Status of the accretion flow solution in the Golden Jubilee year of the discovery of extra-solar X-ray sources

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Abstract. Fifty years have just passed since the first discovery of the extra-solar X-ray sources by Giacconi and his team which we know today to be some stellar mass black holes. By 1973, not only a catalog of these enigmatic objects were made, and their spectra were obtained. Today, forty years have passed since the revolutionary idea of the thin, axisymmetric, Keplerian, disk model by Shakura and Sunyaev was published. Yet, the complete predictability of their radiative properties remains as illusive as ever. The only available and self-consistent solution to date is the generalized viscous transonic flow solutions where both heating and cooling effects are included. I demonstrate that the latest 'Avatar' of the accretion/outflow picture, the Generalized Two Component Advective Flow (GTCAF), is capable of explaining almost all the black hole observational results, when the results of the time dependent simulation of viscous and radiative processes are also taken into consideration. I also discuss the problems with predictability and argue that understanding companion's behaviour in terms of its habit of mass loss, ellipticity of its orbit, magnetic properties, etc. is extremely important for the prediction of emission properties of the accretion flow.

Keywords : black hole physics – accretion, accretion discs – hydrodynamics – X-rays: binaries

1. Introduction

Fifty years ago, the subjects of the physics of stellar mass black holes and the Super-Massive black holes started (e.g., Gioconni et al., 1967; Markert et al., 1973; Schmidt, 1971; Bahcall, Bahcall and Schmidt, 1973 and references therein) By 1973, the thin accretion disk model of Shakura & Sunyaev (1973, hereafter SS73; and Novikov &

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Thorne, 1973) was proposed, not only to explain the soft-Xray bumps in stellar systems, but also the big-blue-bump in ultra-violet region in Quasars and Active Galaxies. The euphoria that the subject is almost closed disappeared soon with the discoveries of instabilities associated with the SS73 disks (Eardley & Lightman, 1974) and with power-law high energy X-rays in stellar mass objects (Sunyaev & Truemper, 1979; Chakrabarti, 1996a; 2008 and references therein). With the launching of the RXTE satellite, the time variation of spectral and timing properties of several black hole candidates were revealed and it became clear that the focus must be to understand the accreting system as a whole, and not parametrically on a case by case basis. The solutions of governing equations which make minimal assumptions survive the test of time and thus one requires to sharpen these theoretical solutions having maximum possible flexibility, while still remaining the solutions of the governing equations. It is with this spirit, the two component advective flow (TCAF) solution by Chakrabarti & Titarchuk (1995, hereafter CT95) was presented to the community which combines the theory of viscous transonic flow (Chakrabarti, 1990a) with the radiative properties of an electron cloud (Sunyaev & Titarchuk, 1980, 1985).

Though it was known that the flows on a black hole should be transonic in nature, Chakrabarti (1989, 1990a) firmly established that if one wants to completely explain the black hole astrophysics, i.e., both spectral and temporal properties, one must live with an ugly feature of the transonic accretion flow – a major part of the parameter space spanned by energy, angular momentum and viscosity, would force the flow to have a centrifugal pressure supported shock wave inside the disk. Unfortunately, this fact is difficult to digest by minds which, albeit irrationally, believe in simpler pictures, very much like workers who believe in a flat earth or a steady state Universe even in the presence of inundated evidences to the contrary. To make the matter worse, Chakrabarti and his collaborators (Molteni, Sponholz & Chakrabarti, 1996, hereafter MSC96; Chakrabarti, Acharyya & Molteni, 2004, hereafter CAM04; Garain, Ghosh & Chakrabarti, 2013, hereafter GGC13) firmly established that when the solution is allowed to be time-dependent the parameter space is further extended to include oscillating shocks in the disk. Explanation of both the spectral and temporal properties by a single theory, which is inevitable in any subject, thus became a reality (Debnath, Mondal & Chakrabarti, 2013a; Debnath, Chakrabarti & Mondal, 2013b). We are thus truly looking at the light at the end of the long tunnel that opened half a century ago. Everyday, evidences are piling up that the accretion flow indeed has two active components (e.g., Smith et al., 2001, 2002, 2007; Cambier & Smith, 2013).

