Chapter 4

EFFECTS OF COMPTON COOLING ON OUTFLOWS

The winds and jets in a compact binary system containing black holes are generally believed to be originated from the disk itself (C96; C99; Das et al. 2001; Das & Chattopadhyay 2008). There are several hydrodynamical models of the formation of outflows from the disks ranging from the twin-exhaust model of Blandford & Rees (1974), to the self-similar models of Blandford & Payne (1982) and Blandford & Begelman (1999). Assuming that the outflows are transonic in nature, Fukue (1983) and Chakrabarti (1986) computed the velocity distribution without and with rotational motion in the flow and showed that the flow could become supersonic close to the black hole. Camenzind and his group extensively worked on the magnetized jets and showed that the acceleration and collimation of the jets could be achieved (e.g., Appl & Camenzind 1993). In a subsequent two component transonic flow model, CT95 pointed out that the jets could be formed only from the inner part of the disk i.e., the CENBOL.

While the general picture of the outflow formation is thus understood and even corroborated by the radio observation of the base of the powerful jet, such as in M87 (Junor, Biretta & Livio 1999), that the base of the jet is only a few tens of $r_g$, a major question still remained: what fraction of the matter is driven out from the disk and what are the flow parameters on which this fraction depends? In a numerical simulation using SPH code, MLC94 showed that the outflow rates from an inviscid accretion flow strongly depends on the outward centrifugal force and 15-20 percent matter can be driven out of the disk. Chakrabarti (1998c), C99, Das et al. (2001), Chattopadhyay, Das & Chakrabarti (2004) estimated the ratio of the outflow rate to the inflow rate analytically and found that the shock strength determines the ratio. For very strong and very weak shocks, the outflow rates are very small, while for
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the shocks of intermediate strength, the outflow rate is significant. This is in line with the observations (Gallo, Fender & Pooley 2004; Fender, Belloni, Gallo 2004; Fender, Gallo & Russell 2010) that the spectrally soft states have less outflows.

In this Chapter, we concentrate on the formation of outflows from the accretion disk around black holes by numerical simulation and study the effects of Compton cooling on it using the time dependent radiation hydrodynamic simulation code (GGC12). While computing the time variation of the velocity components, density and temperature, we also compute the temporal dependence of the spectral properties. As a result, not only we compute the outflow properties, we correlate them with the spectral properties (GGC12). Not surprisingly, we find that whenever the Compton cloud or the CENBOL is cooled down and the spectrum becomes softer, the outflow, originating from CENBOL, loses its drive and its rate is greatly reduced. In the following, we discuss the simulation procedure and the results of our study. Same conclusions are found in GGC12 where simulations are done using different sets of input parameters on similar simulation set up.

4.1 Simulation set up

In Fig. 4.1, we present the schematic diagram of our simulation set up for the Compton cloud with a specific angular momentum $\lambda = 1.75$ (see also, GGC12). The sub-Keplerian matter enters the simulation box through the outer boundary at $R_{in} = 100r_g$ ($r_g = 2GM_\bullet/c^2$). The Keplerian disk resides at the equatorial plane of the cloud. The outer edge of this disk is assumed to be at $R_{out} = 200r_g$ and it extends inside up to the marginally stable orbit $R_{ms} = 3r_g$. At the centre, a non-rotating black hole of mass $M_\bullet = 10M_\odot$ is located. The soft photons emerging out of the Keplerian disk are intercepted and reprocessed via Compton or inverse-Compton scattering by the sub-Keplerian matter. An injected photon may undergo no scattering at all or a single or multiple scatterings with the hot electrons in between its emergence from the Keplerian disk and its escape from the sub-Keplerian halo. The photons which enter the black hole are absorbed.

4.1.1 Density, velocity and temperature profiles inside the halo component

The inflowing halo matter has some angular momentum with respect to the black hole. Therefore, as it approaches the black hole, the outward centrifugal force be-
Figure 4.1: Schematic diagram of the geometry of our Monte Carlo simulations. The colors represent the normalized density in logarithmic scale. The zig-zag trajectories are the typical paths followed by the photons. The velocity vectors of the infalling matter inside the cloud are shown. The velocity vectors are plotted for $\lambda = 1.75$ (see also, GGC12).
comes comparable to the gravitational force at a certain radius. As a result, the matter slows down and we find the formation of shocks in the incoming supersonic flow (Chakrabarti 1989a,b; C90). Subsequently, the matter accelerates and becomes supersonic again as it approaches the black hole. In the post-shock region, the density and the temperature of the halo increases to much higher value. This region is the CENBOL of the TCAF model (CT95).

