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Accretion disc spectrum in presence of mass outflow around black holes

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Abstract. We study the effect of mass outflow on the accretion disc spectrum in presence of heating and cooling processes. Radiation spectrum shows a softening of spectral index in presence of mass outflow. This can explain the state transition of outbursting as well as persistent galactic black hole candidates, in particular when the sources are in hard or intermediate states.

Keywords : black hole physics – accretion, accretion discs – radiation mechanisms: general – outflows

1. Introduction

It is generally accepted that accretion process is the source of energy for galactic compact X-ray sources, AGNs, Blazars, Quasars etc. The first accretion model around a normal star (with Newtonian potential) was proposed by Bondi (1952) and later it was used to explain the emitted luminosity from AGNs. But this spherically symmetric flow model was not quite successful because the flow is radiatively inefficient. In early 70's, Shakura & Sunyaev (1973) proposed a disc model where they kept the matter in Keplerian angular momentum distribution around black hole. This model could successfully explain the so called UV bump of AGN systems. But it was clear that only a Keplerian disc was not sufficient to explain the high energy emission from the sources like Cyg X-1 (Eardley et al. 1975) and one probably needs hotter branch of solution. In subsequent years, many different accretion disc models were proposed in the literature with variety of hotter components, such as Compton cloud, magnetic corona (Galeev et al. 1979) etc. but without indicating a consistent origin of such a component. The essential focus was looking for a model which is a mixture of Keplerian (Shakura & Sunyaev 1973; Novikov & Thorne 1973) and sub-Keplerian (Chakrabarti 1996; Chakrabarti & Das 2004) component. The inner boundary condition of accretion onto black holes forces the flow to be transonic in nature and the sub-Keplerian flow is transonic with significant advective motion. The advection

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dominated accretion flow (Narayan et al. 1997) or ADAF was one of the popular model which is characterized by a single sonic point. During the same time, it was shown by various authors (Chakrabarti 1996; Lu et al. 1999; Chakrabarti & Das 2004) that multiple sonic points may exist in a dissipative accretion discs. Therefore, ADAF is only a subset of general advective solution (Lu et al. 1999; Das et al. 2009; Kumar & Chattopadhyay 2013).

Jets and outflows are generated from the accretion disc and these activities are very common in galactic black hole candidates as well as AGNs systems. But the entire accretion disc does not participate in the formation of outflows, rather only the central region of the accretion disc where centrifugal force is significantly dominant, lifts the outflows due to strong thermal and radiation pressure. Hence the base of the jet is confined in a small compact region close to the central object which is supported by observation (Junor et al. 1999) as well. The high energy radiation, mainly in X-ray and gamma ray, which is coming from the inner most part of the accretion disc is expected to be correlated with the jet activity. In particular, for galactic black hole candidates the relation between outflows and spectral states are observationally well established (Gallo et al. 2003; Fender et al. 2010; Rushton et al. 2010) whereas no such conclusion can be made for AGNs. Generally, we see outflows in hard and intermediate states (Gallo et al. 2003; Fender et al. 2010; Rushton et al. 2010) with strongest outflows in steep power-law state and no outflows in the canonical soft state.

In an earlier work Chakrabarti & Titarchuk (1995) assumed a two-component axis-symmetric accretion disc where the optically thick Keplerian disc is situated at the equatorial plane and an optically thin sub-Keplerian disc flanks the Keplerian disc both above and below the equatorial plane. The Keplerian disc produces multicolour black body photons typically in soft X-rays and most of which escape the disc without being scattered. The central region of the accretion disc, being hot and dense due to geometric compression, Comptonize a small fraction of these soft photons from the Keplerian disc. The Comptonization effect is even more dramatic if the flow encounter the presence of shocks due the centrifugal barrier produced by the angular momentum in the sub-Keplerian flow, as the post-shock region is very hot because of conversion of flow kinetic energy into thermal energy. In subsequent years, Mandal & Chakrabarti (2005); Chakrabarti & Mandal (2006) updated the two-component model by including synchrotron and the self-Comptonization of all the locally produced photons in a sub-Keplerian disc. All these earlier radiative models adopted flow velocity and density due to a free fall motion and also did not take the effect of outflows into account. In this paper, we calculate the radiation spectrum using a transonic hydrodynamic solution in presence of outflow.

