Bull. Astr. Soc. India (2002) 30, 125–134

Advective Flow Paradigm of Disks and Outflows Around Black Holes

Sandip K. Chakrabarti

S.N.Bose National Centre for Basic Sciences, Salt Lake, Calcutta 700098, India
and
Honorary Scientist, Centre for Space Physics, 114/v/1A Raja S.C. Mullick Rd. Kolkata 700047

Abstract.
For the past fifty years, accretion process is being studied initially on normal stars and later, on compact objects, such as black holes and neutron stars. In this Review, I present the modern development of this subject and show that the advective disk paradigm comprises the most complete solution presented so far. I discuss predictions made by this paradigm and how the observations support these predictions.

Key words: accretion - outflows - black hole physics

1. Introduction

The study of accretion and winds on central objects has taken a full circle recently when accretion and outflow physics were combined to a single paradigm called *advective disk paradigm* (see, Chakrabarti, 2000 for a recent review). It may be recalled that the Bondi solution (1952) of spherical flow included accretion and winds (later known as Parker winds [1960] in the context of outflows from solar surface). The advective disk paradigm incorporates accretion and outflows within the same framework, but unlike in a Bondi flow, here one includes angular momentum, viscosity, heating/cooling etc. This paradigm was originally called the 'transonic flow' paradigm in the context of black hole accretion (Chakrabarti, 1990). In the present Review, I systematically point out the strengths and weaknesses of the Advective Flows and show that it is the most complete of all the disk/outflow models.

2. Advective Flow Paradigm: What Is It?

In a Bondi flow (1952), adiabatic spherical accretion was considered and it was shown that if the star is sufficiently compact then matter would accrete onto it after passing through a (spherical) sonic surface. Since a star has a hard surface, a supersonic flow cannot satisfy the boundary condition of 'zero' radial velocity, so, it must form a 'boundary layer' in which the radial momentum must be dissipated. In the context of a spherical accretion on a black hole, such a problem does not arise, since the black hole does not have a hard surface and since matter must enter through the horizon with a velocity of light, it must be supersonic while entering. Thus a spherical flow need not have a 'boundary layer' around a black hole. The same solution also allowed matter to come out of a star-surface (or out of the inflow itself) through a sonic point in the form of un-collimated winds.

Since there is no boundary layer, a spherical flow is not very efficient in radiating its energy. In early days after the discovery of the quasars, efforts were made to increase its efficiency by (a) magnetic heating (Shapiro, 1973) and (b) by so-called 'pre-heating' (Ostriker el at. 1976). Stochastic magnetic fields, which are in excess of equipartition can reconnect and deposit thermal energy into the flow thereby increasing efficiency of radiation. On the other hand, radiation emitted at the inner edge of the flow can be intercepted by the outer regions of the flow and the flow may be heated up, may become subsonic, and form a stationary shock wave where some energy is released to space (Chang and Ostriker, 1985). While magnetic heating and pre-heating are well recognized to be dissipative mechanisms, they do not enhance the efficiency of Bondi-flow significantly.

A difficulty in a Bondi flow is that matter must start with a positive Bernoulli constant $\mathcal{E} \sim na_\infty^2$, where n is the polytropic constant and a_∞ is the adiabatic sound speed at a large distance. When matter has a significant amount of angular momentum but positive energy at a large distance, the behaviour remains virtually the same, namely both the accretion and wind branches exist. By significant angular momentum we mean an angular momentum comparable to the value at the marginally stable orbit. In the unit $G = M_{BH} = c = 1$ (where, G, M_{BH} and c are the gravitational constant, mass of the black hole and the velocity of light respectively), this is 3.67 for a Schwarzschild black hole. The flow typically has three sonic points out of which, the outer saddle type sonic point is similar to that in the Bondi accretion and the innermost saddle type sonic point is due to the general relativistic effect (Liang and Thompson, 1980). When the Bernoulli constant is positive, depending on specific angular momentum, one can have a very interesting situation, in which the flow jumps from the supersonic branch to the subsonic branch as a prescribed place (typically, at a distance of $10 - 20r_g$) where usual Rankin-Hugoniot conditions are satisfied. This is known as a shock transition and is probably the most important of all ingredients in a black hole accretion flow. At the shock transition, the radial kinetic energy is converted into thermal energy and the post-shock region behaves as a reservoir of hot electrons. Through inverse-Comptonization these electrons transfer their thermal energy to soft photons intercepted from distant Keplerian flow and form a thermal power-law component of the black hole disk spectrum (Chakrabarti & Titarchuk, 1995). In the event standing shocks do not form, the flow would either (a) form a diffused centrifugal barrier where the flow slowly dissipates its energy, or (b) form an oscillating shock front. The flow itself can oscillate up and down (vertically oscillating) like the flapping of a flag in the presence of a strong wind (Molteni et al., 2001; Acharya et al. 2001).

