Jets and Outflows From Advective Accretion Disks

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Abstract. Jets and outflows must be produced directly from accretion disks and inflows, especially when the central gravitating objects are compact, such as neutron stars and black holes, and themselves are not mass losing. Here, we review the formation of jets from advective inflows. We show that the centrifugal pressure supported boundary layer (CENBOL) of the black holes may play crucial role in producing outflows. CENBOL is not present in Keplerian disks. Thus energetic jet formation is directly connected to sub-Keplerian flows close to compact objects.

INTRODUCTION

Jets and outflows are ubiquitous in quasars and active galaxies. They are often superluminal, moving almost at the speed of light. Over the last decade, a few sources in our own galaxy have been observed which also display energetic outflows. Most interesting of these sources is the black hole candidate GRS1915+106 [1,2] which has been studied very extensively and in this review we shall devote some space on this object.

Extensive work has been carried out over last quarter of a century to explain the origin of jets [3]. Not surprisingly, most of these invoke accretion flows to be the source of outflowing matter. Since the standard Keplerian accretion disk by Shakura & Synyaev [4] did not have any scope of the formation of jets, in the early 80’s, accretion solutions of purely rotating disk were improved to include the effect of radiation pressure [5–9] (See Chakrabarti [10] for a review.) and see if these thick disks were useful for the production and collimation of jets. Jet solutions have changed from speculative ideas such as de-Laval nozzles [11] to electrodynamically acceleration model [12], self-similar centrifugally driven outflows [13], ‘caul-
drorns’ [14] etc. Centrifugally driven outflows are subsequently modified to include accretion disks [15]. Chakrabarti & Bhaskaran [16] (see also, Contopoulos [17]) showed that it is easier produce outflows from a sub-Keplerian inflow.

It is important to note that in black hole accretion, matter is relativistic close to the black hole horizon, while in jets, matter become relativistic farther away from the the black hole. In both the cases, matter is assumed to begin its journey subsonically and end its journey supersonically. Bondi [18] studied simplest form of accretion and wind solutions with these properties for spherically symmetric flows without any heating and cooling. Especially important are the outflow solutions which were immediately used to study solar and stellar winds [20,19]. In the context of Active Galaxies and Quasars, some notional unification of disk-like and jet-like solutions were presented by Chakrabarti [21,22]. It was shown that the same solution of purely rotating flow around a black hole could describe accretion flows on the equatorial plane and pre-jet matters near the axis. With a natural angular momentum distribution of \( l(r) = c \lambda(r)^n \), (where \( c \) and \( n \) are constants and \( \lambda \) is the von Zeipel parameter) it was found that for large \( c \) and small \( n \) \((n < 1)\), solutions are regular on the equatorial plane and they describe thick accretion disks. However, for small \( c \) and large \( n \) \((n > 1)\), the solutions are regular on the polar axis and they describe pre-jet matter. It was conjectured that that some viscous process might be responsible to change the pair of parameters \((c, n)\) from one set to the other. Eggum, Coroniti & Katz [23] considered radiatively driven outflows emerging from a Keplerian disk. The angular momentum distribution in the outflow qualitatively looks similar to the natural distribution described above. Chakrabarti [24] used the natural distribution to study acceleration of the pre-jet matter inside the funnel of a thick disk and found that jets could be accelerated at the cost of thermal and rotational energies close to a black hole. Addition of magnetic field in the wind solution enhances the terminal velocity substantially [26].

**EMERGENCE OF GLOBAL INFLOW OUTFLOW SOLUTIONS (GIOS)**

Generalized Bondi flows have been solved when angular momentum, heating and cooling are added [25–27]. All possible accretion and wind type solutions are found, including solutions which may contain standing shocks and the entire parameter space is classified according to the nature of solutions [25,26]. Fig. 1 shows some of the interesting solutions (Mach number is plotted against logarithmic radial distance [in Units of the Schwarzschild Radius] in outer three small boxes.) and the classification of the parameter space (Specific energy is plotted against specific angular momentum in the central box.) when the Kerr parameter \( a = 0.5 \) and when the equatorial plane solutions are considered. The inward pointing arrows in Fig. 1 indicate accretion solutions and the outward pointing arrows indicate wind solutions. A flow from regions I and O passes through the inner sonic point and outer sonic point respectively. Those from NSA have no steady shocks in accretion,
Fig. 1: Classification of parameter space (spanned by specific energy and angular momentum) in several regions depending on whether or not solutions include (SA and SW) steady or oscillating (NSA, NSW) shock waves. Solutions from $I^*$ region would not be complete unless viscosity is added. These would be regular Keplerian disks which pass through inner sonic points [inset]. Magnetic heating changes Keplerian flows into flows with shocks as indicated by dark arrows.