In the next section, we describe the model properties and solution methods. In Section 3, we present the results of this study and finally, in Section 4 we present the concluding remarks.

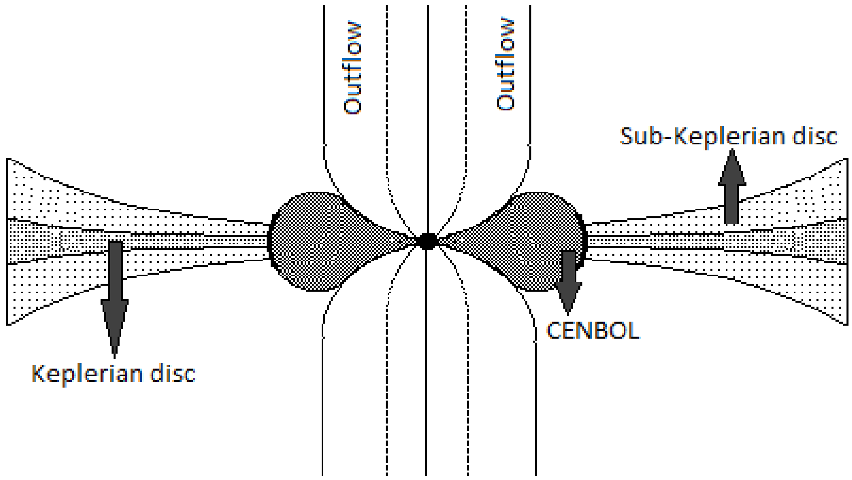

Figure 1. A schematic diagram of two-component accretion disc-jet system.

2. The Model and methods

We assume a two-component axis-symmetric accretion disc model. A cartoon diagram of the model with different components is shown in Fig. 1. The governing hydrodynamic equations including heating and cooling for calculating the radiation spectrum are given in Mandal & Chakrabarti (2005); Chakrabarti & Mandal (2006). Since in this work our main purpose is to investigate the effect of outflow in accretion disc spectrum, we have to solve the hydrodynamic equations due to a coupled disc-jet system. A general solution of hydrodynamic equations for coupled disc-jet system including all physical heating and cooling processes is extremely difficult. Hence to keep life simple, we have adopted the following steps to calculate the radiation spectrum.

(1) We have ignored all other heating and cooling processes except viscous heating and solved a coupled disc-jet system simultaneously (Kumar & Chattopadhyay 2013) to calculate a viscous transonic solution in presence of outflow for a given value of specific energy (ϵ), specific angular momentum (λ) and viscosity parameter (α) of the flow. The outer boundary of the flow is set at $x_{inj} = 10^4$.

(2) We calculate the radiation spectrum following Mandal & Chakrabarti (2005); Chakrabarti & Mandal (2006) and using the transonic solution from step (1) for a given value of Keplerian accretion rate ($\dot{m}_d$) and sub-Keplerian accretion rate ($\dot{m}_h$).

The flow is assumed to be in vertical equilibrium along z direction. The accretion rates are measured in units of Eddington rate, the radial distance is measured in units of Schwarzschild radius ($r_s = 2GM/c^2$), where M is mass of the black hole in units of solar mass ($M_\odot$), G is gravitational constant and c is speed of light.

