Chapter 1

A NEW PARAMETER IN ACCRETION DISK MODEL

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Abstract  Taking optically thin accretion flows as an example, we investigate the dynamics and the emergent spectra of accretion flows with different outer boundary conditions (OBCs) and find that OBC plays an important role in accretion disk model. This is because the accretion equations describing the behavior of accretion flows are a set of differential equations, therefore, accretion is intrinsically an initial-value problem. We argue that optically thick accretion flow should also show OBC-dependent behavior. The result means that we should seriously consider the initial physical state of the accretion flow such as its angular momentum and its temperature. An application example to Sgr A* is presented.

1. INTRODUCTION

It has long been assuming that the parameters describing the accretion flow include the accretion rate, the mass of the central black hole, the viscosity parameter, and the parameter describing the strength of the magnetic field in the accretion flow. Once these parameters are given, we can obtain almost all the information of the accretion flow including the dynamics and the emergent spectrum. However, the set of equations describing the accretion flow are nonlinear differential equations, therefore it is intrinsically an initial-value problem. Thus the outer boundary condition (OBC) possibly plays an important role.

On the other hand, the complicated astrophysical environments make the physical states of the accreting gas at the outer boundary $r_{out}$, such as its temperature and angular momentum, various. For example, in semi-detached binary system, where the critical Roche lobe is filled up and the accretion of matter takes place through the inner Lagrangian point, the angular momentum of the accreted gas should be high; while in detached binary system the accretion matter is stellar winds therefore their angular momenta are much lower.
Figure 1.1 Solutions for one temperature global solutions with different OBCs for $M = 10M_\odot$, $\dot{M} = 10^{-3}M_\odot$ and $\alpha = 10^{-2}$. The solid, dot-dashed and dashed lines represent $(T_{\text{out}} = \lambda_{\text{out}} = v/c_s = v/\sqrt{\rho p}) = (2 \times 10^8 \text{K}, 0.4)$, $(3.6 \times 10^9 \text{K}, 0.08)$ and $(3.6 \times 10^9 \text{K}, 0.107)$ respectively. The units of $\Sigma, T$ are $\text{g cm}^{-2}$ and K, $r, Be$ and $l$ are in $c = G = M = 1$ units. Mach number is simply defined as $v/c_s$. The upper-left plot represents the ratio of the advected energy to the viscous dissipated energy. Adopted from Yuan (1999).

(IIlarionov & Sunyaev 1975). In the nuclei of galaxies, where the supply of the accretion matter is unclear, the initial physical states of the accretion flows should be more complicated. The complexity of astrophysical environments makes it important to investigate the role of OBC in accretion disk model.

2. THE ROLE OF OBC IN OPTICALLY THIN ACCRETION FLOWS

In previous papers (Yuan 1999; Yuan et al. 2000), taking optically thin accretion onto a black hole as an example, we calculated the dynamics and the emergent spectrum of one- and two-temperature accretion plasma by self-consistently solving the radiation hydrodynamical equations. For the one temperature case, only bremsstrahlung emission and its Comptonization are considered, while for the two temperature case, synchrotron emission and its Comptonization are also included. We concentrated on the role of OBC by setting the same "general parameters" such as accretion rate, viscosity parameter and black hole mass while adopting different OBCs. We adopted the temperature $T_{\text{out}}$ and the ratio of the radial velocity to the local sound speed $\lambda_{\text{out}}$ (or, equivalently, the angular velocity $\Omega_{\text{out}}$) at a certain outer boundary $r_{\text{out}}$ as the outer boundary conditions and found that in both cases, the topo-
Figure 1.2  Solutions for two temperature global solutions with different $T_{\text{out},i}$. The solid line (type I solution) is for $T_{\text{out},i} = 2 \times 10^8 K$, the dotted line (type I) for $T_{\text{out},i} = 6 \times 10^8 K$, the dashed line (type II) for $T_{\text{out},i} = 2 \times 10^9 K$ and the long-dashed line (type III) for $T_{\text{out},i} = 3.2 \times 10^9 K$. Other OBCs are $T_{\text{out},e} = 1.2 \times 10^8 K$ and $\lambda_{\text{out}} = 0.2$. The outer boundary is set at $r_{\text{out}} = 10^3 r_g$. Other parameters are $\alpha = 0.1$, $\beta = 0.9$, $M = 10^9 M_\odot$ and $\dot{M} = 10^{-4} \dot{M}_{\text{Edd}}$. The units of $\Sigma$ and $T$ are $\text{g cm}^{-2}$ and $\text{K}$. Adopted from Yuan et al. (2000).