Post-shock region also does another important thing. It can supply hot matter to the outflow. Thermally, centrifugally or magnetically driven outflows are possible from this region more easily than from a Keplerian disk (Chakrabarti & Bhaskaran, 1992). Thus in this paradigm, the post-shock region not-only contributes to shape the spectrum of outgoing radiation, it also produces the jets and outflows so ubiquitous to black hole candidates.

It is clear that matter in the outer parts of an accretion flow moves in a Keplerian disk and dissipates slowly its energy by viscous processes. This disk necessarily has a negative specific energy and higher viscosity. Matter with lower viscosity and higher specific energy forms a moving corona above this Keplerian component. When this component is energized by magnetic dissipation or pre-heating, it is capable of producing standing or oscillating shocks as described above. One therefore has a two component flow, where Keplerian and sub-Keplerian components accrete simultaneously, forming a 'boundary layer' close to a black hole (this boundary layer is called CENBOL: Centrifugal pressure supported boundary layer) where most of the energy is dissipated. This model is known as the Two Component Advective Flow (TCAF) model. If a flow is highly viscous to begin with, it will remain Keplerian all the way to the marginally stable orbit before disappearing into the black hole supersonically. The flow has to be sub-Keplerian close to a black hole, otherwise, it cannot pass through a sonic point. It has been observed through numerical simulations (Molteni, Sponholz & Chakrabarti, 1996; Ryu, Chakrabarti & Molteni, 1997) that oscillating shocks are very common. X-ray intensity from the post-shock region also oscillates and cause quasi-periodic oscillations.

The picture described above, namely a two-component accretion with a possible shock, standing or oscillatory, at the inner edge and outflows from the shock region and distinct components of spectrum from the Keplerian and the sub-Keplerian components, is very complete and all comprehensive. Disk models prior to this paradigm (such as standard Keplerian disk, or purely rotating thick accretion disk. winds from all over the disk, hard photons from corona all over the disk) are grossly incomplete. There are some guesswork 'model's (such as ADAFs, Narayan & Yi, 1994) in the literature which are used in want of expertise in the advective disk solutions, primarily among observers. These models are found to be incorrect when examined in detail and are inapplicable to real astrophysical condition.

3. How does an Advective Flow Behave and Why?

With the advent of satellites having very high temporal, spatial and energy resolution, it has become very challenging for the guesswork model builders. Simplest way to have a long lasting paradigm is to stick to the governing equations and solve them using as few assumptions as possible (and most certainly avoid 'self-similarity' assumption even if it provides analytic answers). The progress of the Advective Flow Paradigm proceeded with theoretical solutions (some analytical, but mostly numerical) of steady state equations in one dimensional or one-and-a-half dimensional (full equations along the radial direction, neglecting vertical velocity component in the vertical direction and assuming axisymmetry) flow (Chakrabarti, 1990). Further progress was made using fully time dependent simulations (with more than one code, if possible) and comparing behaviours with those obtained from theoretical work (Chakrabarti, 1993; Chakrabarti & Molteni, 1993, 1995; Molteni Lanzafame and Chakrabarti, 1994; Molteni, Sponholz and

Chakrabarti, 1996; Molteni, Ryu and Chakrabarti, 2001; Ryu et al. 1997; Lanzafame et al. 1997; Acharya et al. 2001). Thus the Advective Flow Paradigm is a result of a large number of actual solutions and their verifications. So all the features which are present in this model have physical origin. Here we describe some of these features and their physical origin.

