Advective Flow Paradigm And Microquasar GRS1915+105

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Abstract. Advective accretion disks and winds are the most self-consistent solutions today. We describe this paradigm briefly and show how it attempts to explain some of the interesting observations of the galactic microquasar GRS1915+105.

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1. Introduction

The standard accretion disk model of Shakura and Sunyaev (1973) was modified immediately after it was proposed. The spectrum of black hole candidate Cyg X-1 showed (Sunyaev and Trümper, 1979) that apart from the modified cool black body spectrum, it also exhibits a power-law emission at much higher energies, indicating the presence of electrons much hotter than a standard disk. Subsequently, Sunyaev and Titarchuk (1980) showed that the power-law emission is the result of the Comptonization of soft photons from a standard disk by hot electrons whose source was thought to be outside the standard disk, be it in the form of floating ‘Compton clouds’ or ‘magnetic corona’.

Meanwhile, transonic flow models were developed in the early eighties (Muchotrzeb and Paczyński, 1982, Matsumoto et al. 1984) to modify inner edge of the standard disk to ensure that it passes through a sonic point. These solutions ensure that the specific energy of the flow remains negative as in a Keplerian disk. However, there is another class of transonic disk solutions which are the generalizations of the classical Bondi (1952) solutions when angular momentum, viscosity, heating, cooling etc. were taken into account. These are known as advective flow solutions (Chakrabarti, 1990, 1996a, 1998ab, 2000a). Particularly interesting is that these solutions did away with the external Compton clouds as the inner sub-Keplerian region itself is found to behave like one for all practical purposes.

In this review, I briefly present these solutions for viscous and non-viscous flows. The solutions can be suitably combined to obtain a paradigm of the black hole astrophysics. Truly speaking, a cool, Keplerian disk with a negative energy cannot smoothly join to most of
these steady solutions which require positive energy (at least in quasi-adiabatic flows). For time-dependent flows such restrictions do not apply. In fact, steady transition from a Keplerian disk to an advective disk may require systematic heating of a Keplerian disk or the assumption that all disks are fundamentally non-steady, only the time scale varies. We also try to explain some of the observed features of the galactic micro-quasar GRS1915+105. We find that it always helps to keep a paradigm in the back of one’s mind while attempting to explain any observations. Otherwise, each observational feature would demand a separate ‘model’ which may or may not fit with the global solutions of accretion and winds.

2. Advective Flow Paradigm

2.1. Hydrodynamic and Magnetohydrodynamic Flows

Though most of the literature concentrates on disks and jets separately, it is advisable (and economical) to study them simultaneously. This is because in global studies, always both types of solutions appear together. Examples are Bondi (1952) and generalized Bondi solutions (Chakrabarti, 1990; 1996bc). Numerical simulations have also shown outflows in much of the region of the parameter space (Molteni, LanzaFame & Chakrabarti, 1994 [MLC94]; Molteni, Ryu & Chakrabarti, 1996 [MRC96]; Ryu, Chakrabarti & Molteni, 1997 [RCM97]). Figure 1 shows the broad classification of all possible steady, inviscid solutions of advective disks (adapted from Chakrabarti, 2000a). Solutions shown are obtained for inviscid adiabatic flows (Chakrabarti 1989, 1996b) but they remain valid close to the black hole even when these conditions are relaxed. One important aspect which requires emphasizing is the presence of a centrifugal pressure supported boundary layer (CENBOL) in some of these steady solutions and in most of the non-steady solutions! Rapid inflow keeps the angular momentum to an almost constant value. Thus, centrifugal force becomes a dominant force. It slows downs matter in this barrier, heats them up so that hard X-rays could come out and finally drives hot matter perpendicular to the disk to form outflows. The barrier even oscillates with a large amplitude if conditions are right (Molteni, Sponholz & Chakrabarti, 1996; RCM97) thereby giving rise to quasi-periodic oscillations of X-rays. Beside each solution in Fig. 1 schematic picture is given of accretion and outflows. Inward and outward pointing arrows indicate accretion wind solutions respectively. In (A) and (a), low energy and low angular momentum flow behaves like a conical Bondi inflow and Parker type winds well
known in solar physics. In (B) and (b), a steady shock does not form, the inflow becomes hotter due to slowing down at the centrifugal barrier. Numerical simulation shows that an oscillating shock forms (RCM97) which is accompanied by a non-steady outflow. In (C) and (c), the steady inflow solution has a standing shock. This has been tested by numerical simulations (Chakrabarti & Molteni, 1993 [CM93]; MLC94; MRC96). Positive energy outflow is also found to be steady. In (D) and (d), the inflow passes through an inner sonic point, but the outflow forms a steady shock (CM93). In (E) and (e), no shock is possible in the steady solution though there are three sonic points and we feel that non-steady shocks would form. In (F) and (f), both the inflow and the outflow have no shocks, and energetic steady solutions are present as both pass through the inner sonic point. In (G) and (H), solutions are incomplete since they are not from infinity to the horizon. Thus, no steady solution is possible. Simulations (Ryu and Chakrabarti, 1996) indicated that flow is highly unsteady in these cases which are schematically shown in panels (g) and (h) respectively. Especially interesting is the solution of O*, where disks could be ‘thick’ not because of gas or radiation pressure, but because of turbulent pressure. Solutions from (g) are with negative energy.

