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Formation of non-steady outflows and QPOs around black hole

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Abstract. We study the time dependent properties of sub-Keplerian viscous accretion flow around the black holes. We find that rotating matter feels centrifugal barrier on the way towards the black holes and eventually, shock transition is triggered allowing a part of the post-shock matter to eject out as bipolar outflow. This outflowing matters are supposed to be the precursor of relativistic jets. As viscosity is increased, shock becomes unsteady and start to oscillate when viscosity reached its critical value. This causes the inner part of the disk unsteady resulting periodic ejection of matter from the post-shock region. Also, the same hot and dense post-shock matter emits high energy radiation which modulates quasi-periodically. The power density spectra confirms this features as most of the power is concentrated at a narrow frequency range — a characteristics (*i.e*. Quasi-Periodic Oscillation) commonly seen in several outbursting black hole candidates.

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

1. Introduction

Outflows/Jets are commonly seen in extreme gravitating systems ranging from stellar mass to supper massive black holes. They are believed to be originated from the regions few tens of Schwarzschild radius (r_g) around the central objects. In addition,

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Gallo et al. (2003) reported that quasi steady outflows are generally ejected in the hard state which indicates that the generation of outflows are expected to depend on various states of the accretion disk. Inner boundary condition for accretion onto black hole demands that the accreting matter must be transonic and sub-Keplerian in nature. Close to the black hole, accreting matters are slowed down due to centrifugal pressure and eventually piled up to form a torus like structure at the inner part of the disk. Such a geometry behaves like an effective boundary layer to the accreting matter from the outer edge where flow may undergo steady or non-steady shock transition (Chakrabarti 1989; Chakrabarti 1990; Chakrabarti & Molteni 1995; Chakrabarti 1996; Das 2007). Usually, the post-shock matter is hot and dense because of compression and behaves as a source of high energy radiation (Chakrabarti & Titarchuk 1995; Chakrabarti & Mandal 2006). Also, due to thermal pressure gradient, a part of the accreting matter is deflected from the boundary layer and ejected as bipolar outflow (Chakrabarti 1999; Das et al. 2001; Chattopadhyay & Das 2007; Das & Chattopadhyay 2008). When shock oscillates, the boundary layer becomes non-steady and effectively, both the outflow and the emergent radiation flux modulate quasi periodically in a similar manner. In this work, we study the shock oscillation, outflow, and emitted flux variation in terms of the flow parameters. In the next Section, we describe simulation method and finnaly present results and discussion.

2. Simulation

We consider the time dependent axisymmetric 2-dimensional viscous accretion flow around a Schwarzschild black hole and study the time evolution of flow variables using smooth particle hydrodynamics (SPH) scheme (Chakrabarti & Molteni 1995). We approximate the space-time geometry around a non-rotating black hole assuming the pseudo-Newtonian potential introduced by Paczyński & Wiita (1980). In this work, we adopt the dynamical viscosity prescription from Chakrabarti & Molteni (1995) which is given by,

$$\eta = \nu\rho = \alpha\rho(a^2 + v^2)\sqrt{2x(x-1)^2}$$

where, ν is the kinematic viscosity, α is the dimensionless viscosity parameter, a (= $\sqrt{\gamma P/\rho}$) is the sound speed, and $v = \sqrt{v_x^2 + v_z^2}$ is the total velocity. Other variables have their usual meanings. In this work, the distance, velocity and time are measured in units of $r_g = 2GM_{BH}/c^2$, c and $t_g = 2GM_{BH}/c^3$, where G, M_{BH} and c are the gravitational constant, the mass of the black hole and the speed of light, respectively.

3. Results and discussion

In our simulation, we inject SPH particles with radial velocity $v_{\rm inj}$, angular momentum $\lambda_{\rm inj}$ and sound speed $a_{\rm inj}$ from the injection radius $x_{\rm inj}$. At $x_{\rm inj}$, the disk height is estimated assuming the flow remain in hydrostatic equilibrium along the vertical

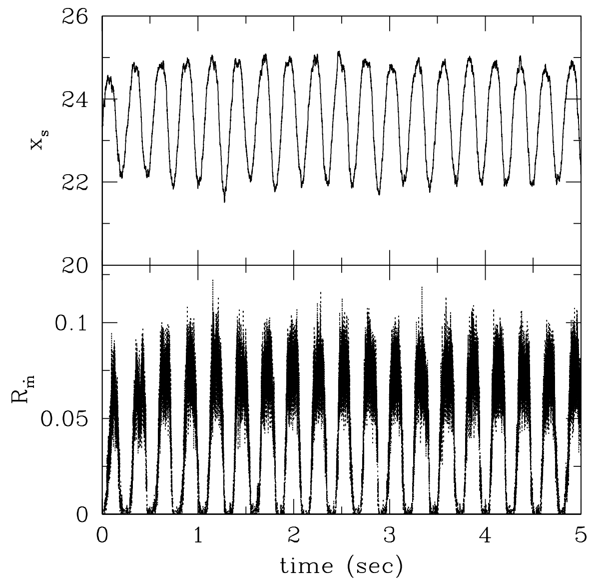

Figure 1. Variation of shock location (*top panel*) and mass outflow rate (*bottom panel*) with time for $10M_\odot$ black hole. Input parameters are $x_{\rm inj} = 50.4$, $\upsilon_{\rm inj} = 0.0643$, $a_{\rm inj} = 0.0633$, $\lambda_{\rm inj} = 1.65$, $\alpha = 0.006$ and $\gamma = 4/3$, respectively.