(a) *Matter must be supersonic very close to a horizon*:

A black hole treats all test matter 'democratically', namely, all types of matter irrespective of their origin would enter through its horizon with velocity of light. Since the velocity of sound is never so high for any realistic equation of state, the Mach number $M = v/a$ (where v is the radial velocity of infalling matter and a is the adiabatic speed of sound) is larger than unity. This is a general result if the problem is solved correctly, it would be automatically satisfied. Thus no extra inner boundary condition is needed as long as the solution branch which passes through the sonic point is chosen. In the case of a neutron star accretion, this is not the case. Depending on its surface condition (temperature, pressure etc.) the correct sub-sonic branch has to be chosen.

(b) *Matter must be sub-Keplerian close to the horizon*

It is easy to show that an adiabatic flow which passes through the sonic point must have angular momentum less that the Keplerian angular momentum (Abramowicz and Zurek, 1981). This result is valid even when non-adiabaticity is introduced (Chakrabarti, 1996). Thus matter must deviate from a Keplerian flow while entering into the disk. In a Keplerian disk (Shakura & Sunyaev, 1973), the flow is always assumed to be sub-sonic. Thus, at some point between the inner edge of the Keplerian disk and the horizon, the flow must become supersonic.

(c) *Matter can form a standing shock close to a black hole*

When specific energy of matter is positive, there is a range of specific angular momentum such that a non-viscous flow has three sonic points, two saddle type or 'X' type and one centre type or 'O' type. If Rankin-Hugoniot conditions are satisfied in between these two 'X' type sonic points, a standing shock can form. Recently it has been shown (Chakrabarti and Das, 2000) that these properties are valid not just for a specific model of the flow. They show that as far as transonic flow properties are concerned, various models, such as constant height flow, conical flow or flow in vertical equilibrium, all produce sonic points and shocks at the same place provided polytropic index of model is mapped onto that of the other in a certain well defined way. In other words, a large class of models could be described by a single parameter, namely, the polytropic index of the flow.

When viscosity is added, shocks can continue to form as long as the viscosity parameter (of Shakura-Sunyaev, 1973) is less than a certain value. This has been verified in 1D (Chakrabarti & Molteni, 1995) and 2D simulations (Lanzafame, Molteni and Chakrabarti, 1997). Flow with viscosity parameter larger than a certain critical value does satisfy standing shock conditions, but they can have oscillating shocks.

(d) *Matter can have oscillating shocks in the accretion*

In several ways oscillation of the shocks have been examined in the context of a black hole accretion. Molteni et al. (1996) showed that when cooling processes are included, and the cooling time scale is comparable to the infall time, then the shocks exhibit oscillations with time period roughly comparable to the cooling time scale. These oscillations are quite regular and happens even when the shock conditions are satisfied.

Another possibility is that when there are three sonic points, but the shock conditions are not satisfied, then a shock forms nevertheless, but instead of remaining stationary, it oscillates back and forth searching for a stationary solution (Ryu Chakrabarti & Molteni, 1997). This type of oscillations are a bit irregular and can 'ride' on the top of the cooling induced oscillations mentioned above.

(e) *Keplerian and sub-Keplerian flows can be segregated in the inflow*

One intriguing property of a viscous transonic flow is that Keplerian matter can become sub-Keplerian and vice-versa, depending on viscosity. Chakrabarti (1996) computed the location where the angular momentum of a sub-Keplerian flow becomes Keplerian depends strongly on viscosity and the location can come closer to the black hole for a high viscosity flow and can go away from the hole when viscosity is lowered.

On the equatorial plane, viscosity parameter is expected to be higher, and by arguments presented above, Keplerian matter would like to extend closer to the black hole on the equatorial plane. Matter with lower viscosity, such as flows away from the equatorial plane, tends to deviate from a Keplerian disk farther away (Chakrabarti, 1996). Thus it is expected that the inflow would have two components, Keplerian and sub-Keplerian. When the Keplerian component is also converted to a sub-Keplerian component, all matter mix to have a sub-Keplerian flow with an average energy and angular momentum which then may or may not form a standing shock. The existence of a two component flow hinges on the assumption that viscosity parameter decreases with height. This is a reasonable assumption for any realistic disk model.