Assuming axisymmetry, we calculate the flow dynamics using the TVD code in a similar way as described in the previous Chapter. At each time step, we carry out Monte Carlo simulation to obtain the cooling/heating due to Comptonization. We incorporate the cooling/heating of each grid while executing the next time step of hydrodynamic simulation. For the present case, the numerical simulation for the two-dimensional flow has been carried out with $512 \times 512$ equi-spaced cells in a $100r_g \times 100r_g$ box (GGC12; GGC13). We choose the units in a way that the outer boundary $R_{in}$ is unity and the matter density at the outer boundary is also normalized to unity (MRC96; Giri et al. 2010; GGGC11). We assume the black hole to be non-rotating and we use the pseudo-Newtonian potential $-\frac{1}{2(\gamma-1)}$ (PW80) to calculate the flow geometry around a black hole.

### 4.2 Simulation procedure

All the simulations have been carried out using the time dependent radiation hydrodynamic simulation code described in the previous Chapter. Before starting the simulation, we generated a steady state flow profile using the non-radiative hydro code. This steady state is used as the initial condition for the radiation hydrodynamic simulation (GGGC11; GGC12). The Keplerian disk at the equatorial plane supplies soft photons. These photons interact with the high energy electrons of the halo and they exchange their energy through Compton or inverse-Compton scattering.

We use a standard Keplerian disk (SS73) as the source of soft photons. The emission is of blackbody type characterized by the local surface temperature. The radial variations of the surface temperature and the number of generated photons from the disk surface are given in Eq. (1-1) and (2-7), respectively. We also incorporate the directional effects as described in Chapter 3. In these simulations, we neglect the reflection and/or absorption of the soft photons by the Keplerian disk.

For a particular simulation, we use the Keplerian disk rate ($\dot{m}_d$) and the sub-Keplerian halo rate ($\dot{m}_h$) as parameters. The specific energy ($e$) and the specific
angular momentum \((\lambda)\) determine the hydrodynamics (shock location, number density and velocity variations, etc.) and the thermal properties of the sub-Keplerian matter (GGC12; GGC13). We assume the absorbing boundary condition at \(r = 1.5\) since any inward pointing photon at that radius would be sucked into the black hole.

### 4.3 Results and discussions

<table>
<thead>
<tr>
<th>Case</th>
<th>(\epsilon, \lambda)</th>
<th>(\dot{m}_h)</th>
<th>(\dot{m}_d)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
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<td>No Disk</td>
<td></td>
</tr>
<tr>
<td>Ib</td>
<td>0.0021, 1.80</td>
<td>1e-4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ic</td>
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<td>2e-4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Id</td>
<td>0.0021, 1.80</td>
<td>5e-4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IIa</td>
<td>0.0021, 1.75</td>
<td>0.1</td>
<td>No Disk</td>
<td></td>
</tr>
<tr>
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<td>1e-4</td>
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</tr>
<tr>
<td>IIc</td>
<td>0.0021, 1.75</td>
<td>2e-4</td>
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</tr>
<tr>
<td>IIId</td>
<td>0.0021, 1.75</td>
<td>5e-4</td>
<td></td>
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</tr>
</tbody>
</table>

In Table 4, we list various Cases with all the simulation parameters used in this Chapter. The specific energy \((\epsilon)\) and specific angular momentum \((\lambda)\) of the sub-Keplerian halo at the outer boundary are given in Column 2. These parameters are chosen from the region of the parameter space for which shock formation is possible in an accretion flow in vertical equilibrium (Chakrabarti & Das 2001). Columns 3 and 4 give the halo \((\dot{m}_h)\) and the disk \((\dot{m}_d)\) accretion rates. The corresponding cases are marked in Column 1. In Cases Ia and IIa, no Keplerian disk was placed in the equatorial plane of the halo. These are non-radiative hydrodynamical simulations and no Compton cooling is included. To show the effects of Compton cooling on the hydrodynamics of the flow, the Cases I(b-d) and II(b-d) are run till the same time as the Cases Ia and IIa (GGC12).

