

On the Formation of Accretion-powered Galactic and Extra-galactic Jets

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Abstract. Though widely observed to be emanating from a variety of astrophysical sources, the underlying physical mechanism behind the formation of galactic and extragalactic outflows is still enshrouded in a veil of mystery. In addition, it has not been possible to calculate accurately the amount of matter expelled in these events. In this article we present a *non-self-similar analytical model*, which, for the first time, we believe is able to explain the outflow formation phenomenon as well as compute the mass outflow rate by simultaneously solving the equations governing the exact transonic accretion and outflow. Our model predicts the dependence of this rate on various flow parameters as well as the *exact* location from where the outflows are launched.

Keywords: AGN-quasars - microquasars - jets - accretion, accretion discs - black hole physics - hydrodynamics - outflow - wind - shock-wave

1. Introduction

It is now a well established fact that Quasars and Microquasars suffer mass loss through outflows and jets (Mirabel & Rodriguez, 1999, Ferrari, 1998, Begelman, Blandford & Rees, 1984). These galactic and extra-galactic jet sources are commonly believed to harbour accreting compact objects at their hearts as the prime movers for almost all non stellar energetic activities around them including the production of bipolar outflows and relativistic jets. Unlike normal stellar bodies, compact objects do not have their own physical atmosphere from where matter could be ripped off as winds, hence outflows from the vicinity of these prime movers *have to be generated only from the accreting material*. So instead of separately investigating the jets and accretion processes as two disjoint issues around the dynamical centre of the galactic and extra-galactic jet sources, it is absolutely necessary to study these two phenomena within the same framework and any consistent theoretical model for jet production should explore the outflow formation only from the knowledge of accretion parameters. Also to be noted that while self-similar models are a valuable first step, they can never be the full answer, and indeed any model which works equally well at all radii is fairly unsatisfactory to prove its viability. Thus the preferred model for jet formation must be one which is able to select



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the *specific* region of jet formation. Keeping these basic facts at the back of our mind, we propose a *non self-similar analytical model* capable of self-consistently exploring the hydrodynamic origin of accretion powered jets/outflows emanating out from galactic and extra-galactic sources. Using this model it has been possible to simultaneously solve the accretion and wind equations to compute (from the first principle) what fraction of accreting material is being blown as wind and the exact location (distance measured from the central accretor) of the jet launching zone has been successfully pointed out.

Denoting \dot{M}_{in} and \dot{M}_{out} to be the instantaneous time rate of inflow and outflow around an accreting compact object, we define a quantity “Mass Outflow Rate ($R_{\dot{M}}$)” as the ratio of \dot{M}_{out} to \dot{M}_{in} , which is basically a measure of the fraction of barionic accreting material being expelled as outflows/jets. Our major aim was to compute the exact value of $R_{\dot{M}}$ in terms of *minimum* number of accretion parameters and to investigate the dependence of $R_{\dot{M}}$ on various flow parameters. We do our calculation for accretion with considerable intrinsic angular momentum (Disc-Outflow system, see §2 for detail) and for spherical/quasi-spherical accretion with negligibly small angular momentum (see §3 for detail).

Because of the absence of any matter donating real physical atmosphere around accreting compact objects, we first need to incorporate some virtual surfaces around these objects from where outflows may be generated. Formation of these surfaces are explained in §2.1 (for the disc-outflow system) and in §3.1 (for spherical/quasispherical accretion-outflow system).

In this article, we are basically interested in highlighting the conceptual ideas behind our model rather than presenting the mathematical details, thus we keep this article free from any formulae or equations. Interested readers may kindly refer respective works (Das, 1998, 1999, 1999a, 1999b, 2000, 2000a, Das & Chakrabarti, 1999 (DC99 hereafter)) for detail mathematical formalism.

2. The Disc-Outflow System

2.1. MODEL DESCRIPTION AND PRESCRIPTION FOR THE FORMATION OF OUTFLOW GENERATING SURFACE

We consider thin, axisymmetric polytropic inflows around a Schwarzschild Black hole in vertical equilibrium. We ignore the self-gravity of the flow and calculations are done using Paczyński-Wiita (Paczynski & Wiita, 1980) potential which mimics surroundings of the Schwarzschild

black hole. Considering the inflow to be polytropic, we explore both the polytropic and the isothermal outflow.