logical structure and the profiles of angular momentum and surface density of the flow differ greatly under different OBCs, as shown by Figures 1 (for a one-temperature plasma) and 2 (for a two-temperature plasma; only the ions temperature $T_{\text{out},i}$ varies: for other cases, see Yuan et al. 2000). In terms of the topological structure and the profile of the angular momentum, three types of solutions are found. When $T_{\text{out}}$ is relatively low, the solution is of type I. When $T_{\text{out}}$ is relatively high and the angular velocity $\Omega_{\text{out}}$ is higher than a critical value $\Omega_{\text{crit}}$, the solution is of type II. Both types I and II possess small sonic radii, but their topological structures and angular momentum profiles are different. When $T_{\text{out}}$ is high but the angular velocity is lower than $\Omega_{\text{crit}}$, the solution becomes of type III, characterized by a much larger sonic radius. Similar transition has been found previously in the context of adiabatic (inviscid) accretion flow by Abramowicz & Zurek (1981). In that case, they found that when the specific angular momentum of the flow decreased across a critical value, a transition from a disk-like accretion pattern (with small sonic radii) to a Bondi-like one (with large sonic radii) would happen (Abramowicz & Zurek 1981; Lu & Abramowicz 1988). Here in this paper we find that this transition still exist when the flow becomes viscous, confirming the prediction of Abramowicz & Zurek (1981). Figure 3 shows the emergent spectrum of the solutions presented in Figure 2. Considering that they possess the same
“general” parameters the discrepancy among the spectra completely caused by the difference of OBC is impressive. At last, we should emphasize that such “OBC-dependent” effect on the spectrum has relation with the value of \( r_{\text{out}} \): the smaller \( r_{\text{out}} \) is, the more significant the effect becomes. Thus, this effect should be very obvious in the accretion flow where standard thin disk-ADAF transition occurs. As a result, some confusing problems can be promisingly solved (Yuan & Yi, in preparation).

3. AN ILLUSTRATIVE APPLICATION TO SGR A*

As an illustrative example, we apply the above results to the compact radio source Sgr A* located at the center of our Galaxy. Advection-dominated accretion flow (ADAF) model has been turned out to be of great success to explain its low luminosity and spectrum (Narayan, Yi & Mahadevan 1995; Narayan et al. 1998). However, there exists a discrepancy between the mass accretion rate favored by ADAF models in the literature and that favored by the three dimensional hydrodynamical simulation, with the former (\( \sim 6.8 \times 10^{-5} \dot{M}_{\text{Edd}} \), see Quataert & Narayan 1999) being 10-20 times smaller than the latter (\( \sim 9 \times 10^{-4} \dot{M}_{\text{Edd}} \), see Coker & Melia 1997). By seriously considering the outer boundary condition of the accretion flow, we find that due to the low specific angular momentum of the accretion gas (Coker & Melia 1997), the accretion in Sgr A* should belong to type III which possesses a very large
Figure 1.4  The X-ray spectrum of Sgr A*. The observational data are compiled by Narayan et al. (1998). The spectra represented by the solid and the dashed lines are produced by the accretion flows with the same accretion rate $\dot{M} = 4 \times 10^{-4} \dot{M}_{\text{Edd}}$ but different angular momentum at $r_{\text{out}}$, $\Omega_{\text{out}} = 0.15 \Omega_{K}$ for the solid line and $\Omega_{\text{out}} = 0.46 \Omega_{K}$ for the dashed line. Due to the difference of the angular momentum of the flow at the outer boundary, the X-ray flux differs by a factor $\sim 8$. Adopted from Yuan et al. (2000).

sonic radius. This accretion pattern can significantly reduce the discrepancy between the mass accretion rate, as Figure 4 shows (see Yuan et al. 2000 for details).

4. DISCUSSION

The present study is concentrated on the low-$\dot{M}$ case where the differential terms in the equation such as the energy advection play an important role therefore the effect of OBC are most obvious. How about the role of OBC when the flows become optically thick? In this case, the electron and the ion possess the identical temperature due to the strong couple between them and the local viscous dissipation and radiation loss terms in the energy balance play an important role. As a result, the temperature profile is mainly determined \textit{locally} rather than \textit{globally} as in the case of optically thin flows. Thus, the discrepancy of the temperature caused by OBC will lessen rapidly with the decreasing radii from the outer boundary. This is also the reason why the temperature profiles of one-temperature plasma and ions in Figures 1 and 2 converge rapidly with decreasing radii. However, from our calculation to the one-temperature accretion flow whose temperature is also principally determined locally (Yuan 1999), we predict that the optically thick accretion flow should still present OBC-dependent behavior in, e.g., the angular momentum and the Mach number.
profiles which are in principle determined by the momentum rather than the energy equations. When the angular momentum of the accretion flow is less than a certain critical value, the accretion pattern should become of “type III” (Bondi-like). Although these conjectures need the confirmation of detailed calculation, we note that the angular momentum profile of slim disk model (see Figure 3 of Abramowicz et al. 1988), and a recent numerical simulation (Igumenshchev, Illarionov & Abramowicz 1999) seems to support this point.

Why the role of OBC in accretion disk models has been long neglected? In the standard thin disk model, all the differential terms in the equations are neglected and the differential equations are reduced into an algebraic one which don’t entail any boundary conditions at all. In the later works on the global solutions for slim disks (Matsumoto et al. 1984; Abramowicz et al. 1988; Chen & Taam 1993) and optically thin advection-dominated accretion flows (Narayan, Kato & Honma 1997; Chen, Abramowicz & Lasota 1997), some authors did investigate the role of OBC, but failed to find its importance. The main reason is that for optically thick accretion flows (slim disk) or one-temperature optically thin accretion flow, the local viscous dissipation plays an important role in the energy equation, so the effect of OBC lessen rapidly away from the outer boundary. In addition, the angular momentum in their outer boundary condition was always somewhat large. This might be the reason why they didn’t find the solutions with very large sonic radii.

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