J. Astrophys. Astr. (2002) **23,** 143–147

Standing Shocks around Black Holes and Estimation of Outflow Rates

Santabrata Das & Sandip K. Chakrabarti *S N Bose National Center for Basic Sciences, Block - JD; Sector - III, Salt Lake, Kolkata - 98, West Bengal, India.*
e-mail: sbdas@bose.res.in chakraba@bose.res.in

Abstract. We self-consistently obtain shock locations in an accretion flow by using an analytical method. One can obtain the spectral properties, quasi-periodic oscillation frequencies and the outflow rates when the inflow parameters are known. Since temperature of the CENBOL decides the spectral states of the black hole, and also the outflow rate, the outflow rate is directly related to the spectral states.

Key words. Accretion—accretion disk—black hole physics—shock waves—outflows.

1. Introduction

In the two component advective flow (TCAF) model the sub-Keplerian flow flanks the Keplerian flow above and below the equatorial plane and these two components merge to make a single component sub-Keplerian flow close to the black hole (Chakrabarti & Titarchuk 1995). The two components mix close to a black hole, and may form shocks. In the post-shock region, the specific energy ($\mathcal{E}$) and the specific angular momentum (λ) of the sub-Keplerian flow are estimated by dynamically mixing these two components. We analytically calculate the shock locations for a set of initial parameters following the procedure used by Das, Chattopadhyay & Chakrabarti (2001a) (hereafter, DCC01a and references therein). Around the shock, incoming sub-Keplerian matter slows down due to the centrifugal barrier and becomes hotter. This CEntrifugal pressure supported BOundary Layer (CENBOL) region is responsible for the generation of the outflowing winds and jets, the rate of which is estimated knowing the properties of the CENBOL. CENBOL is also found to be responsible to explain the spectral state transitions and the Quasi-Periodic Oscillations (Chakrabarti 1996).

2. Basic model

We consider a thin, axisymmetric steady flow on the equatorial plane of a Schwarzschild black hole described by the Paczyń'ski-Wiita pseudo-Newtonian potential (Paczyński & Wiita 1980). In the accretion process, we assume, the viscous stress is negligible. The governing equations in the accretion flow are in Chakrabarti (1989). We assume the radial distances, velocities and times are measured in units of Schwarzschild radius $r_g = 2GM/c^2$, velocity of light c and r_g/c respectively. G and M are the gravitational constant and mass of the black hole respectively.

A sub-Keplerian flow with a positive energy passes through the X-type outer sonic point, becomes super-sonic and forms a shock depending on whether the Rankine-Hugoniot shock conditions are satisfied or not. The analytical calculation for the shock locations has been already done (DCC01a) and we use these results to compute the mass outflow rate due to hydrodynamic processes alone.

For some inflow parameters, when the shock conditions are not satisfied but entropy at the inner sonic point is higher than that at the outer sonic point, the shock starts oscillating with a time period $T_s(\sim x_s/\vartheta_s)$, where x_s and ϑ_s are the shock location and velocity of matter at the post-shock region (DCC01a). The observed quasi-periodic oscillation frequencies are comparable to $1/T_s$.

In the pre-shock region, matter is cooler. The free-fall (energy $\mathcal{E} \sim 0$) velocity is $\vartheta(x) = \left[\{x^2 - \lambda^2(x-1)\}/\{x^2(x-1)\}\right]^{1/2}$, where, x is the radial distance and λ is the specific angular momentum of the flow. At the shock, the compression ratio is described as, $R = \frac{\Sigma_+}{\Sigma_-}$. Here, Σ is the vertically integrated density of the matter and the subscripts "-" and "+" refer to the quantities before and after the shock.

We assume that the thermal pressure is negligible in comparison to the ram pressure in the cool pre-shock region. In the post-shock region, the temperature is roughly constant and we consider the region as isothermal in nature. The isothermal sound speed in this region is given by, $C_s^2 = W_+/\Sigma_+ = (R-1)\vartheta_-^2/R^2$, where, W is the vertically integrated thermal pressure and the second equality is obtained from the pressure balance condition for the shock (Das *et al.* 2001b, hereafter DNCC01b).

In general, the outflow is originated from the inner part of the accretion disk and the CENBOL is likely to deposit radiation momentum into it (see, Chattopadhyay & Chakrabarti, this volume). A useful assumption is that the outflow is isothermal at least up to the sonic point. There may be some angular momentum transport in the outflow due to radiative viscosity but presently we are not considering it. This is to make the problem simple and we believe that these effects will not change the result dramatically.