When viscosity is present, closed topologies open up to join with Keplerian disks and when heating (such as magnetic, viscous) flow from a Keplerian disk can pass through shocks and sonic points (Chakrabarti 1990, 1996, 2000a). For instance, solutions in (C) become similar to those of (I) and (i) while those in I* become similar to those of (J) and (j). These solutions are the backbones of the advective disk paradigm and are useful in obtaining complete solutions of the disk/jet systems. When magnetic field is added, the flow passes through the fast and the slow magnetosonic point and the Alfvén point. Possible outflowing solutions with or without shocks have been presented in Chakrabarti (1990). It is likely that in some regions of the parameter space, these magnetohydrodynamic shocks should also show oscillations.

2.2. Effects of Radiative Transfer

Fully self-consistent two temperature flow in the advective disks was studied very recently. Chakrabarti & Titarchuk (1995) computed temperatures of electrons and ions for various accretion rate parameters in the CENBOL region and found that for high Keplerian rate CENBOL cools down completely and shock disappears. Soft photons intercepted by CENBOL are reprocessed by hot electrons to produce hard X-rays which are observed as a power-law tail in the hard states. In soft states, the hard tail is formed due to bulk motion Comptonization.
Figure 1. Nature of the solutions (Mach number along Y-direction and logarithmic radial distance along X-direction) of inviscid (A-H) and viscous (I-J) advective disks. Schematic flow behaviour of these solutions in meridional plane are shown in (a-j). Shock locations (C, D) and incomplete solutions (G, H) are indicated by puffed up (c, d) and turbulent regions (g, h) respectively. Solutions with three sonic points having no steady shock are shown oscillating with arrows at both ends (b, e).

Hot CENBOL drives outflows from the disk along the vertical axis. When the outflow rate is very high, the sonic sphere (i.e., region of the wind till its first sonic surface) becomes dense enough to cool down due to Comptonization by the soft photons from the Keplerian disk. Estimation of the rate of wind generation (Chakrabarti 1998ab, Chakrabarti 1999a) shows that in purely soft states no outflow is possible and in purely hard states, outflow is very small. Thus above mentioned cooling
of the sonic sphere is not possible. When compression ratio of the shock is intermediate, outflow rate is significant.

After the sonic sphere is cooled sonic surface comes closer to the black hole and matter below it returns back to the disk, while matter above it separates as blobs. Thus blobby jets are expected in this intermediate states (this may also be called flare/quiescence or On/Off transition states). The return flow acts as a feedback on the already accreting flow and the count rate undergoes very interesting behaviour. Fig. 2 (Chakrabarti, 2000b) shows how the ratio \( R \) of the outflow rate \( \dot{M}_{\text{out}} \) and the inflow rate \( \dot{M}_{\text{in}} \) assumed to be proportional to \( 1/R^2 \); \( R \rightarrow 1 \rightarrow \) soft state; \( R \rightarrow 7 \rightarrow \) hard state) depend on the compression ratio \( R \) of the gas at the shock. This clearly shows that there is a distinct relation between the spectral states and the outflow rate.