direction and obtained as $H_{\rm inj} \sim a_{\rm inj} x_{\rm inj}^{1/2}(x_{\rm inj} - 1)$ (Chakrabarti 1989). During accretion, rotating matter feels centrifugal force that opposes the strong pull of gravity close to the black hole. As a result, matter accumulates there and an effective boundary layer is developed which is termed as CENtrifugal pressure supported BOundary Layer (CENBOL). With the appropriate choice of the outer boundary condition (OBC), the inviscid accreting flow undergoes shock transition at the CENBOL and as time evolves, shock becomes stationary. Subsequently, we turn on the viscosity to transport the angular momentum outwards which apparently drives the shock front to recede away from the black hole and finally stabilizes again. For a given OBC, when the viscosity is increased further and reached its critical value, shock front exhibits regular oscillation which sustain forever. The reason for this resonance oscillation perhaps due to the fact that the flow jumps from super-sonic branch to the sub-sonic branch while attempting to choose the high entropy solution, but could not satisfy the standing shock conditions and eventually oscillates. Due to differential motion, the shock front oscillates like a flap with respect to disk equatorial plan and the post-shock matter periodically experiences compression and rarefaction. With the combined effects of compressional heating and the flapping action of the shock-front, a part of the post-shock matter is ejected out from the disk in the vertical direction with modulation at par with the shock oscillation. When the spewed up matter receives excess driving, matter leaves the disk in the form of outflow, otherwise falls back onto the disk. Accordingly, a cycle of periodic mass ejection is observed from the vicinity of the grav-

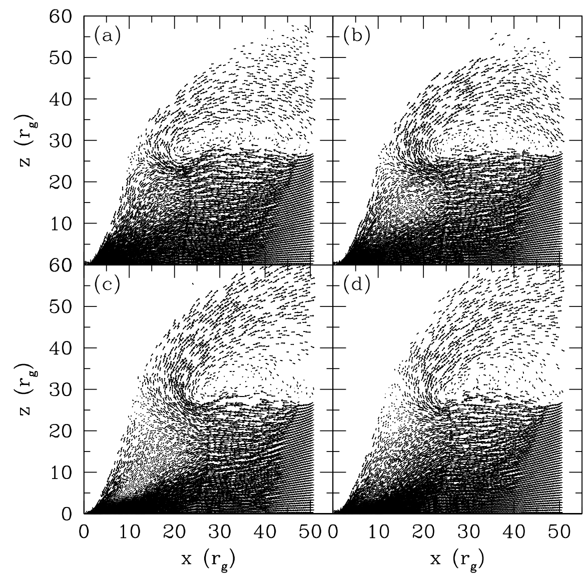

Figure 2. Velocity vectors are in $x - z$ plane. Snap shots are taken at equal interval within a complete period of shock oscillation. Input parameters are same as figure 1.

itating object which is nicely accounted as quasi periodic variation of mass outflow. In Fig. 1, we present the persistent shock oscillation (top panel) taking place over a large period of time for $10M_\odot$ black hole. The input parameters are $x_{\rm inj} = 50.4$ $\rm r_g$, $v_{\rm inj} = 0.0643$, $a_{\rm inj} = 0.0633$, $\lambda_{\rm inj} = 1.65$, $\alpha = 0.006$ and $\gamma = 4/3$, respectively. The corresponding mass outflow rate [$R_{\dot m}$, defined as the ratio of the outflow rate ($\dot M_{\rm out}$) to the inflow rate ($\dot M_{\rm in}$)] variation is shown in the lower panel. In Fig. 2, we depict four snap shots of velocity distribution of SPH particles over a complete cycle of shock oscillation. It is observed that the rate of outflow is regulated by the modulation of the post-shock matter confined within the CENBOL.