Fig. 2: Demonstration of the generic nature of the classification of the parameter space around a Schwarzschild black hole. Three models (a) a flow which is in vertical equilibrium as each point (EQUILIB.) (b) a wedge shaped conical flow (WEDGE) and (c) a flow with a constant height (CONSTANT HEIGHT) are studied. Meaning of various symbols are as in Fig. 1. Pseudo-Newtonian potential [6] has been used.
Fig. 3: Construction of Global Inflow-Outflow Solutions (GIOS) using one solution from SA and one from O regions. Shock formed at $X_{s3}$ generates higher entropy flow and deflects part of the matter along the axis [28].

from SA have shocks in accretion, from NSW have no steady shocks in winds, and SW have shocks in winds respectively. The horizontal line at unit energy in the central box represents the rest mass of the inflow. Note that the outflows are produced only when the specific energy is higher than the rest mass energy. A flow with a lesser energy produces solutions with closed topologies (I* and O*). When viscosity is added the nature of the solutions is changed fundamentally [29] (see, Chakrabarti [27,30] for details) allowing matter to directly come out of a Keplerian disk and enter into a black hole through the sonic point. The box drawn with I* region shows how an I* solution is modified in presence of viscosity (thick arrow). When magnetic heating is added or the flow is away from the equatorial plane, energy of the inflow could become positive and the solutions such as NSA, SA, SW or NSW could be chosen depending on the parameter space.

This classification is generic and is model independent though the actual parameter boundaries would vary. Fig. 2 compares the classification of parameters in conical flow, the flow in vertical equilibrium and the flow with constant height in a pseudo-Newtonian geometry [6]. All the models show the same sub-divisions in the parameter space.

Using these solutions it is possible to self-consistently construct Global Inflow Outflow Solutions (GIOS) in which matter first accrete using solutions with inward pointing arrows and the goes out to long distances using solutions with outward pointing arrows [33,34,28,35]). Fig. 3 shows how an inflow solution from region SA and an outflow solution from region O could be combined to have a GIOS. It has been observed that depending on the parameters, the disk could be completely
evacuated, by the outflow processes, especially when the inflow rate is very low [28].

The steady accretion and wind solutions described above have been verified by complete time-dependent simulations [36–39]. In the case of steady state solutions, outflows are found to occur between the centrifugal barrier and the funnel wall while in a non-steady and viscous solution the outflow could spread in regions outside the centrifugal barrier as well. Presumably, azimuthal component of the magnetic field carried along by the outflow is responsible for the collimation that is observed in jets.

Fig. 4 shows how the solutions of SA type are modified in presence of viscous processed [26]. For weak viscosity the centrifugal barrier still remains and shocks form. The post-shock region gets heated and is consequently puffed up. Winds and outflows are profuse from this region. This is schematically shown in the right panel of the Figure. On the equatorial plane of the disk, viscosity may be high and the disk remains Keplerian. Subsequently, it becomes sub-Keplerian before entering the black hole. However, the sub-Keplerian flow above and below the equatorial plane could be heated up in the corona region by magnetic dissipation. When its energy become positive (unbound), it becomes energetically favorable to produce shocks and outflows.

OSCILLATING SHOCKS IN ACCRETION AND WINDS

Solutions in SA and SW are in general steady (with shocks in accretion and winds respectively), except when cooling processes are added and cooling time scales roughly agree with the infall time scale. Molteni, Sponholz and Chakrabarti [41] produced examples of this types of shocks. Shocks are found to perform large amplitude oscillation with a periodicity of

$$t_{Osc} \sim \frac{R R_{s}^{2} R_{g}}{c \vartheta_{0}} \text{ s}$$  (1)
where, $R_s$ is the mean location of the shock in dimensionless units, $R_g = 2GM/c^2$ is the Schwarzschild radius of the central black hole, $R$ is the compression ratio of the shock, $\alpha \sim 1$ in the post-shock region. Inverse of these time scales agree very well with the quasi-periodic oscillations (QPO) of hard X-rays and are believed to be the cause of QPOs in black hole and neutron star candidates. Since cooling time scale generally goes down as accretion rate is increased, oscillation frequency should go up with accretion rate.

Solutions from the regions NSA and NSW have two saddle type sonic points as in solutions of SA and SW regions. However, Rankine-Hugoniot conditions are not satisfied and therefore steady shocks do not form. It was shown that solutions from these regions still possess shocks, but they are oscillatory, constantly trying to search for the steady location [42]. These shock oscillations also have similar time scales as above, but the oscillation frequency is directly sensitive to the angular momentum and specific energy of the flow and not the accretion rate. Detailed simulation with radiative transfer is essential to understand these oscillations.

