Radiatively Driven Jets around Black Holes

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Abstract. The hot, puffed up, post-shock region of an advective disc is the source of high energy photons and also the jets and outflows. We study the relativistic equations of motion of jets as these high energy photons interact with them. We show that the much discussed terminal velocity of jets depends on the comparative value of radiative energy density, flux and the radiative pressure. We show that electron-positron pair plasma jets achieves highly relativistic terminal speeds for higher disc luminosities.

1. Introduction

Rotating matter while falling onto black holes creates a temporary depository of matter called accretion disc. As matter moves closer to the black hole, at around a few tens of Schwarzschild radii ($r_s$), centrifugal force tends to be comparable to the inward gravitational force and the supersonic inflow is slowed down. If this slowing down occurs in a thin region \cite{1}, the flow is said to suffer a shock, where the Mach number jumps discontinuously from supersonic to subsonic branch. This slowed down post-shock flow is considerably heated up and as a result, puffs up (to maintain hydrostatic balance along z-direction) in the form of a tori called CENBOL (centrifugal pressure supported boundary layer). CENBOL contains a copious hot electrons which inverse-Comptonize the soft photons from outer cool thin disc \cite{2}, producing the hard-power law tail \cite{3}. As a lot of heat is stored in the CENBOL, Chakrabarti and his co-workers (\textit{e.g.} \cite{4}, \cite{5}, \cite{6}) has shown that the thermal pressure along the vertical direction pushes the matter out in the form of jets. In this paper, we investigate the interaction of these jets with the high energy photons radiated by the CENBOL.

Interaction of radiation and jets have been studied by several workers. Piran (\cite{7}) showed that it is difficult to accelerate outflows from thick accretion disc beyond Lorentz factor $\gamma > 1.5$. Icke (\cite{8}) in a very important paper showed that, if outflows are to be accelerated by radiation from ‘infinite’ thin discs, the terminal speed (‘magic speed’ in his parlance) achieved is just $0.451c$, where $c$ is the velocity of light. Fukue (\cite{9}), showed the terminal speed for rotating flow above thin disc, is little less than what Icke had obtained. The conclusion is that radiative interaction actually limits the jet terminal speed. We improve these works by studying the interaction of a jet with radiation coming from the most general form of accretion flow, namely the \emph{advective discs} (\textit{e.g.} \cite{1},\cite{3},\cite{10}). The first three moments of the radiation intensity for \textit{e.g.}, the radiation energy density, radiative flux and various components of radiative pressure are being calculated following the treatment of Chattopadhyay \& Chakrabarti (\textit{e.g.} \cite{11}, \cite{12}). For simplicity, we assume that the radiation originates only from the CENBOL.
In the next section we show that, the terminal speed achieved by the outflowing plasma depends on the comparative value of the various moments of radiation involved. We show that the radiation from the advective flows can produce relativistic jets. In §3, we draw our conclusions.

Figure 1. Comparison of radiation field quantities $E$ (solid), $F$ (dashed), and $P$ (long-dashed) plotted with $\log(z)$ in non-dimensional units. These field quantities are calculated for disc luminosity $L = 0.06L_{\text{Edd}}$. Radial dimension of CENBOL (i.e., shock location) is chosen to be $10r_g$.

2. Equations of motion and radiative acceleration of jets

We assume that the electron-positron plasma jets are non-rotating and confined along the axis of symmetry. To study only the radiation effects, we ignore the gas pressure gradient term. We confine our investigation within the realm of special relativity and the effects of strong gravity is taken care by Paczyński-Wiita potential (e.g. [13]). The unit of length, time, mass and velocity are $r_g = 2GM_B/c^2$, $2GM_B/c^3$, $M_B$ and $c$ respectively, where $G$ and $M_B$ are the gravitational constant and mass of the central black hole. The metric considered is given by, $d\tau^2 = dt^2 - dr^2 - r^2 d\phi^2 - dz^2$. We assume $u^r = u^\phi = 0$ and also $\partial/\partial t = \partial/\partial r = \partial/\partial \phi = 0$. We define a 3-velocity $v$, given by $v^2 = -(u_iu^i)/(u_tu^t)$, where the latin index (e.g. $i, j, k$) denotes space variables. The Lorentz factor is given by, $\gamma^2 = 1/(1 - v^2)$. Hence in our case $u^z = \gamma v$, $u_z = -\gamma v$, $u^t = u_t = \gamma$. The equation of motion (see, Mihalas and Mihalas [14] and Kato et al. [15]) is given by,