This present brief review is to support these tall claims with some examples. In the next Section, I describe the building blocks of a generalized transonic flow which have been rigorously established. In Section 3, we give a summary of the flow behaviour. In Section 4, I present a discussion of predictability of the TCAF solution. Finally, in Section 5, we draw our conclusions.
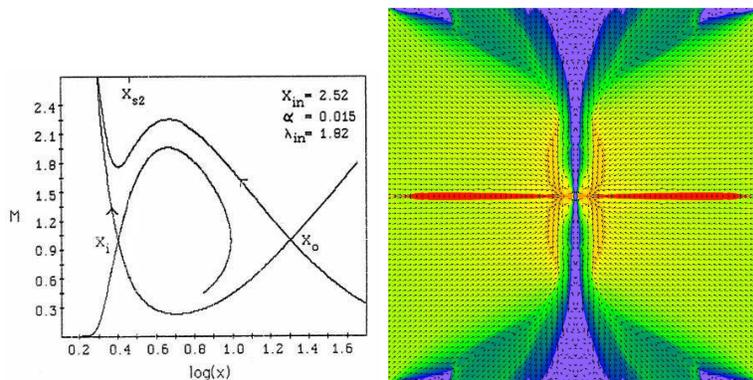
Figure 1. (a) (left) An example of the topology with the critical viscosity parameter α_{in} which separates the parameter space. For $\alpha < \alpha_{in}$ the flow can have shocks and for $\alpha > \alpha_{in}$ the flow will be a Keplerian disk passing through the inner sonic point Chakrabarti (1990a). In (b), (right) we show the formation of TCAF with $\alpha > \alpha_{in}$ Keplerian disk on the equatorial plane, and $\alpha < \alpha_{in}$ sub-Keplerian halo away from the equatorial plane (Giri & Chakrabarti, 2013).

2. Building blocks of GTACF around a black hole

Here are a few major building blocks which are responsible for the observed spectral and temporal properties of the flow. We briefly discuss them.

2.1 The existence of a critical viscosity

The most important of all is the discovery that there exists a critical viscosity above which the solution will not allow a steady shock wave in the flow and below that, a standing shock wave would be present. Figure 1a shows the Mach number (Y-axis) vs. radial distance (X-axis) for a viscous isothermal flow for illustration (Chakrabarti, 1990b). The inner sonic point (X_{in}), the sound speed (K) and the SS73 viscosity parameter α are marked inside the Figure. Here, the solution passes through both the inner and the outer sonic points. This viscosity parameter α_{in} is the critical parameter in this case. When $\alpha < \alpha_{in}$, the flow has a shock wave solution. For $\alpha > \alpha_{in}$ the flow simply becomes a Keplerian disk entering into a black hole through the inner sonic point. Details of the critical parameters for other models may be seen in Chakrabarti (1996b), Chakrabarti & Das (2004) and Das & Chakrabarti (2004). The numerical simulations to demonstrate this is in Lanzafame, Molteni & Chakrabarti (1997) and Giri & Chakrabarti (2012).

A ramification of this critical viscosity is that when the black hole accretes a low-angular momentum flow and there is a sudden surge of viscosity the flow quickly transports angular momentum, and enters into the black hole as a Keplerian disk. However, above a certain height from the equatorial plane, the flow may still have a lower viscosity, and thus will produce a shock wave. In other words, the flow would be divided into two components (CT95, Chakrabarti, 1996b; Chakrabarti, 1997). This is the well studied Two Component Advective Flow (TCAF) solution. Recently, Giri &

Chakrabarti (2013) showed that this configuration is indeed stable. Thus the spectral studies of CT95 are realistic. Figure 1b shows the configuration formed by Giri & Chakrabarti (2013, hereafter GC13) through numerical simulations. The equatorial plane has a Keplerian disk and the sub-Keplerian halo surrounds it. CENtrifugal pressure supported BOundary Layer or CENBOL is also formed.

2.2 The existence of a resonance oscillation of the shocks

MSC96 and CAM04, using power law cooling, and more recently, GGC13, using Compton cooling showed that when the infall timescale from the post-shock flow 'roughly' matches with the cooling time scale, the shock oscillates with a frequency which is inverse of the infall time scale from the shock to the inner sonic point. Oscillation of the shock wave may occur when the Rankine-Hugoniot condition is not fulfilled, and yet there are two physical sonic points in the flow (Ryu, Chakrabarti & Molteni, 1997). While these oscillations are robust, more studies are to be carried out for other cooling effects (such as synchrotron radiation), non-axisymmetric flows etc. (Chakrabarti, 2006).

