Accretion Disks Phase Transitions: 2-D or not 2-D?

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Abstract

We argue that the proper way to treat thin–thick accretion-disk transitions should take into account the 2-D nature of the problem. We illustrate the physical inconsistency of the 1-D vertically integrated approach by discussing a particular example of the convective transport of energy.

Key words: accretion, accretion disks — convection — hydrodynamics

Traditionally, accretion disks are modeled using a dimensional splitting method, in which the vertical structure is solved locally at each radius. Although this procedure is evidently correct for thin disks, it may be questionable for thick disks that have a non-negligible geometric thickness, and for thin or thick disks experiencing a sharp transition (stationary or non-stationary) from one state to another.

Advection-dominated accretion flows (ADAFs) are now widely regarded as being the source of Comptonized X-ray radiation observed from many X-ray binary sources. It is believed that in such a source, the ADAF is located in the inner part of an accretion disk around a compact object, while the outer part is most likely a standard Shakura–Sunyaev disk (SSD). A transition from the SSD to an ADAF may occur at hundreds or thousands of gravitational radii from the central compact body. The physical cause of the transition remains elusive. 1-D ADAF models based on vertical integration are remarkably successful in explaining the observed spectra (see e.g. Narayan et al. 1996; Narayan et al. 1997a). It is easy to overlook, however, that this by itself does not prove that these models are able to correctly describe the SSD–ADAF transitions.

Indeed, in this Note we argue that 1-D methods that have been used to study ADAFs, cannot describe transitions between ADAFs and SSDs. The problem here is not only with accuracy, but also with the very physical consistency of these methods. For this reason, several recent ideas and results concerning the SSD–ADAF transitions cannot be trusted.

We illustrate the physical inconsistency of the vertical integration approach, which is the most often used 1-D method, by discussing a particular example of the convective transport of energy. In principle, one may argue (as e.g. Honma 1996a) that a convective energy flux that originates in the inner part of the ADAF could be deposited in inner edge of the outer SSD, causing its ‘evaporation’ thereby sustaining the SSD–ADAF transition. In reality, most of the convective flux goes in the vertical direction and never reaches the SSD. By vertical integration one artificially forces all of this flux to be deposited in the SSD.

The physical inconsistency of the 1-D methods should not be confused with the fact that the global models constructed by such methods could be formally self-consistent. Indeed, the formal self-consistency of the 1-D ADAF models is connected to the fact that the vertically integrated method always produces a smooth radial dependence of the scale height in global solutions (Narayan et al. 1997b; Chen et al. 1997). However, it is most likely that SSD–ADAF transitions are far from being smooth, as has been demonstrated in 2-D hydrodynamics simulations by Abramowicz, Igumenshchev, and Lasota (1998). In this paper, we extend the argument by pointing out that the two-dimensional nature of the transition is also important for the heat flux. We consider a particular case of a convective heat flux, because it is known to be important for ADAFs (Narayan, Yi 1994; Igumenshchev et al. 1996).

In order to evaporate the SSD at a certain radius and
sustain an SSD–ADAF transition, a significant amount of energy must be pumped into the region where the evaporation takes place. The physical mechanism for that is still unclear, and several possibilities have been suggested, among them radial convective heat flux. It is precisely here that the 1-D vertically integrated methods fail dramatically. A treatment based on vertical integration artificially channels all of the convective flux to the inner edge of the SSD. This results in a gross overestimation of the amount of heat pumped into the SSD, and would allow the disk to evaporate, even when in reality this is not possible. The reason is simply because convective flux is carried by convective bubbles, which have the tendency to flow over the disk, rather than converge into the disc inner rim and release their energy there. Moreover, as the bubbles move towards larger radii, their motion deviates from the equatorial plane. Some of the bubbles may even leave the ADAF interior, escaping in roughly polar directions. Figure 1 presents an example snap-shot of such a behaviour of the convective bubbles that was calculated with a help of a fully 2-D, time dependent, hydrodynamical simulation. The bubbles quasi-periodically originate due to convective instability; for detail see Igumenshchev and Abramowicz (1999). Because the bubbles have a tendency to miss the SSD inner rim, they cannot insert any appreciable amount of energy into the evaporation region.

