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Radiatively Driven Winds from Effective Boundary Layer around Black Holes

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Abstract. Matter accreting onto black holes suffers a standing or oscillating shock wave in much of the parameter space. The post-shock region is hot, puffed up and reprocesses soft photons from a Keplerian disc to produce the characteristic hard tail of the spectrum of accretion discs. The post-shock torus is also the base of the bipolar jets. We study the interaction of these jets with the hard photons emitted from the disc. We show that radiative force can accelerate outflows but the drag can limit the terminal speed. We introduce an equilibrium speed v_{eq} as a function of distance, above which the flow will experience radiative deceleration.

Key words. Accretion—accretion disc—black hole physics— winds—outflows.

1. Introduction

Rotating matter spirals onto the black hole to form a temporary depository called the accretion disc. As supersonic matter approaches the compact object centrifugal pressure becomes comparable to the gravitational pull. If the Rankine-Hugoniot shock conditions are satisfied the flow may suffer a thin shock (Chakrabarti 1996). Post-shock flow becomes hotter at roughly the virial temperature $kT_p \sim GM/r_s$, where G, M, r_s, k, T_p are the gravitational constant, mass of the black hole, Bolzmann constant and proton temperature respectively. This causes the flow to puff up in the form of a torus. The soft photons processed in the outer cool Keplerian disc is intercepted by this puffed up post-shock region. Chakrabarti and Titurchuk (1995, hereafter CT95) showed that the intercepted soft photons are reprocessed (inverse-Comptonized) by the hot electrons of post-shock torus and produces the characteristic hard tail of the spectrum. Hence the presence or absence of this post-shock flow, will determine whether the black hole candidate will be in the hard or the soft state.

Chakrabarti and his collaborators (Chakrabarti 1998, 1999; Das & Chakrabarti 1999; Das *et al.* 2001) showed that this post-shock tori (hereafter, CENBOL ≡ CENtrifugal pressure supported BOundary Layer) is also the source of jets. The excess thermal pressure in CENBOL, drives a part of the infalling matter along the axis of symmetry as jets or winds around compact objects. Hence CENBOL acts as an effective boundary layer around black holes. This effective boundary then acts as both the source of hot photons as well as the source of jet matter. We are interested to study the interaction of these two.

Radiatively driven winds in various contexts have been studied by several workers. Icke (1980) studied radiatively driven gas flows from a Keplerian disc (Shakura & Sunyaev 1973), though the drag term was neglected. Sikora & Wilson (1981) showed that radiations from thick disc can collimate the outflow but radiation drag reduces its terminal velocity. Icke (1989) calculated the terminal speed of radiatively driven outflows above a Keplerian disc, in presence of radiation drag and found it to be $0.451c$ (where, c is the velocity of light). Fukue (1996) considered a rotating flow over such a disc and found the terminal speed to be lower. All the major works on this field has been done either by considering a geometrically thin, Keplerian disc or a hot thick disc. They also consider a cold jet, i.e., they ignored the pressure gradient term in the momentum balance equation. We, however, have included the pressure gradient term also. Chattopadhyay & Chakrabarti (2000a, 2000b) have already showed that the acceleration due to radiative momentum deposition is impressive if the radiation drag term is excluded. In this paper, we want to study the issue of radiative acceleration in presence of radiation drag. We consider a class of solutions called the advective discs (Chakrabarti 1996) which have a cold outer thin disc ($T \sim 10^7$K) and inner region could be hot ($T \sim 10^{9-10}$K) and a puffed up torus (CENBOL), which is approximately a thick disc (with advective corrections incorporated). We consider radiative acceleration of outflows coming from the CENBOL region of such a disc. In Compton effect, the energy transferred from a photon per scattering is given by $\Delta\nu/\nu \sim (4kT_e - h\nu)/\nu$. Thus electrons have to be cooler to receive energy from photons emitted by the CENBOL.

For simplicity, we assume the outflow to be conical and inviscid and electron scattering to be the dominant energy transport mechanism. The equation of motions are taken from (Mihalas & Mihalas 1984). The radiative flux and the energy density are calculated following Chattopadhyay & Chakrabarti (2000b).