Due to shock transition, the post shock matter becomes hot and dense which would essentially be responsible to emit high energy radiation. At the critical viscosity, since the shock front exhibits regular oscillation, the inner part of the disk, *i.e.* CENBOL, also oscillates indicating the variation of photon flux emanating from the disk. Thus, a correlation between the variation of shock front and emitted radiation seem to be viable. In this work, we estimate the bremsstrahlung emission as,

$$E_{Brem} = \int_{x_1}^{x_2} \rho^2 T^{1/2} x^2 dx,$$

where, x_1 and x_2 are the radii of interest within which radiation is being computed. We calculate the total bremsstrahlung emission for the matter from the CENBOL region. To understand the correlation between the shock oscillation and the emitted photon

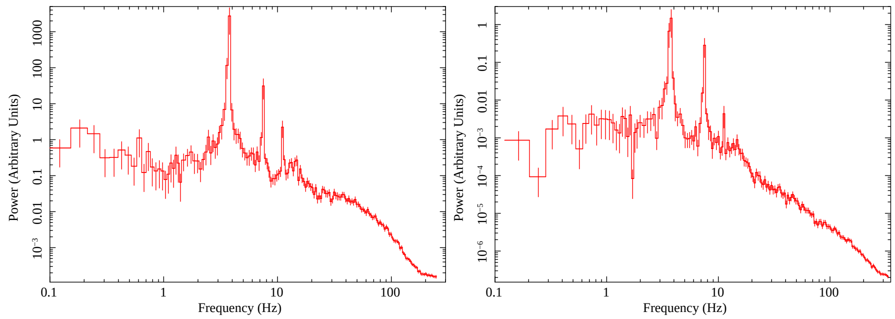

Figure 3. Fourier spectra of shock location variation (*left*). Corresponding power density spectra of bremsstrahlung flux variation (*right*). Input parameters are same as figure 1. See text for details.

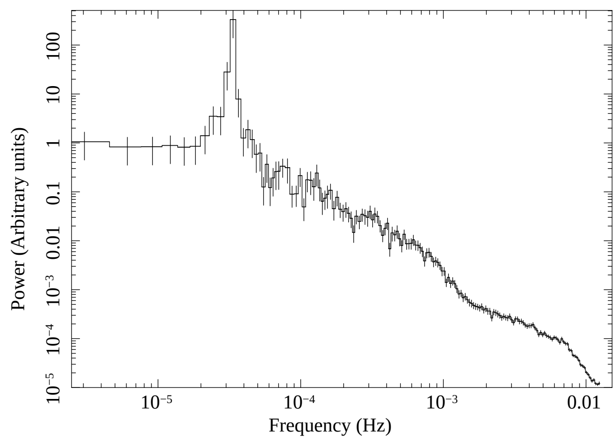

Figure 4. Fourier spectra of shock location variation for super massive black hole of mass $10^6 M_\odot$. Input parameters are $x_{\rm inj} = 50.8$, $v_{\rm inj} = 0.0653$, $a_{\rm inj} = 0.0622$, $\lambda_{\rm inj} = 1.67$, $\alpha = 0.00525$ and $\gamma = 4/3$, respectively.

flux from the inner part of the disk, we calculate the Fourier spectra of the quasi periodic variation of the shock front and the power spectra of bremsstrahlung flux for matter resides within the boundary of CENBOL. The obtained results are shown in Fig. 3 where left figure is for shock oscillation and the right figure is for photon flux variation. We find that the quasi-periodic variation of the shock location and the photon flux is characterized by the fundamental frequency $\nu_{\rm fund} = 3.84$ Hz which is followed by multiple harmonics. The first few prominent harmonic frequencies are 7.55 Hz ($\sim 2 \times \nu_{\rm fund}$), 11.45 Hz ($\sim 3 \times \nu_{\rm fund}$) and 14.6 Hz ($\sim 4 \times \nu_{\rm fund}$). This suggests that the dynamics of the inner part of the disk (*i.e.* CENBOL) and emitted fluxes are tightly coupled. The obtained power density spectra (PDS) of emitted radiation has significant similarity with number of observational results (Casella et al. 2004; Nandi et al. 2012, 2013; Radhika & Nandi 2013) and accordingly, this establishes the fact that the origin of such photon flux variation seems to be due to the hydrodynamic modulation of the inner part of the disk in terms of shock oscillation.

In similar context, we study the quasi periodic variation of shock location around the super massive black hole of mass 10^6 $M_\odot$. Here, the input parameters are chosen as $x_{\rm inj} = 50.8$ r_g, $\upsilon_{\rm inj} = 0.0653$, $a_{\rm inj} = 0.0622$, $\lambda_{\rm inj} = 1.67$, and $\gamma = 4/3$, respectively. We observe that shock starts to oscillates for $\alpha = 0.00525$. We calculate the Fourier spectra of the shock location variation and find that most of the power is concentrated at a narrow range of frequency $\nu = 3.35 \times 10^{-5} Hz$ which is shown in Fig. 4. Following the example of stellar mass black hole, we conclude that the radiant bremsstrahlung fluxes from the CENBOL matter are also exhibit quasi periodic oscillation with similar frequency which is consistent with the recent observational findings (Casella et al. 2004; Nandi et al. 2012, 2013; Radhika & Nandi 2013; Iyer & Nandi 2013).

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