An important characteristics the spectrum should show is that spectral slopes of the power-law component should be harder in soft states and softer in the hard states. This is because, in the hard states, outflows from CENBOL reduced electron density but the soft-photon intensity from the pre-CENBOL flow remains the same. This softens the spectra in hard states (Chakrabarti, 1998c). Similarly return flow hardens the spectrum. A corollary of these effects is that the pivotal point of the power-law tail shifts to a larger energy in presence of winds/return flows.
3. Explanations of Observational Aspects of GRS1915+105

GRS1915+105 exhibits very intriguing light curves. Belloni et al. (2000, hereafter B00) divided them into twelve types. They draw HR1 vs HR2 diagrams where HR1=B/A and HR2=C/A (A:2-5keV, B:5-13keV, C:13-60keV). Color-Color diagrams showed very intricate structures (shapes of atoll, banana, etc.). If the pre-shock flow is indeed the source of the soft photons, photons originating in (0-3) keV range should be roughly proportional to the Keplerian accretion rate. Thus, photon number may show time variation (due to periodic changes in the 'accretion rate' due to return flow mentioned above). However, no QPO should be seen from these photons. Chakrabarti & Manickam (2000, hereafter CM00) demonstrated this (see also, Rao et al. 2000). The harder photons ($E > 3$ keV) would usually come from the post-shock flow. Since the spectra intersect at around 17keV, and for $E > 17$keV, photon number is not large, we make our choice of A, B and C to be in ranges of (0−3) keV, (3−17) keV and (17−60) keV respectively (B and C would be related to sub-Keplerian rate). According to our paradigm, roughly speaking, A, B and C should be proportional to each other (since B and C are produced by interception of soft photons measuring A. Of course, soft X-ray absorption makes matter more complex.) and whenever hardness or softness ratios are plotted basically straight lines are expected, instead of Atoll, Banana and Z shapes. The results are presented in Nandi et al. (2000a) and the details of the physical interpretations are presented in Manickam et al. (2000).

One important conclusion of Belloni et al. (2000) was that the disk apparently has three states: A (low rate and low HR1, HR2), B (high rate, high HR1) and C (low rate, low HR1, variable HR2 depending on length of the event). It seems that the State C exhibits QPO. State A and state B do not exhibit QPO. More interestingly, except for $C \rightarrow B$ transition, all other transitions of states are allowed. Nandi et al (2000b) found evidence of QPO in some of the State A light curve.

As discussed in Chakrabarti (2000ab) there are practically four distinct ways that the solutions in Fig. 1 could be combined for a realistic accretion-wind system. If the accretion rate is very low and shock does not develop, QPO may not be seen. In GRS 1915+105 we need not be concerned with this type of flow. The remaining three are shown in Fig. 3 (Chakrabarti et al. 2000a). If the shock develops, QPO would be seen but wind may be negligible or absent depending on the compression ratio of the shock. The object would be in State C of B00 or hard class of Nandi et al. (2000). If the accretion rate is generally increased, shock is weakened (compression ratio goes down), and in the intermediate state, burst/quiescence or On/Off may be seen. There could be two
types of ‘On’ states (State A and State B of B00). After the winds of State C fills in the sonic sphere and cools it down by Comptonization, CENBOL and the region till the sonic sphere collapse. This is the State A of B00. Now there are two possibilities (Chakrabarti, 1999b) either the flow separates completely as a blob and returns to State C or the flow mostly return back to the accretion disk and enhances the accretion. This would be the State B of B00. This may in turn increases the outflow (see, Fig. 2). But shock itself is getting weakened because of post-shock cooling, hence the outflow is very mild, but may be in a threshold so that a bit more outflow can cause the sonic sphere to collapse again. Thus, occasional trips to State A from State B is possible. Once enhanced matter is drained out and the shock bounces back to roughly the original location (compatible with its specific energy and angular momentum) State C forms again. Since State C produce fewer soft photons, State B is not directly possible from State C without first producing return flow and enhanced accretion. This may explain why a transition from C to B is difficult.

Among other confirmations of our paradigm, we note that Nandi et al. (2000b) demonstrated that the spectral slopes of GRS 1915+105 are hardened by enhanced accretion and softened by return flows. CM00 found that the duration of the Off states strongly depend on QPO frequency. Dhawan et al (2000) observationally demonstrates that jets originate from what we term CENBOL region.

4. Concluding remarks

Advective disk paradigm being made up of the most complete accretion disk/wind solutions, it is not surprising that most of the observations...
could be explained by this paradigm. However, our explanations of the light curves of GRS 1915+105 have been over simplified since we ignored the effects of magnetic fields altogether. Apart from a new spectral component due to synchrotron radiation and perhaps increasing the outflow velocity to a much larger value, no other effect is expected as far as our State description is concerned.

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