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Spectral properties of two component advective flows around black holes with standing shock in presence of Comptonization

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Abstract. We study a self-consistent solution for the spectral properties of a general class of steady state accretion disks in presence of Comptonization. We couple both the hydrodynamics and the radiative transfer process analytically to calculate the emitted spectrum. In our work, we consider a two-component accretion flow, where one component (Keplerian) supplies soft photons, which are reprocessed by the electrons in the halo (sub-Keplerian). We show how the boundary changes as the shock moves inward in presence of Compton cooling. Due to the radiative loss, some energy is removed from the accreting matter and the shock moves towards the black hole to maintain the pressure balance condition. We solve the two-temperature equations with Coulomb energy exchange between the protons and the electrons, and the radiative processes such as the bremsstrahlung and Comptonization. We modify Rankine-Hugoniot relation to obtain the shock-locations when the post-shock region suffers energy loss due to Comptonization. We compute the radiated spectrum from the disk and study the variation of the hydrodynamical and spectral properties as functions of the accretion rates of the Keplerian and sub-Keplerian components. Ours is the most self consistent transonic solution of an inviscid flow around a black hole till now.

Keywords : black holes – accretion, accretion discs – shock waves – hydrodynamics

1. Introduction

Matter accreting in to the black hole is necessarily transonic (e.g. Paczyński & Witta 1980; Chakrabarti, 1990a). In the 1970s, standard disk models were proposed (Shakura & Sunyaev 1973; hereafter SS73, Novikov & Thorne 1973) which produce soft photons and a hot corona (Sunyaev & Titarchuk, 1980; 1985; Zdziarski et al.,

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2003) where soft-photons gain energy due to Comptonization. But, these were not sufficient to explain the black hole accretion completely. Theoretical transonic solution shows that the so-called hot corona is nothing but the low angular momentum flow (Chakrabarti & Titarchuk, 1995; hereafter CT95), which makes the flow essentially two component: one is Keplerian (high viscosity) and other is sub-Keplerian (low viscosity). The latter component is known as CENtrifugal pressure supported BOundary Layer (CENBOL), which is responsible to produce mass outflows/jets (Chakrabarti, 1999), and observed hard radiations. Recently, Giri & Chakrabarti, 2013 has shown the formation of TCAF solution numerically. The full transonic solution of TCAF model is also shown by Mondal & Chakrabarti, 2013. In CT95, it was shown that increase in disk accretion rate increases the soft photon flux, which softens the spectrum where shock location was treated as a parameter. Here, we show the same solution where shock and the height of the shock come from the *ab initio* calculation. We do not include the so-called bulk motion Comptonization in deriving the spectrum as the effect of spectral saturation (CT95, Titarchuk & Seifina; 2009) will remain unchanged. The main radiative processes are considered here as bremsstrahlung and Comptonization. In the next Section, we discuss the geometry of our model and solution procedure. In §3, we present the results and discussions.

2. Geometry of the model and solution procedure

In this work, we have considered the model of CT95, where the Keplerian disk is inside the sub-Keplerian halo. We consider the flow as axisymmetric at the equatorial plane and post shock region is quasi-spherical. We consider the vertical equilibrium model to calculate the height of the shock and also the temperature of the shock location. In this model, the Keplerian disk supplies soft photons to the post shock region. The cartoon diagram of the model is in Mondal & Chakrabarti 2013 (hereafter MC13). The flux from the Keplerian disk is basically SS73 flux, which is given by,

$$F_{ss} = 9.5 \times 10^{25} r^{-3} \Im (\frac{M_{bh}}{M_\odot})^{-2} \frac{\dot{M}}{1.4 \times 10^{17}} \;\; ergs\ cm^{-2} s^{-1}, \tag{1}$$

where, M_{bh} is the mass of the black hole, the mass accretion rate is $\dot{M}$ and $M_\odot$ is the mass of the Sun. As the matter is converging towards the black hole, it becomes hot. On the other hand, due to inverse Comptonization, it cools down causing the electrons to heated up due to coulomb coupling which we have considered in our two temperature equation to calculate the temperature of the electrons and the protons. To calculate the spectral index of the emitted radiation we use Titarchuk & Lyubarskij (1995) prescription which is given by,

$$\alpha = \frac{\beta}{ln[1 + (\alpha + 3)\Theta/(1 + \Theta) + 4 d_0^{1/\alpha} \Theta^2]}, \tag{2}$$

where, α is energy spectral index, β is the optical depth of the CENBOL and

$$d_0(\alpha) = \frac{3[(\alpha + 3)\alpha + 4]\Gamma(2\alpha + 2)}{(\alpha + 2)(\alpha + 3)^2}, \tag{3}$$