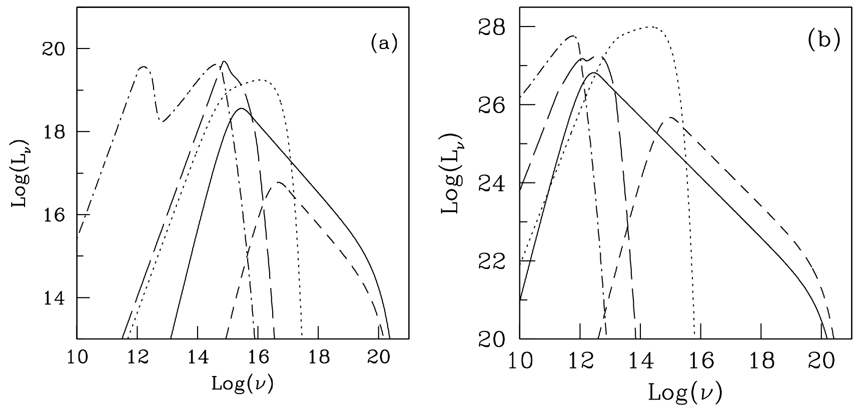

Figure 2. A general representation of radiation spectra of accretion disc around a black hole with luminosity per frequency along y-axis and frequency of radiation along x-axis. The different components of the spectra and parameters are explained in the text. (a) Spectra for a $10M_\odot$ mass black hole whereas (b) is the same for a $10^8M_\odot$ mass black hole.

3. Results

A general behaviour of the accretion disc radiation spectra with all different radiation components in absence of mass outflow are shown in Fig. 2, where the mass of the central objects are (a) $10M_\odot$ and (b) $10^8M_\odot$. The other parameters are $\epsilon = 10^{-3}$, $\alpha = 0.049887$, $\lambda = 70.7$ which is equal to the local Keplerian value at outer boundary and this produces a shock at $x_s = 30.8$. The accretion rates are $\dot{m}_d = 0.1$ and $\dot{m}_h = 0.1$. The dash-dotted line represents the preshock synchrotron contribution and the long-dashed line represents the same from post-shock disc. The multicolour black body from the Keplerian disc is drawn by dotted line whereas the short-dashed line is the Comptonization of the black body photons. Finally, the solid line indicates the self-Comptonization of post-shock synchrotron radiation. We see that with the increase of mass of the central object the luminosity increases as well as the radiation spectrum shifts to the lower frequency side. The most important difference is that for a stellar mass black hole the dominant contribution in high energy comes from synchrotron self-Comptonization (solid line in Fig. 2a) whereas for supper-massive black hole that is due to Comptonization of black body photons (short-dashed line in Fig. 2b). This is due to fact that density decreases with the increase of mass and hence less contribution from synchrotron and it's self-Comptonization process.

If we include mass outflow and solve the disc-jet coupled equations for the same set of parameters mentioned for Fig. 2, the shock location moves from $x_s = 30.8$ to $x_s = 18.03$ with 15% mass outflow from the disc. In Fig. 3 we have compared the spectrum without (solid line) and with (dotted line) mass outflow for (a) 10 $M_\odot$ and (b) $10^8M_\odot$ mass black holes. Spectrum shows a clear indication of spectral softening in presence of mass loss as the shock moves inward and also post-shock density decreases. So, mass outflow also can trigger the state transition of black hole candi-

