Segregation of a Keplerian disc and sub-Keplerian halo from a transonic flow around a black hole by viscosity and cooling processes

Kinsuk Giri, Sudip K. Garain and Sandip K. Chakrabarti

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INTRODUCTION

- A standard Keplerian disc is not capable of explaining the entire X-ray and gamma-ray spectrum characterizing an accreting black hole candidate.
- To overcome this difficulty, several models were proposed to explain the power-law component arising out of Comptonization of soft photons by a hot electron cloud.

- Chakrabarti and Titarchuk (1995) explained the spectra using a truly global solution called two-component advective flow (**TCAF**).
- **TCAF** : a sub-Keplerian flow which produces a centrifugal barrier close to a black hole (called **CENBOL** means **CEN**trifugal pressure dominated **BO**undary **L**ayer) and surrounds a Keplerian disc.

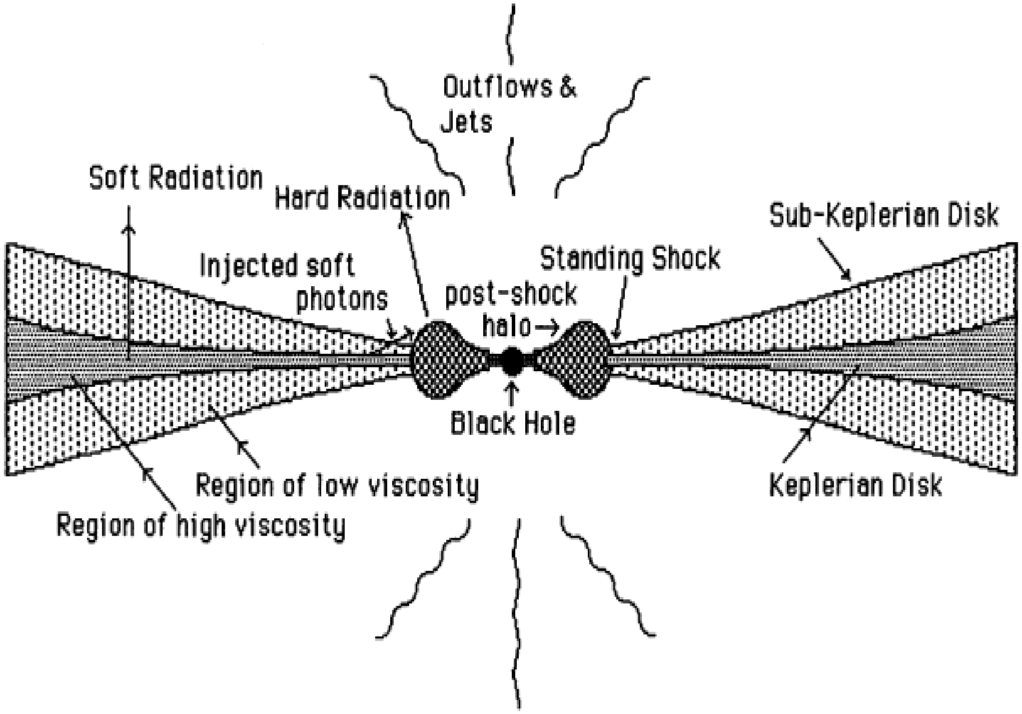


FIG. 1.—Schematic diagram of the accretion processes around a black hole. An optically thick, Keplerian disk which produces the soft component is surrounded by an optically thin sub-Keplerian halo which terminates in a standing shock close to the black hole. The postshock flow Comptonizes soft photons from the Keplerian disk and radiates them as the hard component. Iron line features may originate in the rotating winds.

- Unlike other self-similar solutions for accretion (especially the popular one ADAF), the TCAF solution was taken straight out of theoretical study of the behaviour of topology of viscous flow around black holes (Chakrabarti 1990,1996).
- There have been several works which support the TCAF solution observationally (Smith et al. 2001a, 2001b; Miller et al. 2001; Soria et al. 2009, 2011; Cambier & Smith 2013).

- There have been a lot of work which established TCAF as only theoretical solution describing the whole system (disc plus outflows), spectral and temporal properties.
- This work to be discussed in detail is fourth paper in a series of papers on hydrodynamic simulation and establish TCAF solution with hydrodynamic and radiative properties exactly as proposed originally 20 years ago.

- In this work, the cooling processes have been used which depend on optical depths at a given point.
- In earlier works as well, it was established that depending on the viscosity parameter, a viscous flow may produce a Keplerian disc on equatorial plane and a sub-Keplerian flow away from the equatorial plane.

- Regarding viscous transonic flow, it was pointed out that the flows with critical viscosity parameter everywhere can only form a Keplerian disc.
- For TCAF solution, one component with higher viscosity parameter is a cooler, Keplerian disc on the equatorial plane, accreting in a viscous time scale. The second component is a low angular momentum flow with lower viscosity parameter which forms a centrifugal pressure supported standing or oscillating shock and is accreting in almost a free-fall time scale.

BASIC EQUATIONS AND COOLING LAWS

- Two-dimensional axisymmetric flow around a Schwarzschild black hole. Cylindrical coordinate system is adopted with z-axis being rotation axis of the disc.
- A smooth distribution of viscosity parameter is chosen such that viscosity parameter is high on the equatorial plane and low away from it.