Due to the fact that close to the BH the radial component of the infall velocity of accreting material would be enormously high, viscous time scale would be much longer than the infall time scale and a rotating inflow entering into a black hole will have almost constant specific angular momentum close to the black hole for any moderate viscous stress (Das, 1998 and DC99). Though at the outer edge of the accretion disk the angular momentum distribution may be Keplerian or even super-Keplerian, matter would be highly sub-Keplerian close to the black hole to satisfy the inner boundary condition at the event horizon of the BH (see Chakrabarti, This volume and references therein). This almost constant angular momentum produces a very strong centrifugal force which increases much faster compared to the gravitational force and becomes comparable at some specific radial distance, location of which is easy to compute. Here, (actually, a little farther out, due to thermal pressure) matter starts piling up and produces the centrifugal pressure supported boundary layer (CENBOL). Further close to the black hole, the gravity always wins and matter enters the horizon supersonically after passing through a sonic point. Formation of CENBOL may be attributed to the shock formation in accreting fluid or to the maximisation of polytropic pressure of the inflow. In CENBOL region the flow becomes hotter and denser and for all practical purposes behaves as the stellar atmosphere so far as the formation of outflows are concerned. A part of the hot and dense shock-compressed inflowing material is then ‘squirt’ as outflow from the CENBOL. In case where the shock does not form, regions around pressure maximum achieved just outside the inner sonic point of the *inflow* would also drive the flow outwards. The outflow is shown to be thermally and centrifugally accelerated but is assumed to be confined by external pressure of the ambient medium. Subsonic outflows originating from CENBOL would pass through sonic points and reach far distances as in wind solution.

It is interesting to ‘visualize’ how the combined accretion-outflow system along with the central accretor would ‘look like’ in reality. In the following figure we attempt to illustrate the 3-D geometry of coupled disk-outflow system according to our model. **B** is the accreting Schwarzschild black hole while **C**’s represent the hot and dense CENBOL region. **D(K)** and **D(SK)** represent the thin Keplerian part and puffed-up sub-Keplerian part of the advective accretion disk respectively (measurements not in scale). Due to the axisymmetry assumption in accretion, two oppositely directed jet are expelled from the close vicinity of **B**. The inner and the outer surfaces of the outflow are the

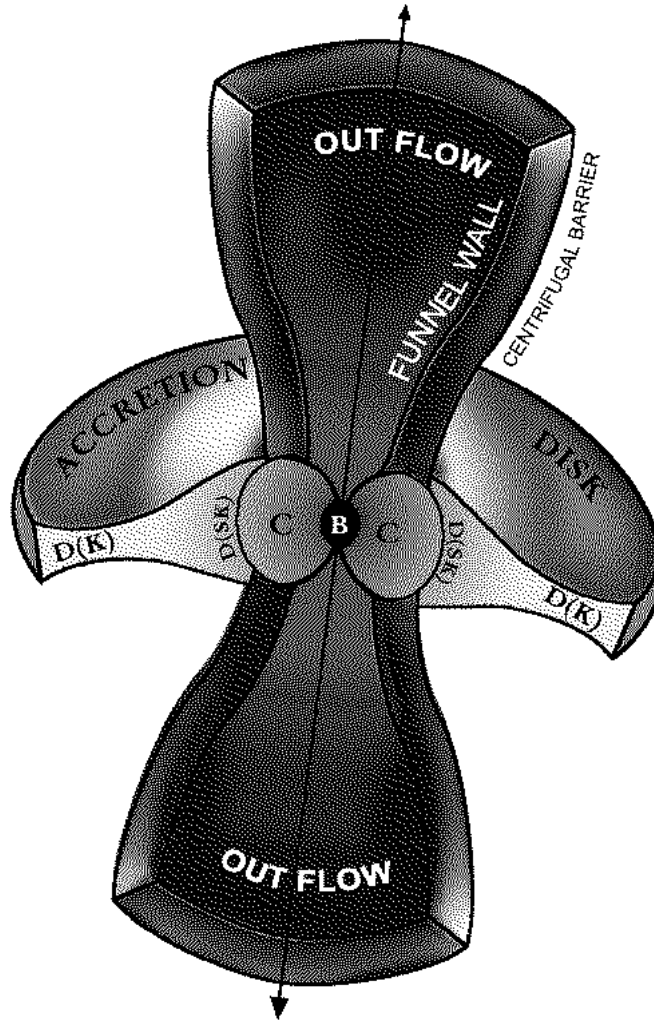


Figure 1. Multicomponent combined flow geometry in 3-Dimension.

funnel wall and centrifugal barrier respectively as explained in Das, 1998 and in DC99.

2.2. THE OVERALL SOLUTION SCHEME

Let us suppose that matter first enters through the outer sonic point and passes through a shock. At the shock, part of the incoming matter, having higher entropy density is likely to return back as winds through a sonic point, other than the one it just entered. Thus a combination of topologies, one from the region of accretion and the other from the wind region is required to obtain a full solution. In the absence of the shocks,

the flow is likely to bounce back at the pressure maximum of the inflow and since the outflow would be heated by photons, and thus have a smaller polytropic constant, the flow would leave the system through an outer sonic point different from that of the incoming solution. By simultaneously solving the proper set of equations in appropriate geometry (see Das, 1998, DC99 and Chapter 2.1 & 2.2 of Das, 2000a for detail solution scheme and flow geometry), we get the *combined* flow topologies (Fig 2. of DC99) where the value of $R_{\dot{M}}$ along with *all* other outflow parameters can be exactly computed only from the knowledge of the *minimum number of* accretion parameters namely specific energy (\mathcal{E}), specific angular momentum (λ), accretion rate (scaled in the unit of Eddington rate) (\dot{M}_{in}) and adiabatic indices (γ) of the flow. Also the dependence of $R_{\dot{M}}$ on *all possible* flow parameters has been investigated self-consistently (see Das, 1998 and DC99 for detail).