2. Radiatively driven winds and terminal velocity v_{eq}

In our analysis, the acceleration mechanism considered are, **(1)** thermal pressure and **(2)** the radiative force. If only the first mechanism was chosen it would have been Bondi-type outflow, where the specific energy of the flow would have a positive Bernoulli constant. The terminal velocity achieved would be $\frac{1}{2}v_\infty^2 \sim na_{in}^2 - 1/2(z_{in} - 1)$, where, n, v_∞, a_{in}, $-1/2(z_{in} - 1)$ are the polytropic index, terminal velocity, initial sound speed, gravitational potential (psuedo-Newtonian, see, Paczýnskii-Wiita 1980) at the initial injection point. We see that, v_∞ is of the order of initial sound speed. If we now add the radiative acceleration the terminal velocity should increase, because the radiative work done (i.e., $\int_{z_{in}}^{\infty}(\mathcal{D}_z - 2v\mathcal{E})dz$, where the first term inside the parenthesis is the radiative acceleration and the second one is the radiative drag term) onto the outflow will increase the terminal velocity. Fig. 1(a) shows the variation of v_{1000} (v at $z = 1000r_g$; r_g is the Schwarzschild radius) with initial energy of the flow. The general behaviour is that the acceleration of the outflow increases with the radiative intensity of the disc, but for a very high initial energy, the dependence of v_{1000} on the intensity is weak as the radiative work done is negligible compared to E_{in}. For a very cold flow, radiative force may impart enough momentum onto the flow so that even bound matter may also be freed to join the outflow. In Fig. 1(b) the solution topology of a radiatively driven outflow with an initially bound energy is compared with only

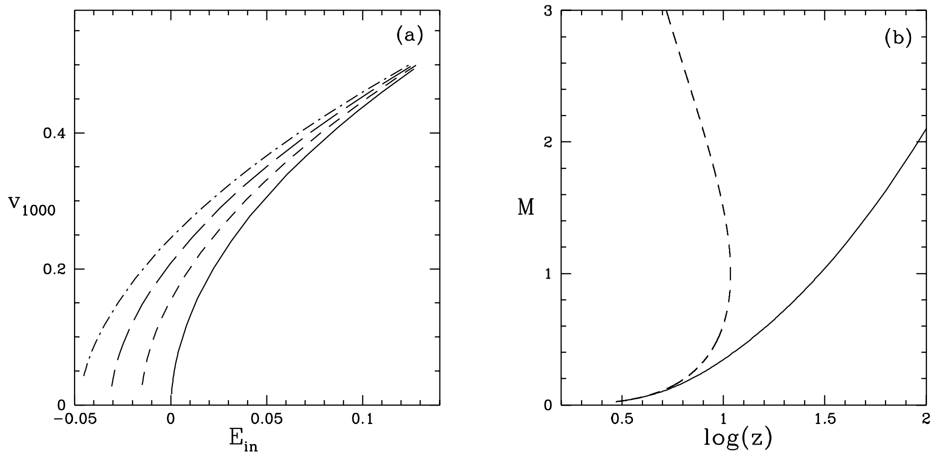

Figure 1. **(a)** Comparison of (v_{1000}) with initial energy (E_{in}) of the flow. Various curves represent flows acted on by radiation momentum deposition from inflow with $\dot{M}_{acc} = 15\dot{M}_{Edd}$ (dash-dot), with $\dot{M}_{acc} = 10\dot{M}_{Edd}$ (long-dashed), with $\dot{M}_{acc} = 5\dot{M}_{Edd}$ (short-dashed) and Bondi-type (solid) outflow. **(b)** Comparison of the variation of Mach number (M) with $\log(z)$. The solid curve represents the outflow acted on by radiation deposition due to $\dot{M}_{acc} = 5\dot{M}_{Edd}$. The dashed curve represents the outflow driven only by the thermal energy. Initial parameter is, $E_{in} = -0.002$ at $z_{in} = 3$.

thermally driven outflow. Radiatively driven flow is found to be transonic while the other dives back on to the black hole.