2.3 The outflows originating from post-shock region

A quantitative measurement of the outflow rate was made by Molteni, Lanzafame & Chakrabarti (1994). Later, in Chakrabarti (1998, 1999); Das & Chakrabarti (1999); Das, Chattopadhyay, Nandi & Chakrabarti (2001) and Singh & Chakrabarti (2011), the ratio of outflow to inflow rate was obtained by purely theoretical means. It was observed that a few percent of the inflow leaves the system as an outflow and hotter the post-shock region is, or higher the angular momentum is, higher is the ratio. This outflow was found to be partly or totally quenched as the accretion rate of the Keplerian rate goes up (Garain, Ghosh and Chakrabarti, 2012).

3. The generalized TCAF solution

Figure 2 shows schematically all the components of a generalized TCAF solution (GT-CAF) which traces most of the matters' journey from the companion to the black hole and the rest towards forming the jets. The high viscous Keplerian disk is immersed inside a low angular momentum halo component. For all practical purposes, CEN-BOL is the boundary layer of a black hole, except that instead of being supported by a hard surface, it is supported by a centrifugal barrier. The steady jets and outflows in this picture are produced primarily from CENBOL. The CENBOL and the base of the Jet (pre-Jet) is also the so-called Compton cloud which intercepts soft-photons from the Keplerian disk and re-radiates them after Comptonization. The jets are accelerated by combinations of the hydrodynamic, magnetic and radiative forces (Chattopadhyay, Das & Chakrabarti, 2004). The collimation is possibly done by the toroidal field lines which are ejected from the disks due to buoyancy effects (Chakrabarti & D'Silva, 1994). The disks may not have a constant accretion rates at all radii, especially in the Keplerian disk, since the matter supply from the companion may vary in the orbital and viscous time scales.
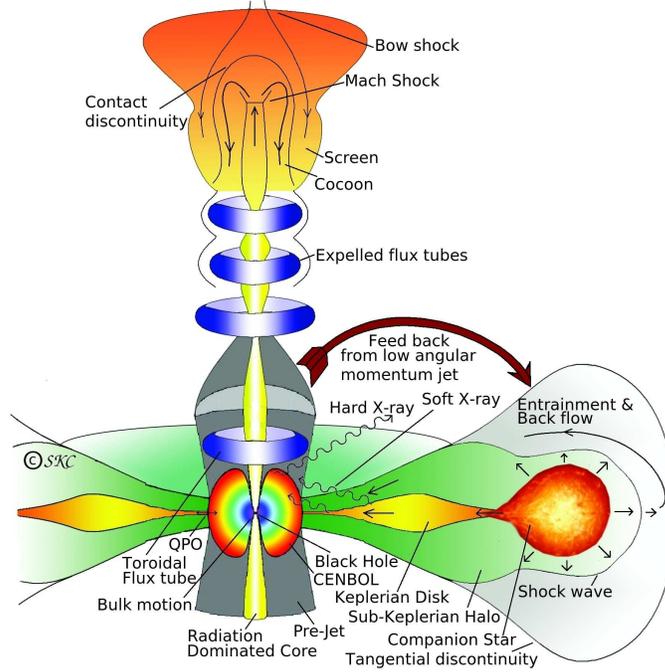
Figure 2. Generalized TCAF with CENBOL, Keplerian and sub-Keplerian flows and the pre-Jet configuration gives the whole scenario which includes the companion star and double jets. The schematic diagram is roughly in logarithmic scale in both directions and different relevant components are zoomed in to show details.

In the case of outburst sources, fitting of the data with a TCAF solution suggests that the main cause could be the sudden rise in the viscosity at the outer boundary (perhaps due to magnetic activities of the companion star, matter accumulation at the outer edges). As long as the viscosity is high enough, the rising phase persists. During the intermediate phases (Nandi et al. 2012, Debnath et al. 2013c), the viscosity remains moderately high. Declining phase starts only when viscosity starts to decrease.

