RECENT PROGRESSES OF ACCRETION DISK MODELS AROUND BLACK HOLES

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Accretion disk models have evolved from Bondi flows in the 1950s to Keplerian disks in the 1970s and finally to advective transonic flows in the 1990s. We discuss recent progresses in this subject and show that sub-Keplerian flows play a major role in determining the spectral properties of black holes. Centrifugal pressure supported enhanced density region outside the black hole horizon produces hard X-rays and gamma rays by reprocessing intercepted soft photons emitted by the Keplerian disk terminated farther out from the black holes. Quasi-periodic oscillations can also be understood from the dynamic or thermal resonance effects of the enhanced density region.

1 Introduction

Matter accreting on galactic and extragalactic black holes need not be spherically symmetric Bondi flow or purely thin and Keplerian. In fact, since by definition, matter must enter into a black hole with radial velocity on the horizon similar to the velocity of light, it must be supersonic and hence sub-Keplerian. If one assumes that matter forms a thin, subsonic, Keplerian disk very far away then it has to pass through at least one sonic point before the flow enters the black hole. Second, since just outside of the black hole, the infall time scale is much shorter compared to the viscous time scale (even when viscosity is high), angular momentum is roughly constant in the last few Schwarzschild radii and as a result, the centrifugal force increases rapidly enough as the flow approaches the black hole so as to form a centrifugal barrier behind which matter piles up. The resulting enhanced density region may be abrupt (if behind a shock), or smooth if the shock conditions are not satisfied.

2 Nature of Advective Solutions

Chakrabarti classified all possible solutions of the inviscid adiabatic flows around black holes. Since angular momentum is likely to be almost constant close to a hole even for highly viscous flows, the inviscid solutions would be important even when viscosity is significant. It is observed that a large region of parameter space can produce standing shocks behind the centrifugal barrier. The classification is discussed in detail in Chakrabarti. In presence of

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viscosity, the advective disk may still produce shocks provided the viscosity parameter is less than some critical value. The steady solutions with or without shocks in one and two dimensions have been tested to be stable by explicit numerical simulations. In a large region of the parameter space, two saddle type sonic points are present, but the shock conditions are not satisfied. The numerical simulations indicate that the shocks form nevertheless, but they are unstable, and oscillate back and forth. The period of oscillation depends on the specific angular momentum, but typically they can be around a fraction of a second for galactic black hole candidates and around a day for extragalactic massive black holes. Even when stable shock conditions are satisfied, shocks can be oscillatory when significant cooling effects are present.

As viscosity is added, the closed topologies in the Mach No. vs. radial distance space of the inviscid solutions open up and the solution joins with a Keplerian disk farther out, provided the accretion rate is large enough to have efficient emission from the disk. For low enough viscosity and the accretion rate the advective flow may join with a Keplerian disk very far away (forming a giant primarily rotating ion torus which surround the disk of size $10^3-10^4$ x $g$, see, g21-g41 topologies in Fig. 2a of Chakrabarti), while for higher viscosity and accretion rate the Keplerian disk will come closer to the black hole (see, g13-g14 topologies in Fig. 2a of Chakrabarti). In intermediate viscosities, these flows may have shocks. For low and intermediate viscosities the flow would definitely have a centrifugal barrier and consequent enhanced density region in between the black hole and the Keplerian disk. If viscosity varies with height, it is expected that all the three types of flows would be manifested in a single flow. Chakrabarti discussed in detail the nature of the multi-component advective disk. The boundaries of Keplerian and sub-Keplerian regions, as well as the accretion rates in different components will vary from case to case as well as from time to time. As the viscosity at the outer edge increases, more and more matter goes from sub-Keplerian component to the Keplerian component. The soft photons from the Keplerian flow cools the sub-Keplerian component (thermal Comptonization) and hence the inner edge of the Keplerian component also advances. Eventually, the sub-Keplerian component cools completely and the Keplerian disk advances till the last stable orbit. Quasi-spherical flows in between the horizon and the last stable orbit reprocesses the soft photons out of the Keplerian component by transferring the bulk momentum of the electrons to the photons (bulk motion Comptonization) and as a result, long extended power law component is formed even in the very soft state.
3 Spectral Properties