We consider the outflow geometry to be conical in nature. Various conservation equations are discussed in DCC01a. The mass outflow rate ($R_{\dot{m}}$) is defined as the ratio of the outgoing matter in the vertical direction to incoming matter coming through the disk. The analytical expression for that is given by (DNCC01b),

$$R_{\dot{m}} = \frac{\Theta_{\rm out}}{\Theta_{\rm in}} \left[\frac{x_s^2(x_s-1}{x_s^2 - \lambda^2(x_s-1)}\right]^{-1/2} \frac{RC_s x_c^2}{x_s(x_s-1)} \exp(-f), \tag{1}$$

where, $f = \frac{1}{2} - \frac{1}{2C_s^2}\frac{x_s - x_c}{(x_s-1)(x_c-1)}$.

Here, $\Theta_{\rm out}$ and $\Theta_{\rm in}$ are the solid angles subtended by the outflow and the inflow at the origin. Subscripts "s" denote the quantities at the shock and subscripts "c" denote the same at the sonic point in the outflow. The result is similar to that obtained in Chakrabarti (1999) where the angular motion of the inflow was ignored. The general behavior of the mass outflow rate remains unaltered when we consider an adiabatic outflow (DCC01a). In all these cases, $R_{\dot{m}}$ is only a function of R and λ. Since these are computed from the inflow parameters, the mass outflow rate becomes a function of the inflow parameter for a given flow geometry.

In Fig. 1, we show the general behavior of the analytical solution of the mass outflow rate as a function of the compression ratio when only the sub-Keplerian component

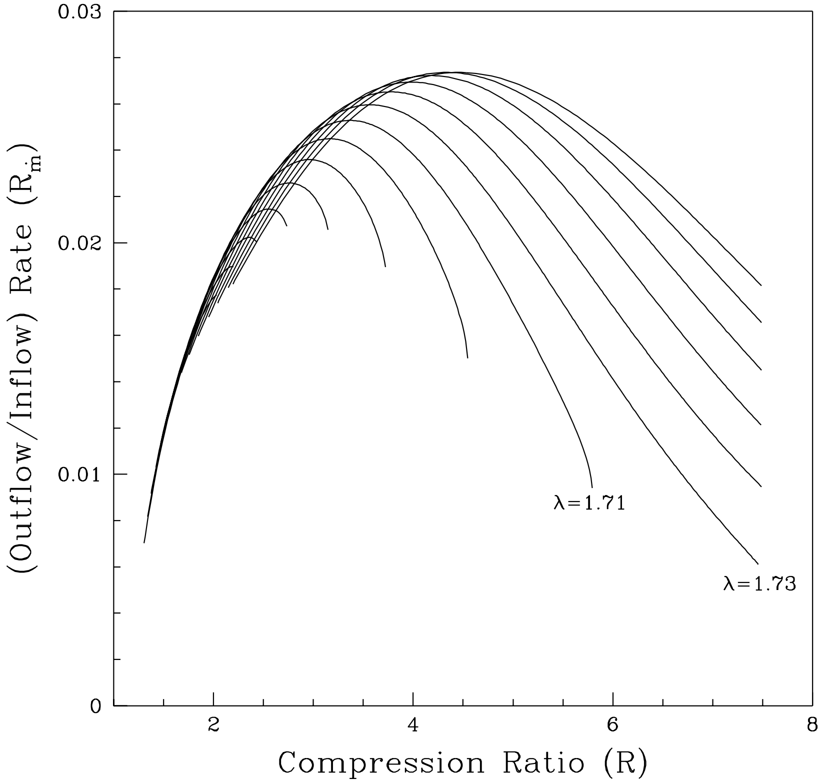

Figure 1. Variation of the ratio of the outflow to inflow rates $R_{\dot{m}}$ with the compression ratio R for various angular momentum (λ). λ varies from 1.57 (right) to 1.79 (left). Curves are drawn at intervals of $d\lambda = 0.02$(DNCC01b).

is considered. Outflow rate is negligible when the shock is weak ($R \sim 1$) and first increases and then decreases gradually as $R \to 7$ which corresponds to a very strong shock. In the intermediate shock strength, $R_{\dot{m}}$ is maximum. These features can be explained in the following way. A strong shock forms far away from black hole and though the CENBOL area is large, the temperature of that region is low which results in a small outflow rate. A weak shock forms close to the black hole and matter velocity is very high but the CENBOL area is very small. So the product is again low. There is a peak at about $R \sim 4$ and $R_{\dot{m}}$ is about 2.8% (assuming a half angle of 10^0 for both the disk and the jet). The peak of each curve increases monotonically for increasing λ due the increase of density of the CENBOL. Thus the outflow is thermally as well as centrifugally driven.