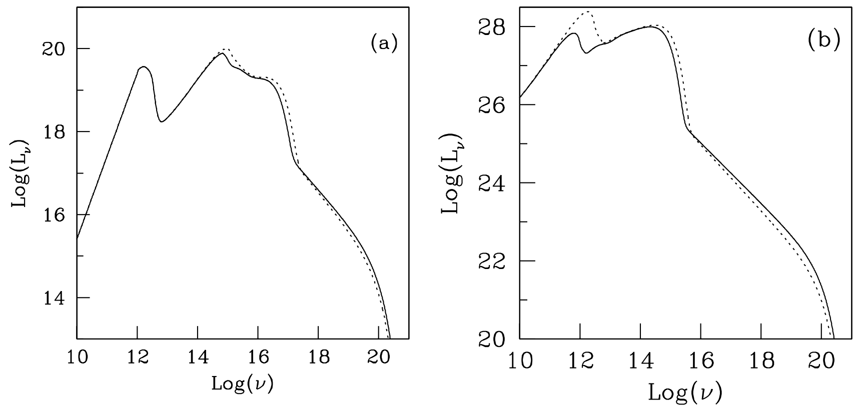

Figure 3. Comparison of accretion disc spectrum without mass loss (solid) and with mass loss (dotted) for (a) $10M_{\odot}$ mass black hole and (b) $10^8 M_{\odot}$ mass black hole.

dates. In Fig. 4a, we have shown the effect of viscosity on spectral index in presence of outflow. This figure has been drawn for a $10M_{\odot}$ mass black hole with $\dot{m}_d = 0.015$ and $\dot{m}_h = 0.02$, keeping all other parameters same as other figures. For a fixed outer boundary and all other parameters, if we increase viscosity shock moves inward which increases the supply of Keplerian soft photons and post-shock synchrotron cooling and hence spectrum becomes softer. The solid line in Fig. 4a shows this effect whereas the dotted line represents that for same viscosity parameter the presence of outflow makes the spectrum even more softer. Fig. 4b represents the variation of spectral index with accretion rate for a fixed viscosity parameter $\alpha = 0.049887$. The spectral index decreases (i.e., spectrum is getting hard) with the increase of sub-Keplerian rate (solid line in Fig. 4b) keeping a fixed Keplerian rate ($\dot{m}_d = 0.1$). Whereas spectrum softens with the increase of Keplerian rate (dotted line in Fig. 4b) for a fixed sub-Keplerian rate ($\dot{m}_h = 0.05$). We have selected the accretion rate such that the range of spectral index corresponds to hard and intermediate state where we do see frequent outflow activities for galactic black hole candidates.

4. Conclusions

We have calculated the radiation spectrum from an accretion disc in presence of outflow and heating-cooling processes. We see that shock moves inward with the increase of viscosity and softening of spectral index. The radiation spectrum shows even more spectral softening in presence of outflow. This may explain spectral evolution of the outbursting sources in hard and intermediate states where very frequent outflow activities as well as quasi-periodic oscillations (QPOs) are observed. Outflow activities and QPOs are correlated with spectral evolution of galactic black hole candidates. As the source moves from hard to intermediate state both outflow activity and QPO frequency increases but in canonical soft state the central region is cooled down by the Keplerian soft photon suppressing the outflow activities.

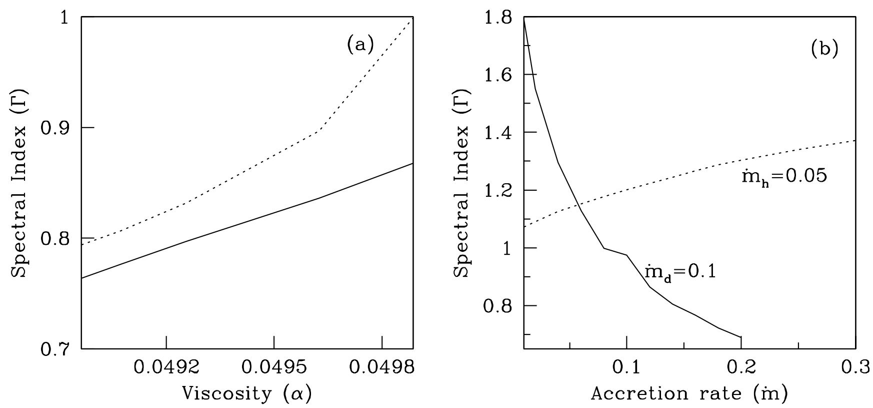

Figure 4. Variation of spectral index with (a) viscosity for a $10M_{\odot}$ mass black hole in presence (dotted) and absence of outflow (solid). The spectral index variation with accretion rate is shown in (b).

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