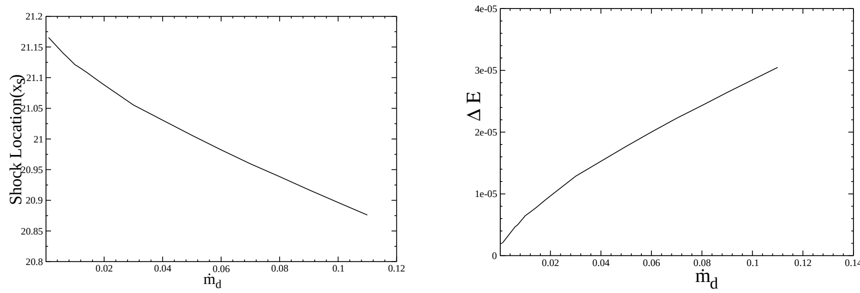

Figure 1. *Left panel*: Variation of shock location with disk accretion rate, which decreases with increasing disk rate for the fixed halo rate 0.5. *Right panel*: Variation of the cooling energy with accretion rate, which also implies that the increase in disk rate increases the amount of cooling of the post-shock region.

and $\Theta = kT_e/m_e c^2$ which represents the average dimensionless temperature of the electron in the post shock region. We have also considered the modified Rankine-Hugoniot shock Condition for our solution (Das et al. 2010; hereafter DCM10; SM13).

3. Results and discussions

Fig. 1 shows the solution of accretion flow around black hole when Compton cooling is present. Our solution implicates that the shock moves towards the black hole as the cooling rises due to cooling effects in the post-shock region (see also, Das & Chakrabarti 2004; DCM10; SM13). First we consider the non-dissipative flow where the specific energy is 0.0021 and the specific angular momentum is 1.74. After that we include Comptonization keeping halo rate fixed and see that as we increase the disk accretion rate, the amount of cooling increase as well as shock moves towards the black hole. Our solution gives the location of the shock when the disk rate $\dot{m}_d$ = 0.015 and 0.1 and halo rate is fixed at 1.0. With this, shock (x_s), (x_{s3} in C89), initially was at $x_s = 21.188$ (for non-dissipative flow), and moved to $x_s = 20.62$, and 19.32 respectively when cooling is increased. As the CENBOL cools down, the emitted spectrum becomes softened, which we have shown in the Fig. 2 where, A, B and C are the corresponding emitted spectra for the disk rates $\dot{m}_d = 0.001$, 0.04 and 0.15 respectively. We observe that as we increase the accretion rate spectrum become softer and the area of the parametric space shrinks down (see also, DCM10; SM13). The inverse Compton process mainly removes the thermal energy of the inflow and supplies the matter for jet and outflow (Chakrabarti 1999) from the CENBOL. In all the calculations we consider the mass of the black hole as $5M_\odot$.

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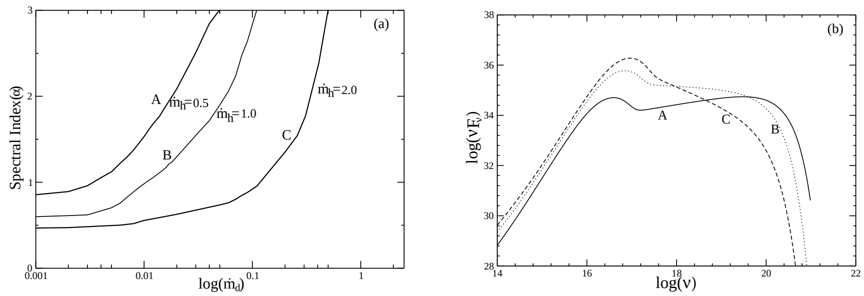

Figure 2. The variation of (a) energy spectral index (α) with disk accretion rate ($\dot{m}_d$) for the halo rates 0.5, 1.0 and 2.0 respectively and (b) corresponding softening of the spectrum.

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