In the TCAF, the low angular momentum matter may be supplied in many ways: First of all, the stars will have winds which may produce shocks all around to satisfy the boundary condition that the ambient medium is stationary. These shocked flow could be be directed to the central black hole. Since they are coming from spherically symmetric (in the frame of the companion) flow, they would have very low angular momentum. Another possibility is to have a part of subsonic pre-jet and outflow (which are formed out of very low angular momentum of the inner CENBOL region) returns back to the equatorial plane at a larger radii and falls back to the black hole. Similarly, magnetic field of the companion, if entangled with the outer disk, could not only remove angular momentum from a Keplerian disk there, it would bring sub-

Keplerian matter from the stellar pole to the outer disk. It requires a complete numerical simulation to establish the complete scenario.

4. Predictability of TCAF solution

Since TCAF is the more general solution, in the appropriate limit, it will have the same predictability as those of the Shakura-Sunyaev disk (Shakura & Sunyaev, 1973), or a thick accretion disk (Paczy'nski & Wiita, 1980) or a radiatively inefficient transonic flows (Chakrabarti 1989). No solution is expected to have a predictability more than a fraction of the orbital time of the companion. TCAF requires outer boundary condition and these are not properly known. However, given such boundary values of disk and halo rates, TCAF is capable of predicting several observations. We present some examples due to sort of space.

A. Spectral state transition

In a TCAF, the relative importance of the soft photon source (accretion rate of the Keplerian disk) and the hot electrons (rate of the low angular momentum matter) decides whether the CENBOL could be cooled or not. If yes, it would be a spectrally soft state, otherwise it would be a spectrally hard state. In CT95 and Ebisawa et al. (1996) paper, it was shown that the energy spectral index α in hard state is insensitive to the optical depth of the CENBOL. At a disk rate of around Eddington rate, the sensitivity α on disk rate is very high and the transition to soft state is very rapid. Meanwhile, as CT95 showed, the spectral index due to the Bulk Motion Comptonization is dominating. There is a regime when broken power law spectra could be seen, though, at a very high disk rate ($\dot{m}_d \gg 1$) the spectrum will have a power-law slope corresponding to the bulk motion. Spectra of Cyg X-1 is fitted very well (Chakrabarti & Mandal, 2006) when synchrotron photons along with shock accelerated electrons also participate in the process. Similarly, the spectra of supermassive black hole M87 also fitted well using TCAF solution (Mandal & Chakrabarti, 2008). So far, TCAF has been implemented in XSPEC without taking the bulk motion Comptonization (BMC) into account. Hence better fits are obtained for harder states (Debnath et al. 2013ab). The BMC is being incorporated. Fitting of the spectral data is possible with the TCAF solution. So far, TCAF has been implemented in XSPEC without taking the bulk motion Comptonization into account. Hence, better fits are obtained for harder states. Five parameters, namely, the accretion rates of the disk, halo, shock location, compression ratio and the mass of the black hole are extracted out of the XSPEC fit. TCAF is the only solution in which spectral fits yield temporal behaviour, since the shocks which fit the spectra also produce QPOs. For details, see (Debnath et al. 2013ab).

B. Energy dependence of QPO behaviour

Since the TCAF solution shows that QPOs are formed due to the oscillation of the Compton cloud (CENBOL), only Comptonized photons are supposed to take part in QPOs. Thus, TCAF predicts that the power in QPO oscillation should be very low for the photons coming out of a Keplerian disk, but the power would be higher for

the photons which are Comptonized. However, too many scatterings will increase the energy but will reduce coherency of oscillations (Chakrabarti & Manickam, 2000).

C. QPO frequency and resonance condition

Since the CENBOL cools down and moves in when the Keplerian rate is increased, the QPO frequency should go up accordingly (MSC96, Chakrabarti & Manickam, 2000; Chakrabarti et al. 2008; Debnath et al. 2013c). Typically,

$$\nu_{QPO} \sim t_{infall}^{-1} \sim \frac{\sqrt{GM_{BH}}}{Rf_t(X_s)^{3/2}}\text{Hz}, \tag{1}$$

where, X_s is the shock location in Schwarzschild radius, R is the compression ratio (ratio of post shock density and pre-shock density), G is the gravitational constant and M_{BH} is the mass of the black hole. This can be rewritten as,

$$\nu_{QPO} = 18.5 m_{10}^{-1} f_{t,3}^{-1} r_4^{-1} X_{s,10}^{-3/2}\text{Hz}. \tag{2}$$

Here, m_{10} is the mass of the black hole in units of $10M_\odot$, r_4 is the compression ratio in units of 4, $X_{s,10}$ is the shock location in units of $10r_g$. Here, we have introduced a factor f_t which reduces the infall velocity due to the centrifugal pressure induced turbulence inside the CENBOL. A reasonable guess would be $f_t \sim \lambda^2$, where λ is the dimensionless angular momentum. $f_{t,3}$ is in units of 3. The QPO frequency goes up as the shock location goes down.