All of the simulations, presented in this Chapter, have been run for \(\sim 2\) sec. For these cases, the time averaged values of the infall time scale for the matter is found to be \(\sim 0.12\) s for \(\lambda = 1.80\) cases and \(\sim 0.1\) s for \(\lambda = 1.75\) cases. These numbers have been computed from the numerical simulation results. Therefore, it is seen that the simulations have been run for \(\sim 20\) dynamical times. It can be seen that accretion flow configuration reaches the equilibrium in about 0.1 s and the flow does not change if the accretion rate parameters are not changed with time. Thus, we believe that all the results are stable.
4.3.1 Properties of the shocks in presence of cooling

In Figs 4.2(a) and (b), we present the time variation of the shock location (in units of $r_g$) for various Cases (marked on each curve) given in Table 4. All the solutions exhibit oscillatory shocks. For no cooling, the higher angular momentum produces shocks at a higher radius, which is understandable, since the shock is primarily centrifugal force supported. However, as the cooling is increased the average shock location decreases since the cooling reduces the post-shock thermal pressure and the shock could not be sustained till higher thermal pressure is achieved at a smaller radius. The corresponding oscillations are also suppressed. The average shock location is found to be almost independent of the specific angular momentum at this stage (see also, GGC12).

In Fig. 4.3, we show the colour map of the temperature distribution at the end of our simulation. We zoomed the region $50r_g \times 50r_g$. The specific angular momentum is 1.80 in the left panel and 1.75 in the right panel. Cases are marked. We note the collapse of the post-shock region as $\dot{m}_d$ is increased gradually (see also, GGC12).

We take the post-shock region in each of these cases, and plot in Figs 4.4(a) and (b) the average temperatures of the post-shock region only for those cases where the cooling due to Comptonization is included. The average temperature was obtained
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Figure 4.3: Colour map of final temperature distributions in the region $(50r_g \times 50r_g)$ of the accretion disk for different disk rates are shown. The left panel is for $\lambda = 1.80$ and the right is for $\lambda = 1.75$. As $\dot{m}_d$ is increased, we find that, the high temperature region (dark red) shrinks (see also, GGC12).
by the optical depth weighted averaging procedure prescribed in CT95. The average temperature in the post-shock region is reduced rapidly as the supply of the soft photons is increased (see also, GGC12).

4.3.2 Effects of Comptonization on the outflow

We now concentrate on how the outflow rate is affected by the Comptonization. Outflows move to very large distances and thus must not be bound to the system, i.e., the specific energy should be positive. Matter should also be of higher entropy as it is likely to be relativistic. Because of this, we wish to concentrate on the behaviour of matter which have highest energy and entropy (GGC12). Though we injected matter at the outer edge with a constant specific energy, the energy of matter in the post-shock region is redistributed due to turbulence, Compton cooling and shock heating. Some entropy is generated as well. The high energy and high entropy matter escape in the form of a hollow cone around the axis. It is thus expected that if the post-shock region itself is collapsed due to Comptonization, the outflows will also be quenched (GGC12). We show this effect in our result below.

In Fig. 4.5, we present the specific energy distribution for both the specific angular momenta (left panel for $\lambda = 1.80$ and right panel for $\lambda = 1.75$) for all
Figure 4.5: Colour map of final specific energy distribution inside the accretion disk for different disk rates. The high energy matter (dark red) are ejected outward as a hollow jet. The matter with a high energy flow decreases with the increase in disk rate. Velocity vectors at the injection boundary on the right is of length 0.05 (see also, GGC12).
the cooling Cases (marked in each box) at the end of our simulation. The velocity vectors are also plotted. The scale on the right gives the specific energy. First we note that the jets are stronger for higher angular momentum. This is because the post-shock region (between the shock and the inner sonic point close to the horizon) is hotter. Second, lesser and lesser amount of matter has higher energy as the cooling is increased (see also, GGC12).

A similar observation could be made from Fig. 4.6, where the entropy distribution is plotted. The jet matter having upward pointing vectors have higher entropy. However, this region shrinks with the increase in Keplerian rate, as the cooling becomes significant the outward thermal drive is lost (GGC12). Here, the velocity vectors are of length 0.05 at the outer boundary on the right and others are scaled accordingly.

In order to quantify the decrease in the outflow rates with cooling, we define two types of outflow rates (GGC12). One is $M_{out}$ which is defined to be the rate at which the outward pointing flow leaves the computational grid. This will include both the high and low energy components of the flow.

In Figs 4.7(a) and (b), we show the results of time variation of the ratio $R_m (M_{out} / M_{in})$ for the four cases (marked in each box), $M_{in}$ being the constant injection rate on the right boundary. While the ratio is clearly a time varying quantity, we observe that with the increase in cooling, the ratio is dramatically reduced and indeed become almost saturated. Our rigorous findings once again verified what was long claimed to be the case, namely, the spectrally soft states (those having a relatively high Keplerian rate) have weaker jets because of the presence of weaker shocks (Chakrabarti 1998b; C99; Das et al. 2001).