(f) *Spectral states of a black hole depends on the composition of the Inflow*

The spectrum of the disk around a black hole candidate typically has two components: one is a multicolor blackbody component and the other one is a power-law hard tail. Spectrum of radiation can have more power in soft radiation ($\sim 2-3$keV) in the so-called soft states and more power in the hard radiation ($\sim 3-20$keV) in the hard states. In soft states the power law hard tail has a energy spectral index ($E_\nu \sim \nu^{-\alpha}$) of $\alpha \sim 1.5$ and in the hard states, the index is $\alpha \sim 0.5$.

Chakrabarti and Titarchuk (1995) showed that when the Keplerian component has a large accretion rate $\dot{M}_K/\dot{M}_{Ed} \geq 0.1$, and the sub-Keplerian accretion is $\dot{M}_S/\dot{M}_{Ed} \sim 1$, then the optical depth of the post-shock region is high enough to cool this region by inverse Comptonization process. Cooler matter rushes to the black hole with a velocity comparable to the velocity of light and photons scattered at this stage has an energy spectral slope of ~ 1.5. When, on the other hand, the Keplerian rate is very low $\dot{M}_K/\dot{M}_{Ed} \leq 0.1$, photons are unable to cool the post-shock region for significant sub-Keplerian rates. (Here, $\dot{M}_K$, $\dot{M}_S$ and $\dot{M}_{Ed}$ are the Keplerian, sub-Keplerian and Eddington rates respectively. As a result, photons are energized repeatedly to very large energy resulting in a higher power in hard X-rays. This is the hard state of a black hole candidate.

When one considers a super-massive black hole the spectrum remains the same, shape wise, but is shifted to a much lower energy. For instance, the Keplerian component emits multi-colour blackbody which peaks at around 1keV for a stellar mass black hole, but at a few eV for a super-massive black hole. The power-law forms at a lower energy.

(g) *Outflows may be produced in the post-shock region*

Post-shock region being very hot, it can thermally drive matter to a velocity comparable to the initial sound velocity very similar to stellar winds. It has been estimated that the ratio between the outflow and inflow rates is a very strong function of the compression ratio R of the shock (Chakrabarti, 1999). In the absence of a shock ($R = 1$), the outflow rate is found to be negligible. For a strong shock $R \sim 4-7$ the outflow again decreases to a small value. In the intermediate range the ratio peaks to a few percent. This indicates that in the soft states ($R \sim 1$, when the post-shock totally cools down) no outflow should be expected. Similarly, in the hard states very small rate of outflow should be seen. In the intermediate situation the outflow rate would be higher.

In the case when the inflow rate is really high, say, $2-3\dot{M}_{Ed}$, it is possible that the outflow is also cooled down due to Comptonization especially for intermediate R. At this stage outflow would be cutoff and this matter would fall back to the accretion disk causing excess accretion and softer states. Thus, even when supply of matter at a far distance remains the same, due to local non-linear coupling of accretion and winds through radiative effects, softer and harder states form in very short, viscous time scales.

(h) *Outflows may affect the spectral properties*

When matter is ejected out from the post-shock region or CENBOL region, the electrons in this region cool down faster due to inverse Comptonization as long as the optical depth does not become too low so that interaction become few and far between. Thus in the hard states, when winds are present, the spectrum is expected to be softer. In the soft states, winds are not expected, but some of the winds may also cool down and fall back on the accretion disk, raising the density of hotter electrons in the CENBOL and thus hardening the spectrum. This softening of the hard state and hardening of the soft state causes the pivotal point (where power laws of soft and hard states intersect) to shift at a higher energy (Chakrabarti, 1998).

(i) *Quasi-Periodic Oscillation of radiations in Black Hole Candidates is possible*

As mentioned before, the post-shock region can, (1) oscillate back and forth thereby changing dynamically the size of the Comptonising cloud and (2) intercept soft-radiations from the Keplerian disk and re-process them by inverse Comptonization. It is therefore possible that reprocessed radiations would show quasi-periodicity. In stellar mass black holes this would be observed in hard X-rays, while in super massive black holes this would be observed in extreme UVs. Time scale of oscillation is of the same order as the cooling time scale. Thus when accretion rate is increased, since the cooling time-scale goes down, the frequency of quasi-periodic oscillation is expected to rise.