3. Outflows from Spherical/Quasi-spherical Accretion

3.1. THE OUTFLOW GENERATING SURFACE

For this class of accretion, absence of angular momentum rules out the possibility of formation of CENBOL. A novel mechanism is present in the literature (Kazanas & Ellison, 1986, Protheroe & Kazanas, 1983) where the kinetic energy of spherically accreting material has been randomized by proposing a steady, standing, collisionless, relativistic hadronic pressure supported spherically symmetric shock around a Schwarzschild black hole which produces a nonthermal spectrum of high energy (relativistic) protons. A fraction of the energy flux of infalling matter is assumed to be converted into radiation at the shock standoff distance through hadronic ($p - p$) collision and mesonic (π^\pm, π^0) decay. Pions generated by this process, decay into relativistic electrons, neutrinos/antineutrinos and produces high energy γ rays. These electrons produce the observed non-thermal radiation by Synchrotron and inverse Compton scattering. Shock accelerated relativistic protons are not readily captured by the black hole rather considerable high energy density of these relativistic protons would be maintained to make this shock self-supported (Protheroe & Kazanas, 1983). In this work, we take this pair-plasma pressure mediated shock surface as the alternative of the CENBOL from where the outflow could be launched.

Here we consider that a Schwarzschild type black hole quasi-spherically accretes fluid obeying polytropic equation of state. We also assume that for our model, the effective thickness of the shock is small enough compared to the shock standoff distance. We investigate polytropic as well as isothermal outflows from polytropic accretion.

3.2. THE OVERALL SOLUTION SCHEME

The *exact* value for the shock location and all relevant pre- and post-shock quantities can be computed in terms of \mathcal{E} , \dot{M}_{in} and γ . Now using the solution scheme as described for the disc-outflow system, the set of equations are simultaneously solved in proper geometry to get the combined flow topology for polytropic and isothermal outflows (see Das 1999, 1999a, 2000 for detail solution scheme and flow geometry) where R_M along with *all other* outflow parameters was calculated and its dependence on all flow parameters has been studied.

4. Some Important Results and Directions for Future Work

4.1. EXPLANATION OF QUIESCENT STATES OF X-RAY NOVAE

An interesting situation arises in our model when the polytropic index of the outflow is large and the compression ratio is also very high. In this case, the flow virtually bounces back as the wind and the outflow rate can be equal to the inflow rate or even higher, thereby evacuating the disk completely (see Fig. 6. of Das, 1998). These cases can cause runaway instabilities by rapidly evacuating the disk. It is possible that some of the black hole systems, including that in our own galactic centre, may have undergone such evacuation phase in the past and gone into quiescent phase. Thus our model could explain the quiescent states in X-ray novae systems like GS2000+25 or GRS1124-633 etc. (Tanaka, 1995, Ueda, et al, 1994) and also in some systems with massive black holes, especially the black hole at our galactic centre.

4.2. SPECTRAL PROPERTIES OF OUR GALACTIC CENTRE

We suggest that (Das, 1998, Das, 2000a, DC99) a possible explanation for extreme low luminosity and low radiative efficiency (upper limit on the mass accretion rate of $SgrA^*$ is of the order of $\sim 8 \times 10^{-5} M_{\odot} Yr^{-1}$, Bondi accretion rate on it has been approximated as $\sim 3 \times 10^{-5} M_{\odot} Yr^{-1}$ (Quartaert, Narayan & Reid, 1999 and references therein)) could be due to the presence of profuse mass loss from near vicinity of this source ($SgrA^*$). We have obtained that for such a low accretion rate as that of has been observed for $SgrA^*$, the mass outflow rate is exorbitantly high, almost to the point of evacuating the disk, which prompted us to strongly speculate that the spectral properties of our galactic centre could be explained by inclusion of wind using our model.

4.3. OUTFLOW DRIVEN CONTAMINATION OF METALICITY TO THE OUTER GALAXIES

A number of observational evidences suggest that the fluid accreting onto black hole has potential to generate appropriate temperature which supports significant nucleosynthesis to take place in accretion disks around black holes (Mukhopadhyaya & Chakrabarti, 1999 and references therein). It is interesting to investigate whether the fate of the shock induced nucleosynthesis generated heavier elements could be predicted by our disk-outflow model. One of the major speculations of our model (Das, 1998, DC99 and §5.1 of Chapter 2.2 of Das, 2000a) that outflows from the hot and dense CENBOL (where the composition change is much more significant) would carry away modified compositions and contaminate the atmosphere of the surrounding stars and galaxies in general. Strong indications of disk-evacuation by wind for some region of parameter space suggests (Das, 1998, DC99) that overall such contributions to metallicity must not be neglected. Significant work in this direction is in progress and is expected to be reported in near future (Das, in preperation).

Acknowledgements

I would like to thank the LOC of this workshop and my special thanks goes to Prof. A. Castro-Tirado for providing the local and International travel hospitality.

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