**RATE OF OUTFLOW GENERATION**

Although hydrodynamic processes alone are not thought to be the sole mechanisms in generation and acceleration of cosmic jets and outflows, a great deal of the behavior of jets could be learned about the jets from hydrodynamic considerations. Chakrabarti [35] computed the rate of outflow generation assuming the outflow to be isothermal at least up to the sonic point. It was found that the ratio of the inflow and outflow rates $\dot{R}_m$ could be expressed in terms of just three parameters: (a) $R$, the compression ratio of the flow at the accretion shock, (b) $\Theta_{in}$, the solid angle subtended by the accretion flow at the centre and (c), $\Theta_{out}$, the solid angle subtended by the outflow at the centre. The result [34] is given by:

$$\dot{R}_m = \frac{\dot{M}_{out}}{\dot{M}_{in}} = \frac{\Theta_{out}}{\Theta_{in}} \frac{R}{4 \left( \frac{R^2}{R-1} \right)^{3/2}} \exp \left( \frac{3}{2} - \frac{R^2}{R-1} \right).$$  \hspace{1cm} (2)

This function $\dot{R}_m$ has a peak when $R \sim 2.5$, i.e., when the shock is of intermediate strength. In the soft states of black holes, shocks are weakened as the post-shock region is cooled down completely [31]. As the compression ratio approaches unity, the outflow rate also goes to zero. In the hard state, as the compression ratio approaches $4 - 7$, $\dot{R}_m \to 0.1$, i.e., roughly ten percent of infalling matter goes out of the system. Details about the relation between the spectral states and the outflows would be dealt with elsewhere [43].

**EFFECTS OF RADIATIVE TRANSFER IN PRESENCE OF WINDS**

Chakrabarti & Titarchuk [31] showed that post-shock region behaves as the so-called Compton cloud in determining the spectral states of black hole. In general,
when the soft photons (generated by the Keplerian matter) intercepted by the CENBOL is very large, this region is cooled down and the black hole is seen in a soft state. However, when soft-photons are very few, CENBOL remains hot and the black hole spectrum shows characteristics of a hard state. Thus state change is equivalent to redistribution of matter into the Keplerian (producer of soft photons in the pre-shock flow, and hot electrons in the post-shock region) and the sub-Keplerian components (producers of hot electrons) in this model. Fig. 5a shows the general disk-jet system in the hard state.

There are two very major effects when winds are generated from the CENBOL. In presence of significant winds, density of hot electrons in CENBOL goes down, even though the number of intercepted soft photons from the Keplerian disk remains the same. The resultant spectrum is thus softened [47]. When the rate of wind production is very high, the region up to the sonic surface of the wind could be cooled down by Comptonization process. Since the sound speed in this region is suddenly reduced, the sonic surface of the wind is shifted downward, and a part of the wind, originally sub-sonic, becomes supersonic and is separated out as a blob, while the rest below the new sonic surface returns back to the accretion disk (Fig. 5b). This causes enhanced accretion for a brief period and count rates go up [32,44,45].

Figure 6 shows the cause of non-linearity in the light curve $L_\gamma(t)$. $\dot{M}_{in}$ is the net inflow rate which is the sum of the Keplerian rate $\dot{M}_d$ and the sub-Keplerian rate or halo rate $\dot{M}_h$ [31]. This matter together with time dependent return flow from the sonic sphere above CENBOL enters CENBOL whose density, temperature determines intensity of emitted radiation $L_\gamma$ as well as the outflow rate $\dot{M}_{out} + \dot{M}_{rf}$. CENBOL may emit bremsstrahlung or Comptonized soft photons. However, $S_\gamma$ the soft photon intensity intercepted from the Keplerian disk depends on CENBOL parameters themselves. As Molteni, Sponholz and Chakrabarti [41] showed CENBOL undergoes oscillations and intercepts photons of varying degree. The net outflow is $\dot{M}_{out}$ which is also time-dependent. The net inflow onto the black hole is $\dot{M}_{BH} = \dot{M}_{in} - \dot{M}_{out}$.

Since the return flow increases electron density in the CENBOL temporarily, the spectrum is hardened in the high-count states or On states. As this excess matter is drained into the black hole, the light curves shows a low-count or Off state. The whole process can repeat again and again, though because of details of non-linear feedback from the wind results need not be strictly periodic. This is thought to produce a very interesting behavior in the light curve of at least one black hole candidate: GRS1915+105. If the accretion rate is not too high, the wind rate will be low for most of shock parameters, and such periodic cooling would not occur. This may be the reason, why other black holes which are known to have lower rates, do not exhibit as exotic light curve as GRS1915+105.