$$\frac{du^z}{d\tau} = -\frac{1}{2(z-1)^2} + \kappa_{\text{es}}[\gamma F^z - \gamma^2 Eu^z - P^{zz}u^z + u^z(2\gamma F^z u^z - P^{zz}u^z u^z)], \quad (1)$$
where, $\kappa_{es}, F^z, E, P^{zz}$ are the Thomson scattering opacity, the $z$-component of radiative flux on the $z$-axis, energy density on the axis of symmetry, and the $z-z$ component of pressure tensor on the axis of symmetry. The term $-1/(2(z-1)^2)$ is the gravity term with Paczyński-Wiita potential. Using the expressions of $u^z$ and $u^t$ we can reduce Eq. (1) in terms of the 3-velocity $v$, and is given by,

$$\frac{dv}{dz} = -\frac{1}{2(z-1)^2} + \frac{[\gamma F - \gamma^3 v E - \gamma v P + \gamma^3(2u^2 F - v^3 P)]}{\gamma^4 v},$$

(2)

where, $F$, $E$, and $P$ are radiative flux, energy density and $z-z$ component of pressure tensor which has been multiplied by $\kappa_{es}$. To find the expression for terminal speed, we put the term in the square bracket of Eq. (2) equal to zero and get a quadratic equation for $v_t$,

$$F v_t^2 - (E + P) v_t + F = 0.$$ 

It is easy to show that at $z \rightarrow$ large, $P \lesssim F \lesssim E$, and also that all three quantities vary slowly with $z$ (Fig. 1). Thus for large $z$, let $P = A$, hence $F = A + \delta$ and $E = A + \eta$, where $\delta \ll A$ and $\eta \ll A$ with $\delta \lesssim \eta$. Hence, from the above quadratic equation we get,

$$v_t = \frac{(E + P) - \sqrt{(E + P)^2 - 4F^2}}{2F}.$$ 

(3)

Putting the radiation field quantities in terms of $A$ in Eq. (4), we have,

$$v_t \approx \frac{1 + \eta/(2A)}{1 + \delta/A} \lesssim 1$$

(4)

Equation (4) shows that $v_t$ can be very close to the velocity of light, thus radiation drag does not limit the terminal velocity to some moderately relativistic values. In case of gas flows above a thin disc (e.g. [8],[9]), $P = 1/3E$ and $E \sim 2F$, putting those values in Eq. (4), we have $v_t = \frac{1}{2}(4 - \sqrt{7})$ (see, Icke[8]). We have thus proved that the terminal velocity achieved depends on the radiation field produced by the structure of the disc. If we now integrate Eq. (2) with a very small injection velocity, we can find the solution topologies for jets as shown in Fig. 2a. Though there is no upper limit to $v_t$, even then increasing the luminosity, will not increase $v_t$ drastically, as there is $\gamma^4$ term in the RHS of the denominator of Eq. (2), and hence as $v \rightarrow 1$, $dv/dz \rightarrow 0$. In Fig. 2b the velocity at $z = 10000r_g$ i.e. $v_{10000}$ is plotted with the disc luminosity $L$ and is found that as one increases $L$, the response of $v_{10000}$ is not linear. Figure 2b shows that it is difficult to get terminal speeds $\sim 0.99c$ with radiative acceleration only, as that would require extremely high luminosity, which is difficult to produce without, at the same time, cooling the CENBOL itself.

3. Discussion and Concluding Remarks

In our investigation we have assumed the entire disc luminosity is coming only from the CENBOL region. It can be shown elsewhere that the contribution from the pre-CENBOL thin disc will marginally affect the results shown here. We conclude that, the terminal speeds calculated previously, by using radiation fields
from very specialised accretion discs (e.g., thin disc, thick disc, etc), show mildly relativistic flows, and are basically the artefacts of those disc geometries themselves. If one considers more generic disc model as we have done, the radiation drag does not introduce a mildly relativistic upper limit for terminal speed. We find that achieving terminal velocity close to that of light by radiation pressure effects is possible.

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