4. Do Observational Evidence Support Advective Flow Paradigm?

A large number of observations are recently reported in the literature over the entire wavelength range both for the galactic and extragalactic black hole candidates. We present here briefly only those observations which can be satisfactorily explained only by this paradigm. Other observations can be explained by our paradigm and perhaps by some other models as well.

(a) *Evidence for Bulk Motion Comptonization close to a black hole*

Out of all the indirect evidences of a black hole, the weak hard tail in the soft states are perhaps as close to being the least indirect evidence. According to the advective flow paradigm, matter behaves identically close to a black hole and scatter photons to produce the same energy spectral index of $\alpha = 1.5$. This has been observed in many of the suspected black hole candidates. Titarchuk et al. (1998) and Borozdin et al. (1999) presented catalogue of such cases, and the similarity of these hard tails are astonishing. These examples are all for stellar mass black holes. For super massive black holes, spectral transitions to very soft states are not easy to observe as the time scale is really large. Still there are some evidence of this hard tails in MKN841 as well (Arnaud et al., 1985).

(b) *Evidence for sub-Keplerian accretion in a black hole*

In stellar mass black holes, the two component advective flows (TCAF) have been observed in many black hole candidates (e.g., Crary et al. 1996; Ling et al. 1997; Gilfanov et al. 1997; Smith et al. 2001; Yadav and Rao, 2001). In fact, in some cases the Comptonising region has been seen to change its size (Homan, et al. 2001) exactly as the CENBOL would change in presence of varying viscosity.

In the case of super-massive black holes, there are no concrete evidence for sub-Keplerian flows so far. However, in objects like M87, there are evidence for spiral shocks in the disk (Chakrabarti, 1995; Dopita et al. 1997). These shocks are possible only if the disk is sub-Keplerian (Chakrabarti, 1990).

(c) *Evidence for QPO being the post-shock oscillation*

Since black holes have no hard surface, it was intriguing at first to conjecture what could the possible reason for rapid and regular variation of hard X-rays be. For an advective paradigm this is not a problem. As mentioned in Section 3, CENBOL is found to oscillate, when either 1. cooling time scales becomes comparable to the infall time scale, or when 2. the shock conditions are not satisfied though there are more than one sonic points. Chakrabarti & Manickam (2000) and Rao et al. (2000) showed that only the hard photons participate in the QPO oscillations and the soft, blackbody photons emitted from the Keplerian disk do not participate in the oscillation. Since hard photons are emitted from the CENBOL region, these observations immediately confirm the existence of CENBOL and its oscillation predicted by our paradigm.

(d) *Pivotal point shifted in presence of winds*

Chakrabarti et al. (2001) showed in the context of GRS1915+105, that the spectral slopes of hard and soft states are modified in presence of winds. This is in line with our paradigm. Detailed of the observations are in Nandi & Chakrabarti (2001).

(e) *Outflows are produced very close to a black hole*

Several observations have been made (Pooley et al. 1997; Eickenbery et al. 1998; Feroci et al., 1999; Fender et al. 2000; Dhawan et al. 2000) which indicate a distinct correlation between the Comptonising region and the outflowing jets. Pooley et al (1997) showed that when the source goes from the burst-off state to the burst-on state via the X-ray dip, the radio oscillation starts. Eikenberry et al. (1998) pointed out that X-ray and IR flares are triggered by the same events very close to the black hole. Using data of the light curve (of the so-called β class, Belloni et al. 2000a), they noted that IR flares are associated with a spike formation and right after the spike matter may have come out as baby jets. Feroci et al. (1999) associated disappearance of the inner part of the disk with the creation of radio flares. Since Comptonising region is the CENBOL ($10-20$ Schwarzschild radii), jets must be originated from this region only.