Another measure of the outflow rate would be to concentrate only on the matter which has high positive energy and high entropy (GGC12). For concreteness, we concentrate only on the matter outflowing within $R = 20r_g$ at the upper boundary of our computational grid. We define this to be $J_m = (M_{out} / M_{in})$.

Figures 4.8(a) and (b) show time variation of $J_m$. The different cases are marked on the curves. This outflow rate fluctuates with time. We easily find that the cooling process reduces this high energy component of matter drastically. Thus both the slow moving outflows and fast moving jets are affected by the Comptonization process at the base (see also, GGC12).
Figure 4.6: Color map of the final entropy ($K = \frac{E}{\rho}$) distribution. Other parameters are as in Fig. 4.5. The high entropy flow decreases as the disk rate increases (see also, GGC12).
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Figure 4.7: Variations of $R_{\text{m}} (= \frac{\dot{M}_{\text{out}}}{\dot{M}_{\text{in}}})$ with time for different $n_{\text{id}}$ are shown here. (a) $\lambda = 1.80$ and (b) $\lambda = 1.75$. The Cases are marked in each panel. The outflow rate is the lowest for the highest Keplerian disk accretion rate (Cases are Id and Id) (see also, GGC12).

Figure 4.8: Variations of $J_{\text{m}} (= \frac{\dot{M}_{\text{out}}}{\dot{M}_{\text{in}}})$ with time for different $n_{\text{id}}$ are shown here (see also, GGC12). Here, $\dot{M}_{\text{jet}}$ and $\dot{M}_{\text{in}}$ are the high entropy (also, high energy) outflow and inflow rates, respectively. The left panel is for $\lambda = 1.80$ and the right panel is for $\lambda = 1.75$. The Cases are marked in each curve.
4.3.3 Spectral properties of the disk-jet system

In each simulation, we also store the photons emerging out of the Computational box after exchanging energy and momentum with the free electrons in the disk matter (Ghosh et al. 2039; GGCL10). When the Keplerian disk rate is increased, the number of injected soft photons go up, cooling every electron in the sub-Keplerian halo component. Thus, the relative availability of the soft photons and the hot electrons in the disk and the jet dictates whether the emergent photons would be spectrally soft or hard.

In Figs 4.9(a) and (b), we show three spectra for each of the specific angular momentum: (a) $\lambda = 1.80$ and (b) $\lambda = 1.75$. The Cases are marked. We see that a spectrum is essentially made up of the soft bump (injected multi-colour blackbody spectrum from the Keplerian disk which are unscattered), and a Comptonized spectrum with an exponential cutoff - the cutoff energy being dictated by the electron cloud temperature. As the disk rates are very small ($\sim 0.0001$ Eddington rate), the temperature of the disk is small and the resulting spectra show peaks at extremely low energies in the above Figure. If we define the energy spectral index $\alpha$ to be $I(E) \propto E^{-\alpha}$ in the region $2 - 20$ keV, we note that $\alpha$ increases, i.e., the spectrum...
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Figure 4.10: Time variation of the spectral index [$\alpha$, $I(E) \propto E^{-\alpha}$] for different disk rates. Different Cases are marked. We note that as the accretion rate goes up, the average $\alpha$ increases, i.e., the spectrum softens (see also, GGC12).

In reality, since the disk is not stationary, the spectrum also varies with time, and so is $\alpha$. In Fig. 4.10, we present the time variation of the spectral index for the different Cases. We clearly see that the spectral index goes up with the increase in the disk accretion rate (see also, GGC12). Thus, on an average, the spectrum softens.

In the above works, we have not considered the effects of magnetic field. In presence of magnetic field, synchrotron photons may be emitted from the post-shock region which affect the spectral shape (Mandal & Chakrabarti 2005a, 2005b; Chakrabarti & Mandal 2006; Mandal & Chakrabarti 2008). Synchrotron emission may occur from the Maxwell-Boltzmann electrons of the pre-shock as well as the CENBOL and jet regions and from the shock accelerated power-law electrons. These photons may get inverse-Comptonized in the CENBOL and produce high energy X and gamma rays extending up to a few MeV, as shown in the above references. These effects are not included in our radiative-hydro calculation.