The radiative deceleration term (drag) is proportional to both the bulk velocity (v) and the radiation energy density ($\mathcal{E} \propto$ radiation energy density) at a given point. Hence there is an equilibrium velocity above which there would be radiative deceleration, whose expression is $v_{eq} = \mathcal{D}_z/(2v\mathcal{E})$. In Fig. 2(a), the variation of v_{eq} is shown. To exhibit the acceleration/deceleration mechanism of radiative force, the injection velocity $v_{in} > v_{eq}(z_{in})$. The flow is decelerated upto z_1. In the region $z_1 < z < z_2$, there is acceleration and again $v(z_2) = v_{eq}(z_2)$. In the region $z > z_2$, there should be deceleration, but it is not evident from Fig. 2(b). On the other hand, Fig. 2(c) shows that in the region $z > z_2$ there is deceleration but both the radiation flux and its energy density decreases to such a low value, that the deceleration is negligible. If one plots the specific energy of the flow, the decrease in this region due to the radiative deceleration is also shown to be negligible. This shows that v_{eq} is the upper limit of v_∞ for cold plasma, in absence of gravity. Thus we give a general form of terminal velocity; $1/2(v_\infty^2) \leq 1/2(v_{eq}^2) + E_{in}$.

3. Conclusions

The radiative force can accelerate outflows to a maximum velocity of $0.5c$ but if there is enough thermal energy the terminal velocity could be higher and in principle there is no limit to the final velocity. Galactic microquasars such as SS433, GRS1915+105 etc. do show jets with velocities up to $0.98c$. We believe that these could be accelerated by radiative process.

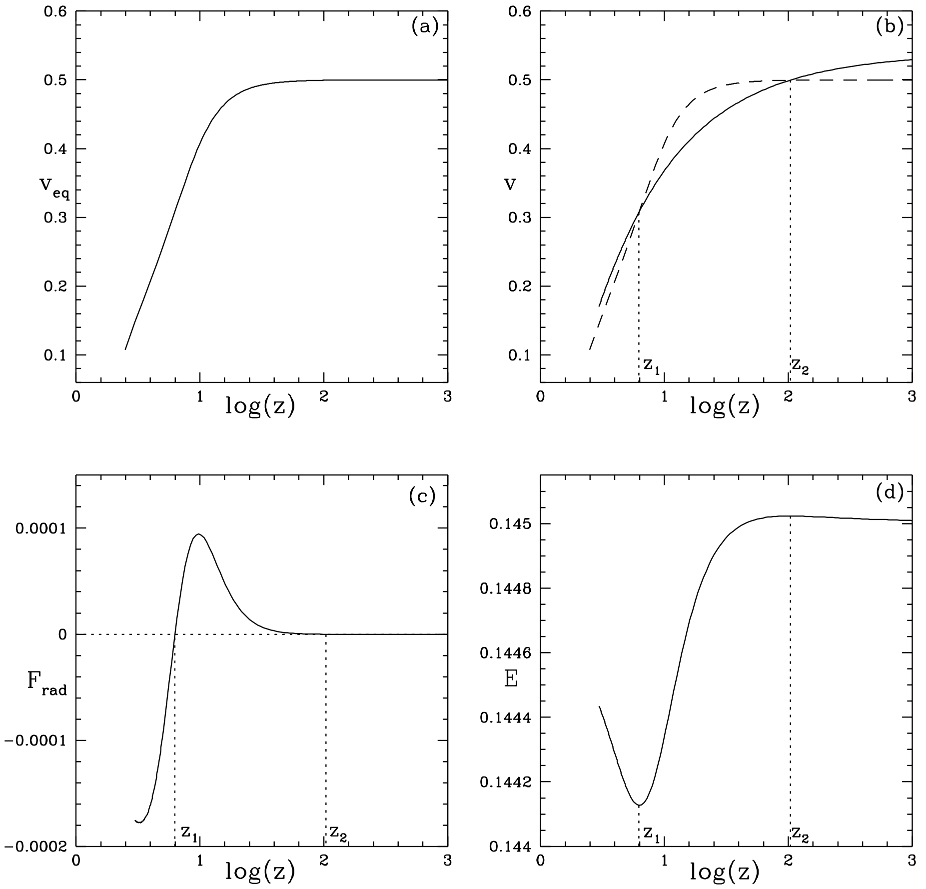

Figure 2. **(a)** Variation of v_{eq} as a function of z **(b)** Comparison of variation of bulk velocity v (solid) with v_{eq} (short-dashed) as a function of z. $v_{in} = 0.17$ at $z_{in} = 2.96$. $v_{eq}(z_{in}) < v_{in}$. The outflow topology (solid) is acted on by RAMOD corresponding to $\dot{M}_{acc} = 5\dot{M}_{Edd}$. **(c)** The net radiative force (F_{rad}) is presented as a function of z. **(d)** Comparison of E of the outflow in the previous case.

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