Indeed, for active galaxies also such a conclusion must hold true. Junor, Biretta and Livio (2000) demonstrated by radio observations that the bases of the jets in M87 are no more than $50-100$ Schwarzschild radii wide. Given that a typical disk could be 10^{5-6} Schwarzschild radii large, this observation is surprising to most of the model builders. Since CENBOL region is considered to be the jet producing region, such observations are readily explained in our model.

(f) *Outflow rates are related to spectral states*

Fender et al. (2000) find that only is hard states there are continuous outflows while in very soft states the outflow could be missing. This interesting result comes naturally when CENBOL is assumed to produce jets (Chakrabarti 1999). Strong shocks (hard states) are produced far out, but the density is low. Hence the outflow rate is low but significant. In soft states, shocks are weaker and the driving force is missing. Hence the outflow rate is negligible. For intermediate strength shocks the outflow rate is very high (burst-on/burst-off states).

4. Concluding Remarks

Advective flow paradigm is the most successful of all accretion disk/wind systems present in the literature. This is essentially because this paradigm is made up of several components, each of which arises from exact solutions of governing equations. One good aspect of having a global paradigm is that it could be utilized not just stellar mass black holes, but for supermassive black holes as well. However, times scales are longer (scales with the mass of the central body) and require very long observations. For instance, if it takes a day for spectral state transition for a $10 M_\odot$ black hole, it would take 3×10^4years for a $10^8 M_\odot$ black hole. Similarly a QPO of 10Hz in the former case, would correspond to an oscillation of $10^{-6} Hz$ is the latter case. Very long observations would be required to establish such phenomena for a super-massive black hole. Thus, although objects such as OJ287, MK421 etc. show variabilities of the order of years and days and perhaps some of them could be interpreted as QPOs, it is very difficult to be certain.

One cautionary remark is that till today, there is no single three-dimensional solution, which includes Keplerian disks on the equatorial plane, sub-Keplerian flow off the plane, CENBOL (often oscillating), outflows from CENBOL, all in the presence of radiative transfer. Similarly, no single numerical simulation has been made which produces all these components simultaneously so far. These are prohibitive with present computing power. In this sense, though this paradigm is as complete as it can be, its entire scope has not yet been explored.

This work is partly supported by a project (Grant No. SP/S2/K-14/98) funded by Department of Science and Technology (DST), Govt. of India.

References

Abramowicz, M. A. & Zurek, W.H. 1981, *Astrophys. J.* 240, 271

Acharya, K., Molteni, D. and Chakrabarti, S.K. 2001 (this volume)

Arnaud, K. et al. 1985, *Mon. Not. R. Astron. Soc.* 217, 105

Bondi, H. 1952, *Mon. Not. R. Astron. Soc.* 112, 195

Borozdin, K, Revnivtsev, M, Trudolyubov, S., Shrader, C., Titarchuk, L. G., 1999, *Astrophysical J.* 517, 367

Chakrabarti, S.K., 1990, *Theory of Transonic Astrophysical Flows* (World Scientific Co.: Singapore)

Chakrabarti, S.K. 1993, in Accretion Disks in Astrophysics, in Numerical Simulations in Astrophysics, (Eds.) J. Franco, S. Lizano, L. Aguilar & E. Daltabuit (Cambridge University Press: Cambridge)

Chakrabarti, S.K. 1995 *Astrophys. J.* 441, 576

Chakrabarti, S.K. 1996 *Astrophys. J.* 464, 664

Chakrabarti, S.K., 1998 *Ind. J. Phys.*, 72B, 183

Chakrabarti, S.K., 1998 *Ind. J. Phys.*, 72B, 565

Chakrabarti, S.K. 1999 *Astron. Astrophys.* 351, 185

Chakrabarti, S.K., 2000 Il Nuovo Cim. 115, 897

Chakrabarti, S.K., Manickam, S., Nandi, A. & Rao, A.R. 2001, *Mon. Not. R. Astron. Soc.* (submitted)

Chakrabarti S.K. & Bhaskaran, P. 1992 *Mon. Not. R. Astron. Soc.* **255** 255

Chakrabarti, S.K. and Das, S. 2000, *Mon. Not. R. Astron. Soc.* (in press).