We thus notice that the spectrum in otherwise harder states are softened and softer states are hardened due to the presence of the wind and the return flows respectively. One bye-product of this is that the intersection point or the pivotal
Fig.5: Nature of the accretion and wind solutions in hard states (a) and in flare states when the sonic sphere is cooled by soft photons from the Keplerian disk (b). Part of the cooled flow separates as blobby jets and while the rest returns back to the accretion disk increasing the accretion rate temporarily.
point of the two spectra (of On and Off states) recedes to a much higher energy. This is precisely what is observed in the superluminal source GRS1915+105. Fig. 7 presents [44] spectra of three separate days of observations and compares them with the low and high spectra of 1997 March 26 (PID No. 20402-01-21-00) and of 1997 August 19 with (PID No. 20402-01-41-00) [46] respectively. The PID of the three RXTE observations are (a) 1997 June 18 (PID 20402-01-33-00), (b) 1997 July 10 (PID 20402-01-36-00) and (c) 1997 July 12 (PID 20402-01-37-01) respectively. It is very clear that in all these days, the pivotal point is much farther out compared to the the pivotal points created by Low and High states. This is a clear evidence that significant winds are present in Off states and a significant return flow is present in the On states.

In a recent paper, Dhawan et al. [50] presented a direct correlation between the RXTE-ASM X-ray data and the IR/Radio observations. If the CENBOL activity (activity which perturbs Comptonized photons) propagates along the jet and causes the Radio activity, then the radio activity at around 500AU made on 31st October, 1997 would be perturbed by CENBOL activity of around 28.5 October, 1997. This assumes that the perturbation propagates with 0.98c, the observed speed of the jet. However, no PCA data is available for 28th or 29th of October. Chakrabarti et al [44] compares the spectra of 30th October, 1997 (PID 20402-01-52-02) with the low state data of 25th of October, 1997 (PID 20402-01-52-00). Here, too a clear evidence of wind was seen.

If the wind is periodically cooled as described above, then, one would expect that the duration of the low-count state, during which the sonic sphere is being filled in with outflowing matter, be correlated with the QPO frequency. After all, location of the sonic sphere is proportional to the shock location [34,35] and QPO frequency is also related to the shock location (eq. 1). A careful analysis reveals [32] that the duration is inversely proportional to the square of the QPO frequency. Fig. 8 shows a log-log plot of these quantities (adapted from [32]) and the agreement
Fig. 7: Unfolded RXTE-PCA spectra of GRS 1915+105 obtained during the low and high states are compared with high-count states (On-states) and low-count states (Off-states) spectra during the irregular bursts observed on (a) 1997 June 18, (b) 1997 July 10, and (c) 1997 July 12. Histograms show fitted models. Because of softening of hard states and hardening of soft states, the pivoting occurs at a higher energy.

with this prediction is excellent.

TRIUMPH OF THE ADVECTIVE DISK PARADIGM

We conclude that when the inner boundary condition on the horizon is considered self-consistently, the advective flow solutions obtained for various flow parameters, with or without shocks, manifest themselves through various observable effects. Given the degree of richness of the nature of the solutions it would be unwise to simplify the study of accretion or jet processes into self-similar or other simplistic models. A flow has to have inner sonic points, centrifugal barrier and steady or non-steady shocks if ‘reasonable’ parameters are assumed. Hard X-rays are generated from the centrifugal pressure supported boundary layers (CENBOL) and not surprisingly, behavior of outflows and rates of outflows agree qualitatively with computed values (Eq. 2) if reasonable geometries are chosen. Even very strange behavior of low-count and high count-states of the oft-studied black hole candidate GRS1915+105 could be understood assuming jets are originated from the very inner region of the disk.

Since our solution is generic, results hold good for black holes of all mass. For massive black holes time scales go up proportionately and hence switching of spectral states or variabilities could not be studied as simply as in galactic black holes. Recent direct observations of the radio jets in the supermassive black hole candidate M87 suggests [48] that the width of the jet could be a few tens of Schwarzschild radii.
Fig. 8: Correlation between the duration of the low-count state and the QPO frequency for the black hole candidate GRS 1915+105 plotted in log-log scale [32].

near the origin. Multiwavelength correlation in outflows of GRS1915+105 [49–51] suggest that the same region which produces Comptonising photons also produce jets. These observations are sure signs that advective flow solutions which we have been proposing for over a decade could be the basis of all future studies.

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