After making simplified assumptions, and computing cooling time scale assuming a constant enhancement factor $\mathcal{E} = 20$, injected soft photon energy $e = 0.5\text{keV}$ and the shock to be in vertical equilibrium, one can show that the ratio of the cooling and the infall time scale is,

$$\frac{t_c}{t_{infall}} = 0.4\dot{m}_{18}^{1/4} X_{s,10}^{-9/4} \mathcal{E}_{20}^{-1} e_{0.5}^{-1}. \tag{3}$$

Here, we chose the mass the black hole to be $10M_\odot$, $\gamma = 4/3$ to be the adiabatic index of the flow, $R = 4$ is the compression ratio of the gas at the shock. $\mathcal{E}_{20}$ is the average factor by which the injected photon energy is enhanced on an average as is in units of 20. It can vary from $E_{20} \sim 1$ (very soft state), to ~ 40 (very hard state). Either way, when the ratio is off balanced from ~ 1 and the low frequency QPOs would not be seen. This little exercise shows the power of TCAF solution. It directly shows that timing properties are spectral properties are connected through the shock location. It also predicts how QPO frequency would become higher on a daily basis as the shock location moves towards the black hole in a outburst source (Eq. 1). For AGNs, the ratio will (Eq. 3) will not be close to 1 when Compton cooling is used. In that case bremsstrahlung cooling could cause QPOs (MSC96). Figure 3, taken from GGC13 shows how the QPO frequency increases with the accretion rate of the Keplerian disk. This behaviour is observed in the rising phase of the outburst sources. Indeed, the fit of QPO frequency with time is acceptable enough so that from the first three to four days of data, one could predict the QPO frequency variations in the next several days – which is impossible by any other model.
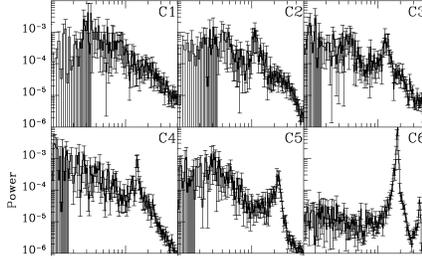
Figure 3. Demonstration of increasing QPO frequencies when the disk rate is increased. This result comes totally from a time dependent hydrodynamic simulation coupled with the Monte Carlo simulation of Comptonization. See, GGC13 for details.

5. Concluding remarks

In this article, we presented briefly the current status of solution onto black holes. It is to be noted that this solution was presented *before* the RXTE was even launched. It turns out to be very promising, as it can satisfactorily explain the state transitions as far as the spectral properties go, and timing properties such as low frequency QPOs and their time variation during the outbursts. To our knowledge, no other solution has as much predictability. However, as we pointed out, the biggest problem is the poor knowledge of the boundary condition for solving the differential equations which govern the flow. As shown in Fig. 2, ideally, one needs to treat "matter supply - accretion flow - jet" as a single physical system. However, the companion's property could be erratic. The mass transfer rate could vary with phase, stellar magnetic cycle, X-ray irradiation, inclination of the companion's spin axis etc. If the orbit is elliptic this should be imprinted on long term count rate variation. Entangled magnetic field may also remove angular momentum from the accretion disk, supplying the halo with low angular momentum matter. Nevertheless, we can assume that in a short time span (as compared to the orbital time of the binary), the conditions at the outer boundary may remain the same (rate and its derivative). Thus we may extrapolate the results successfully using TCAF in near future and near past of an observed event. Because of this, the variability class transitions of GRS 1915+105 is also very much unpredictable. Fortunately, one parameter which is defined to be the Comptonization efficiency (CE) (ratio of the power-law photons number and the black body photon number) has been found which mixes the properties of the two flow components. When Compton efficiencies are plotted against variability classes so that observed transitions take place among nearest neighbours, CE becomes a monotonically increasing straight line, lowest CE being for the softest class. (Pal, Nandi & Chakrabarti, 2013). This CE is the dynamic hardness ratio valid for all black hole candidates.

Acknowledgements

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