ADAF models cannot extend to infinity because they are systems with a negative total energy. Thus, at a certain radius, the disk thickness drops sharply. This behaviour is similar to geometrically thick tori, which have a negative total energy. 2-D simulations of viscous evolution of thick tori given by Igumenshchev et al. (1996) and Stone, Pringle, and Begelman (1999) have shown that the convective heat flux is not focused toward the equatorial plane near to the outer boundary of tori where the disk thickness drops sharply. Thus, focusing of the convective heat flux into the equatorial region is a consequence of the 1-D treatment. A schematic illustration of the artificial focusing effect in 1-D approach is presented in figure 2.

We admit that the present paper does not directly prove that the behaviour assumed in the Honma model cannot take place, but it is important to point out its potentially serious difficulty. The Honma model is now one of the most clever and important ideas in accretion-disk theory. For this reason, the criticism of it that we provide should be known to the community.

A similar problem arises when the radial energy flux is provided by radiation. If vertically integrated intensities (or moments of intensity) are used to model the flux, the heat input into the SSD is overestimated, since in such models the inner rim of the SSD by construction absorbs all of the radiation. In reality, most of the radiation flux passes the SSD.

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**Fig. 1.** Density distribution of ADAF (viscosity parameter $\alpha = 0.1$) in the meridional cross-section. The vertical axis coincides with the axis of rotation. The black hole is located at the origin (0, 0). Axes are labeled in the units of $r_g$. The contours of density $\rho$ are spaced with $\Delta \log \rho = 0.1$. The time-dependent calculation starts from an initial state, and after a few characteristic accretion times the quasi-periodic behaviour of the flow is reached. The accretion flow is convectively unstable and, as a result, hot convective bubbles quasi-periodically originate in the innermost region of the flow. Two subsequent convective bubbles are clearly seen in the upper hemisphere of the model. The bubbles consist of hot and low density matter, and move outwards under action of the buoyancy force, deviating in the polar direction. Typically, the subsequent convective bubbles move outwards in different directions, in the upper and lower hemispheres.
The two-dimensional nature of the SSD–ADAF transition is overlooked in an approach based on vertical integration. Indeed, in a number of papers on global solutions of vertically integrated accretion disk, models of sharp transitions between an SSD and an ADAF have been presented, without sufficiently mentioning the limitations of the 1-D approach (e.g. Narayan, Popham 1992; Honma 1996a, 1996b; Manmoto et al. 2000).

The vertically integrated 1-D calculations of thermal fronts propagation in thin disks meet a similar problem (for the models of cataclysmic variables see Hameury et al. 1998, and references therein; for the limit-cycle models see Honma, Matsumoto, and Kato 1991; Szuszkiewicz, Miller 1997, 1998). In these models the thermal instability causes the formation of a geometrically thick and hot inner region of the accretion disk, which expands outward, forcing (artificially, due to assumptions) the outer, Shakura–Sunyaev type, region of the disk to change its state in the narrow transition region. Although it could be that the 2-D consideration of the transition region in these cases will not change the results of 1-D approach drastically, because of a small contrast (a factor of few) of the thicknesses of perturbed and unperturbed parts of the disk, only 2-D models could eventually remove all doubts about the physical validity of the methods that are now commonly used.

Another example of the problem of disk transition solved in the 1-D approach was given by Meyer and Meyer-Hofmeister (1994), who use the thermal conduction in the vertical direction to transport energy into the evaporation region. Again, this reduces the full 2-D problem to 1-D and excludes from consideration the very important factor of the radial energy conductive flux.

We argue that the proper way to treat the thin–thick disk transitions, in all astrophysical contexts mentioned above, should take into account the 2-D nature of the problem, and that the 1-D methods that have been used so far are not satisfactory in this respect. Unless someone proposes a clever new method to incorporate the relevant physics into the vertically integrated equations, the only remaining alternative is to use 2-D numerical simulations.

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