakrabarti & Das 2004). The condition for steady shock requires conservation of energy flux, mass flux, and momentum flux across the shock front (Landau & Liftshitz 1959) and in presence of mass loss, conservation of mass flux is taken care considering mass outflow rate $R_{\dot{m}}$ defined as the ratio between the mass flux of the outflow ($\dot{M}_{\rm out}$) and the pre-shock accretion rate ($\dot{M}_-$) (Chattopadhyay & Das 2007) which are given by,

$$\mathcal{E}_+ = \mathcal{E}_-; \ \dot{M}_+ = \dot{M}_- - \dot{M}_{\rm out} = \dot{M}_-(1 - R_{\dot{m}}); \ \Pi_+ = \Pi_-, \tag{4}$$

where, subscripts "−" and "+" refer to the quantities before and after the shock, respectively.

We consider that jet is launched with the same energy, angular momentum and density of the post-shock flow and the corresponding mass outflow rate is given by (Chattopadhyay & Das 2007; Das & Chattopadhyay 2008),

$$R_{\dot{m}} = \frac{\dot{M}_{\rm out}}{\dot{M}_-} = \frac{R v_j(x_s)\mathcal{A}(x_s)}{4\pi\sqrt{\frac{2}{\gamma}}x_s^{3/2}(x_s - 1)a_+ u_-}, \tag{5}$$

where, x_s is the shock location, R $(= \Sigma_+/\Sigma_-)$ is the compression ratio and a_+ is the post-shock sound speed. We simultaneously solve the accretion-ejection equations to obtain shocks in presence of mass loss in the following way. We first find the virtual shock location x_s' without considering mass loss. We assign shock energy $\mathcal{E}(x_s')$ and angular momentum $\lambda(x_s')$ as the jet energy $\mathcal{E}_j$ and λ_j and solve the jet equations to obtain corresponding $R_{\dot{m}}$. Now we use $R_{\dot{m}}$ in shock condition to find the new shock location. We continue the iteration to converge for actual shock location and the corresponding $R_{\dot{m}}$ is the relative mass outflow rate. Here, the jet is assumed to have the same energy as the post shock disc. Since these bidirectional outflows are launched from the post-shock disc, therefore, the flow parameters at the jet base should be same as that of the disc from where it is being launched. For simplicity, we consider the immediate post-shock Bernoulli parameter to be that of the jet.

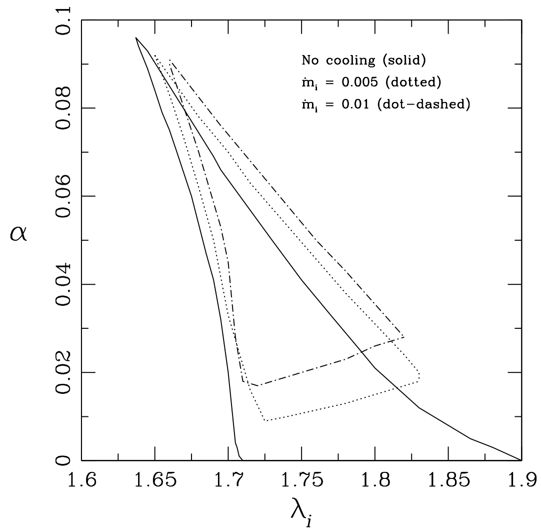

Figure 1. Parameter space spanned by the angular momentum (λ_i) at the inner sonic point and the viscosity. Different boundaries separate the parameter space for mass loss from the disc. Solid boundary is for solutions having no cooling and the boundaries drawn with dotted and dot-dashed curves are for various accretion rates marked in the panel. See text for details.

4. Results and discussion

In this work, we intend to find the range of viscosity that admits mass loss from an advective accretion disc around the black holes. To achieve our goal, we supply the inflow parameters, namely, inner sonic points (x_{ci}), angular momentum (λ_i) and viscosity (α), respectively and look for global inflow-outflow solutions. Of the three parameters, we fixed angular momentum (λ_i) and vary inner sonic points (x_{ci}) and viscosity (α) for all possible range. Essentially, we identify the region of the parameter space spanned by the angular momentum (λ_i) and viscosity (α) for mass loss which is shown in Fig. 1. It is indeed fascinating to see that mass loss is possible for a wide range of viscosity which again strongly depends on the angular momentum of the accreting matter at the inner part of the disc. We classify the parameter space as function of accretion rate $\dot{m}_i$ and separate it with the solid, dotted and dot-dashed boundaries. Solid boundary represents the cooling free solutions that are independent of $\dot{m}_i$. The dotted and dot-dashed boundaries denote the solutions that correspond to $\dot{m}_i = 0.005$ and $\dot{m}_i = 0.01$, respectively. As the cooling is increased, the size of the post-shock region shrinks (Das 2007) and the possibility of mass loss is reduced (Chakrabarti 1999; Das et al. 2001) which is consistent with the conclusions of Das & Chattopadhyay (2008) and Garain et al. (2012). This result has a profound implication as Das & Chattopadhyay (2008) pointed out that with the appropriate choice of the inflow parameters, the present disc-jet model successfully explains the jet luminosity at least for two objects, namely, M87 and Sgr A*. Das & Chattopadhyay (2008) estimated the mass outflow rate of M87 jets as $0.009 M_\odot$ yr^{-1} which gives a kinematic luminosity of $\sim 10^{43}$ergs s^{-1} (Reynolds et. al. 1996) considering few percent efficiency, while for Sgr A* the estimated mass loss was $9 \times 10^{-8} M_\odot$ yr^{-1} that also satisfies the kinematic luminosity of $\sim 10^{38}$ergs s^{-1} accepted in the literature (Yuan 2000; Yuan et. al. 2002). In the similar way, with this methodology one can estimate the jet power in hard states for the galactic stellar mass black hole sources as well.

In this work, we choose a set of γ and η values to represent our results. We examined the dependency of mass loss parameter space on γ and observed only quantitative variation in a way that the parameter space is shifted towards the lower viscosity and angular momentum side for $\gamma > 4/3$. As discussed in Section 2.1, the limit is $\eta \leq 1$ and we use $\eta = 0.1$. For higher η, the effect of radiative loss would be more for the same accretion rate (Eq. 2c) and thereby reduce the thermal driving of the jets. Eventually, the parameter space for mass loss would further be reduced with the increase of η values.

Recently Nandi et al. (2013) reported that several GBH sources exhibit hard to hard-intermediate spectral state transition along with the increase of QPO frequency and radio and X-ray fluxes. However, during the transition from hard-intermediate to soft-intermediate state, the QPO disappears followed by the transient radio flare. This perhaps indicates that the presence of weaker/mildly relativistic, continuous jet is related to a component of the disc which is responsible for QPO. And the disappearance of QPO followed by strong radio flare shows that it is the same component of the disc which gets disrupted and expelled as strong, relativistic ejections during the hard-intermediate to soft-intermediate state transition. This observation confirms the presence of shock in accretion disc and also identifies the post-shock disc (CENBOL) as the seat of hot electrons/Comptonizing cloud whose dynamics is responsible for jet generation and QPOs. With these insights, it would be intriguing to interpret the relations among the jet evolution, spectral states and QPOs in greater details. Indeed, some of the seminal works has already been initiated (Chakrabarti & Manickam 2000; Giri & Chakrabarti 2013). Our present effort which is the identification of ranges of viscosity parameter and accretion rate resulting steady jets, would be an insight for impending numerical simulations to study variabilities of black hole accretion-ejection system. Overall, one can limit the value of viscosity parameter while explaining the jet power for numerous objects which we intend to explore elsewhere.

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