There are ample evidences that the spectral properties of black holes can be easily explained when the disk matter consists of both the sub-Keplerian and the Keplerian matter (Smith *et al.* 2001 and Smith, Heindl & Swank 2002). In Fig. 2, we present the mass outflow rate when a two component flow is considered. We plot the Keplerian and the sub-Keplerian disk rates in units of the Eddington accretion rate in the right and upper panel respectively. It is clear that the outflow rate steadily increases upward as Keplerian rate decreases and spectrum goes to harder state. For weak shocks, when the Keplerian rate is high, the post-shock region cools down and outflow rate is negligible.

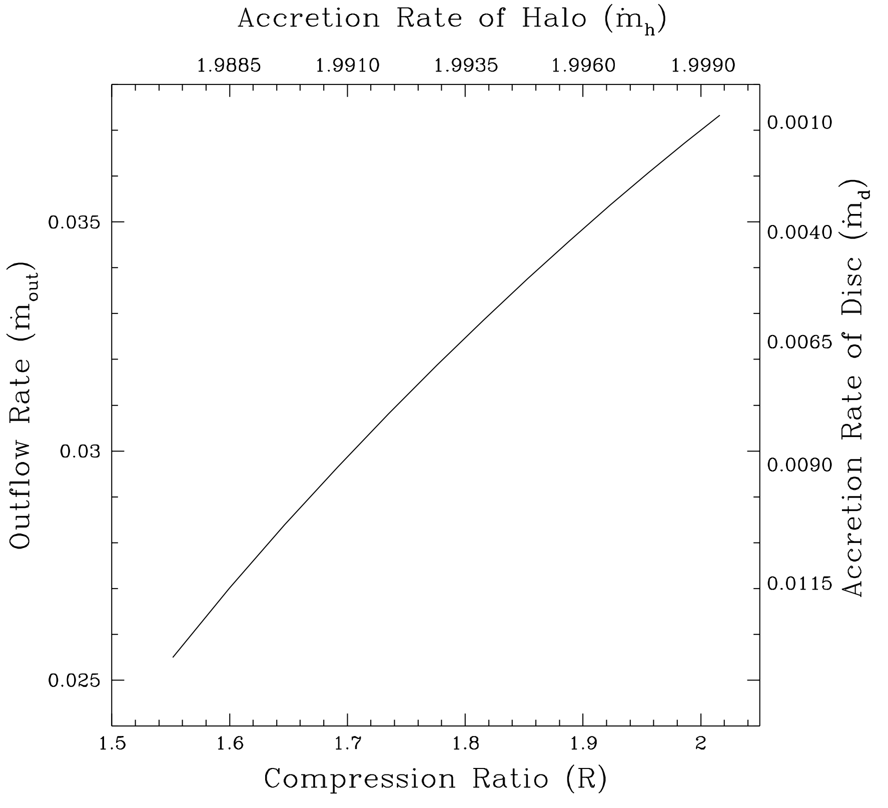

Figure 2. Variation of outflow rates (left axis) with compression ratio. Keplerian and sub-Keplerian accretion rates are plotted in the right and upper panel (DNCC01b).

This indicates that the softer states produce low outflow rates. There is increasing evidence that this is precisely what is happening in galactic microquasars (Klein-Wolt *et al.* 2001; Corbel *et al.* 2001). It is likely that in AGNs also such a behaviour would be observed.

Acknowledgement

This work is partly supported by a project (Grant No. SP/S2/K-14/98) funded by the Dept. of Science and Technology, Govt. of India.

References

Chakrabarti, S. K. 1989, *Ap. J.*, **347,** 365.
Chakrabarti, S. K., Titarchuk, L. G. 1995, *Ap. J.* **455,** 623.
Chakrabarti, S. K. 1996, *Ap. J.*, **464,** 664.
Chakrabarti, S. K. 1999, *A&A*, **351,** 185.
Corbel *et al.* 2001, *Ap. J.*, **554,** 43.
Das, S., Chattopadhayay, I., Chakrabarti, S. K. 2001a, *Ap. J.* **557,** 983 (DCC01a)
Das, S., Nandi, A., Chattopadhayay, I., Chakrabarti, S. K. 2001b, *A& A*, **379,** 683 (DNCC01b)

Klein-Wolt, M. *et al.* 2001, *ApSSS*, **276,** 291.
Paczyński B., Wiita P. J., 1980, *A&A*, **88,** 23.
Smith, D. M., Heindl, W. A., Swank, J. H. 2002, *Ap. J.*, **569,** 362.
Smith, D. M., Heindl, W. A., Markwardt, W. A., Swank, J. H. 2001, *Ap. J.*, **554L,** 41.