Jets, Disks and Spectral States of Black Holes

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Abstract. We show that outflow rates in jets directly depend on the spectral states of black holes. In particular, in soft states, when the Comptonized electrons are cold, outflow rate is close to zero. In hard states, outflow could be steady, but the rate may be very small – only a few percent of the inflow. In the intermediate states, on the other hand, the outflow rate is the highest – roughly thirty percent of the inflow. In this case, piled up matter below the sonic surface of the outflow could become optically thick and radiative processes could periodically cool the outflow and produce very interesting effects including transitions between burst (high-count or On) and quiescence (low-count or Off) states such as those observed in GRS 1915+105.

INTRODUCTION

Jets from a black hole candidate must form out of accretion flows and the surrounding corona since black holes have no atmosphere of their own. However, though black holes have no hard surfaces, they can have ‘boundary layers’. Because of rapid infall near the horizon, viscosity finds little time to transport angular momentum from the matter and the specific angular momentum becomes almost constant close to the horizon. This consideration led earlier workers to study thick accretion disks [1]. The centrifugal force for a constant angular momentum flow varies as $\sim 1/r^3$ while the gravitational force varies roughly as $\sim 1/r^2$. Matter is thus piled up behind the strong centrifugal barrier and an oblique shock is formed [2,3]. At this shock, flow converts kinetic energy into thermal energy and hard X-rays are emitted from the post-shock region. This region may thus be called a centrifugal pressure supported boundary layer (CENBOL) for all practical purposes.

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Post-shock region has similar properties as that of a thick disk, since the flow puffs up and also has a funnel which can collimate outflows. In the absence of Comptonising soft photons from a pre-shock Keplerian disk (i.e., when the Keplerian rate $\dot{M}_d$ [4] is very low) the post-shock region remains hot and the spectrum is hard. However, when the Keplerian rate is high, the post-shock region cools catastrophically and the CENBOL collapses. The emitted spectrum is soft. Chakrabarti & Titarchuk [4] and Chakrabarti [5] computed spectra of such types of flows with or without centrifugal barrier for various parameters.

Given that the post-shock region behaves like a boundary layer, whose electron and ion temperatures depend on the Keplerian and sub-Keplerian accretion rates (which in turn determine the spectral state of a black hole), it is curious to ask if this boundary layer is capable of producing outflows and how the outflow rate depends on spectral states. In the next Section, we describe recent results [6–9].

**SPECTRAL STATES AND OUTFLOW RATES FROM GLOBAL SOLUTIONS**

Discussion on global solutions has been made in several recent reviews [8,10–12] and will not be repeated here. A hot CENBOL can drive outflows and Chakrabarti [7,12] computed the ratio $R_{in}$ of the outflow rate ($\dot{M}_{out}$) and inflow rate ($\dot{M}_{in}$) as a function of the compression ratio $R$ and the ratio $R_\Theta$ of the solid angles subtended by the outflow and inflow. Figure 1 shows how $R_{in}$ looks like when $R_\Theta \sim 1$ is chosen (solid curve). Since in soft states, shocks disappear ($R \to 1$, left hand side of the box) and accretion rate is around $\dot{M}_{Edd}$ while in hard states shocks
are the strongest ($R \to 4 - 7$, right hand side of the box) and the accretion rate is low (say, around $\sim 0.001 - 0.01\dot{M}_{\text{Edd}}$, see, Chakrabarti & Titarchuk [4]) we plot a ‘reasonable’ $\dot{M}_{\text{in}} \propto 1/R^2$ as the long dashed curve. The product $\dot{M}_{\text{out}} = \dot{M}_{\text{in}}R_{\text{in}}$ is plotted as a short-dashed curve. It is clear that the maximum outflow rate is possible when $R \sim 2$, which is possible neither in the soft state nor in the hard state. This region may be called the intermediate state. Because outflow rates are very high, electrons till the sonic sphere could be cooled down due to Comptonization. A part of the matter will fall back and the rest would separate as blobs. Flow separation takes place at the new sonic surface. Thus, outflows are expected to be blobby in this intermediate state. The return flow determines the duration of the On and Off states. As $R$ approaches $4 - 7$ from this state, the duration should progressively increase, provided the geometric properties of the inflow and outflow (i.e., $R_{\phi}$) remains the same. In hard states, continuous outflow would be possible while in true soft states ($R \sim 1$), outflow would be negligible.

Figure 2 shows various types of accretion disk/jet systems when the global solutions of advective disks and radiative transfer effects described above are simultaneously taken into account. The upper left panel shows the situation when Keplerian rate is low $\dot{M}_K \sim 0.01 - 0.001\dot{M}_{\text{Edd}}$, sub-Keplerian rate is comparatively high and the CENBOL is not well defined (shock condition not satisfied). Das & Chakrabarti [13] showed that the region of the pressure maximum may still be con-
sidered as a CENBOL and outflow rates could be computed. Outflow, at a low rate, would be possible. In this case, shock oscillation does not take place and no quasi-periodic oscillations (QPO) are seen. The upper right panel shows another type of hard state when a shock could form and it could oscillate to produce quasi-periodic oscillations [14,15]. The configuration shown in the lower left panel is possible in the burst or intermediate (may also be termed as burst/quiescence or On/Off) states. Here the light curve can have interesting behavior as is seen in GRS1915+105. For the On/Off transitions to take place, it may be crucial that the outflow below the sonic surface becomes optically thick to Compton scattering in a short time (tens to hundreds of seconds). If the accretion rate is very small, this never happens and the light curve does not show On/Off transitions. The lower right panel shows the situation when the Keplerian rate is high and the sub-Keplerian component is weak. CENBOL never forms as it cools down catastrophically. No wind is produced as well.

Our understanding of the relation between spectral states and outflows may have been borne out observationally [16,17]. It may be interesting to see if the radio jets around super-massive black holes also show similar behavior. On the other hand, since density in the wind falls off faster than $1/r$, $\tau$ may never cross unity for supermassive black holes. Also, presence of magnetic fields may cool electrons more rapidly and bring interesting observational effect. These aspects would be studied in the future.

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