Chakrabarti, S.K., Manickam, S. G., 2000 *Astrophys. J.*, 531, L41

Chakrabarti, S.K. and Molteni, D. 1993, *Astrophys. J.* **417**, 671

Chakrabarti, S.K. and Molteni, D. 1995, *Mon. Not. R. Astron. Soc.* **272**, 80

Chakrabarti, S.K., Titarchuk, L. G., 1995 *Astrophys. J.* 455, 623

Chang, K.M. and Ostriker, J.P. 1985 *Astrophys. J.*, 288, 428

Crary, D. J., Kouveliotou, C., van Paradijs, J., van der Hooft, F., Scott, D. M., Paciesas, W. S., van der Klis, M., Finger, M. H., Harmon, B. A., Lewin, W. H. G, 1996, *Astrophys. J.* 462, L71

Dhawan, V., Mirabel, I. F. and Rodriguez, L. F. 2000, *Astrophys. J.*, 543 373

Dopita, M. A., 1997, *Astrophys. J.* 490, 202

Eikenberry, S.S. et al. 1998 *Astrophys. J.* 494, L61

Fender, R.P. et al. 2000 *Mon. Not. R. Astron. Soc.* 312, 853

Feroci, M. et al. 1999 *Astron. Astrophys.* 351, 985

Gilfanov, M., Churazov, E., Sunyaev R.A. 1997, in *Accretion Disks – New Aspects*, (Eds.) E. Meyer-Hofmeister & H. Spruit, Springer (Heidelberg).

Liang, E.P.T. and Thompson, K.A. 1980, *Astrophys. J.*. 240, 271

Homan, J. Wijnands, R., van der Klis, M., Belloni, T., van Paradijs, J., Klein-Wolt, M., Fender, R., Mendez, M., *Astrophys. J. Suppl. Ser.* 132, 377

Junor, W., Biretta J. A. and Livio, M., 1999, Nature **401**, 891

Lanzafame, G., Molteni, D. & Chakrabarti, S.K. 1997, *Astrophys. J.* **474**, 378

Ling, J. C., Wheaton, Wm. A., Wallyn, P., Mahoney, W. A., Paciesas, W. S., Harmon, B. A., Fishman, G. J., Zhang, S. N., Hua, X. M. 1997, *Astrophys. J.*, 484, 375

Molteni, D., Acharya, K., Kuznetsov, O., Bisikalo, D. and Chakrabarti, S.K. *Astrophys. J. Letters* (submitted)

Molteni, D., Lanzafame, G. and Chakrabarti, S.K. 1994, *Astrophys. J.*, **425**, 161

Molteni, D., Ryu D. & Chakrabarti, S.K. 1996, *Astrophys. J.* **470**, 460

Molteni, D., Sponholtz, H. & Chakrabarti, S.K., 1996, *Astrophys. J.* 457, 805

Narayan R. and Yi, I. 1994 *Astrophys. J.* **428**, L13

Ostriker, J. P., Weaver, R., Yahil, A., McCray, R., 1976, *Astrophys. J.* 208, 610

Parker, E.N., 1960 *Astrophys. J.* 132, 175

Pooley, G.G. et al., 1997, *Mon. Not. R. Astro. Soc.* 292, 925

Rao, A. R., Naik, S., Vadawale, S. V. and Chakrabarti, S. K., 2000 *Astron. Astrophys.* 360, L25

Ryu, D., Chakrabarti S.K. and Molteni D., 1997 *Astrophys. J.* **474**, 378

Shakura, N.I. & Sunyaev, R. 1973, *Astron. Astrophys.* 24, 337

Shapiro, S.L. 1973 *Astrophys. J.* **180** 531

Smith, D. M., Markwardt, C., Heindl, W. A. and Swank, J. H., 2001, *Astrophys. J.* (submitted) astro-ph/0103304

Titarchuk, L.G., Shrader, C.R., Trudolyubov, S., Revnivtsev, M. and Borozdin, K. 1998 in Observational Evidence in Black Holes in the Universe, Ed. S.K. Chakrabarti (Kluwer Academic Pub.: Holland), 309

Yadav, J.S. and Rao, A.R., 2001, Astrophys. & Space Sc., (in press)