When the accretion rate of the cooler Keplerian component ($\dot{m}_d$) is much smaller compared to that of the hotter sub-Keplerian component ($\dot{m}_h$), the soft photons emitted from the Keplerian component are unable to cool the hot electrons of the later component by thermal Comptonization processes. Thus, predominantly hard X-rays are produced with little or no soft bump. Generally, this soft bump may not be observed since the soft X-rays may be further reprocessed by the extended atmosphere of the disk. The X-ray spectral index $\alpha (F(\nu) \sim \nu^{-\alpha})$ is around 0.5–0.8 and $\dot{m}_d$ is typically less than 0.1–0.3 when $\dot{m}_h = 1$ depending on Models. As $\dot{m}_d$ is further increased in comparison to $\dot{m}_h$ (which may be due to sudden increase of viscosity in the flow [sudden capture of magnetic clouds from the companion, for instance] which converts some of the sub-Keplerian flow into Keplerian), the soft photons of the Keplerian disk cools the electrons of the sub-Keplerian component catastrophically and the spectra consists of only the soft bump without any extended power law tail. This is called soft state by some observers and this may happen for Keplerian rate of around 0.3–0.7 or so when $\dot{m}_h = 1$ depending on models. One may also see broken power law in this state because of the contribution from both thermal and bulk motion effects. As $\dot{m}_d$ is further increased, the optical depth in the centrifugal pressure supported enhanced density region becomes high and the flow drags most of the photons (which were supposed to be emitted in between $3x_g$ and $1x_g$). The sub-Keplerian flow farther out effectively losses its identity as it cools down completely to a temperature a little above the corresponding Keplerian component. However, a fraction of photons energized by infalling matter due to bulk motion Comptonization can still come out. Chakrabarti & Titarchuk (see also Ebisawa et al. for details) showed that the power law hard component (with energy spectral slope $\alpha \sim 1.5–2.0$) can easily explain the behavior of the very soft state of the black hole candidates. Recent computation shows that the power law extends till almost 1MeV. This power law component is absent for both neutron stars as well as naked singularities. Thus, the presence of power law component in very soft states has enabled observers to distinguish a black hole from a neutron star very easily. Although the black hole horizons permit energetic matter to be swallowed directly and therefore, for a given accretion rate, black hole accretion could be less luminous than the neutron star accretion, argument based on total luminosity cannot be full proof, since there could be any number of other physical effects (such as bipolar outflows which carry away energy and matter) confusing the situation.
4 Quasi-Periodic Oscillations

When Quasi-Periodic Oscillations (QPOs) were discovered in black hole candidates a few years ago, it was surprising, since black holes have neither hard surfaces nor any anchored magnetic fields. It now appears, that the QPOs could be manifestation of the time-dependent solutions of the same set of equations which produced Keplerian and sub-Keplerian flows. As discussed in §2 above, simulations from a large region of parameter space showed that either because of resonance between inflow and outflow time-scales, or between inflow and cooling time scale, the enhanced density region oscillates with frequency very similar to QPO frequency. Furthermore, these oscillating regions intercept different amount of soft photons from the Keplerian component and produces hard X-rays of significant amplitude as is observed. Mechanisms based on acoustic oscillations or some such possibilities are incapable of producing significant modulations.

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1. S.K. Chakrabarti, *Astrophys. J.*, 347, 365 (1989).
2. S.K. Chakrabarti, Theory of Transonic Astrophysical Flows, World Scientific: Singapore (1990).
3. S.K. Chakrabarti, *MNRAS*, (Nov. 1st issue) (1996).
4. S.K. Chakrabarti, *Astrophys. J.*, 464, 664 (1996).
5. S.K. Chakrabarti, *Astrophys. J.*, (in press) (1997).
6. S.K. Chakrabarti and D. Molteni, *MNRAS*, 272, 80 (1995).
7. S.K. Chakrabarti, and L.G. Titarchuk, *Astrophys. J.*, 455, 623 (1995).
8. S.K. Chakrabarti, and S. Sahu, *Astron. Ap*, (in press), (1997).
9. K. Ebisawa, L. Titarchuk, and S.K. Chakrabarti, *PASJ*, 48, 1 (1996).
10. D. Molteni, G. Lanzafame, and S.K. Chakrabarti, *ApJ*, 425, 161 (1994).
11. D. Molteni, D. Ryu, and S.K. Chakrabarti, *Astrophys. J.* (Oct 10th issue), (1996).
12. D. Molteni, H. Sponholz, and S.K. Chakrabarti, *Astrophys. J.*, 457, 805 (1996).
13. D. Ryu, S.K. Chakrabarti, and D. Molteni, *Astrophys. J.*, (Jan. 1st) (1997).
14. L.G. Titarchuk, Proc. 2nd INTEGRAL Workshop “The Transparent Universe” Eds. C. Winkler et al. (in press).
15. S.N. Zhang, et al. 1997, *Astrophys. J.* (submitted).
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