- The reason is the high viscosity on the equatorial plane drives the accretion and the rate of angular momentum transport should be highest there. Away from the plane, the pressure falls very slowly and in order to reduce viscous effects, viscosity parameter itself must go down.

- The power law cooling used a proxy for Comptonization as well as bremsstrahlung cooling.
- At each time step, optical depth was computed along vertical directions starting from upper grid boundary to the equatorial plane. As soon as Keplerian disc starts forming a sudden increase in optical depth is found and the height of the Keplerian disc is defined where the optical depth changes abruptly.

- In case of thin Keplerian disc, the energy is assumed to be radiated from the surface in the form of a blackbody radiation.
- In the region below the Keplerian disc surface, a separate cooling is not necessary as the energy is produced in expense of gravitational energy of the flow.

SETUP OF THE PROBLEM

$$\phi(r, z) = -\frac{G M_{\mathrm{BH}}}{(R - R_{\mathrm{g}})}$$

Relativistic flow around non-rotating black holes

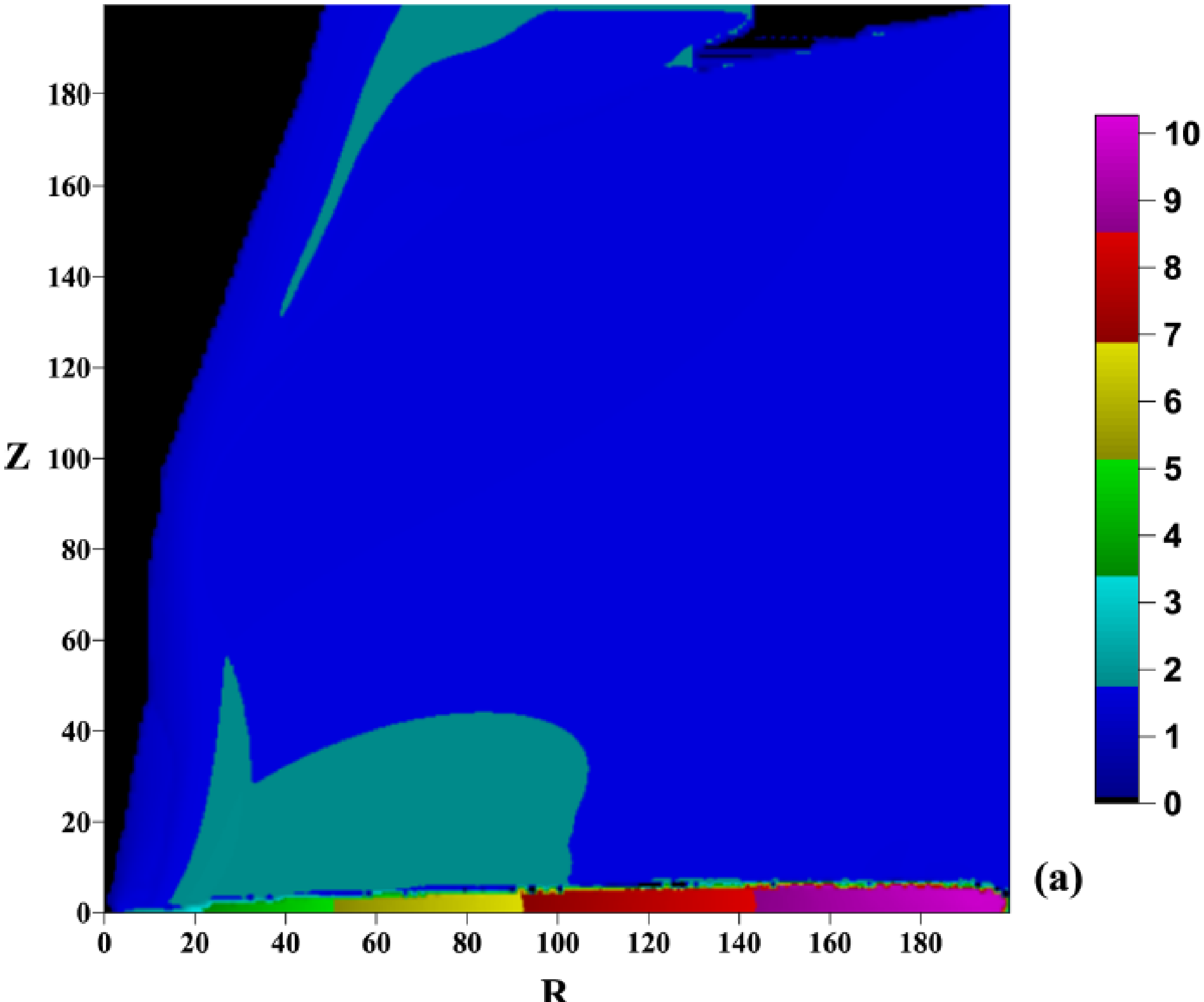
Accretion flow in vertical equilibrium at the outer boundary so that matter can be injected according to exact theoretical transonic solution (Chakrabarti 1989).

- In order to mimic the horizon of black hole, an absorbing inner boundary at 2.5 Schwarzschild radii, inside which all the matter is completely absorbed.
- 512 X 512 cells for calculation.
- All simulations were carried out for a 10 solar mass black holes.
- System of equations numerically solved using a grid-based finite difference method called TVD (Total Variation Diminishing) technique.

Table 1. Parameters used for the simulations at a glance.

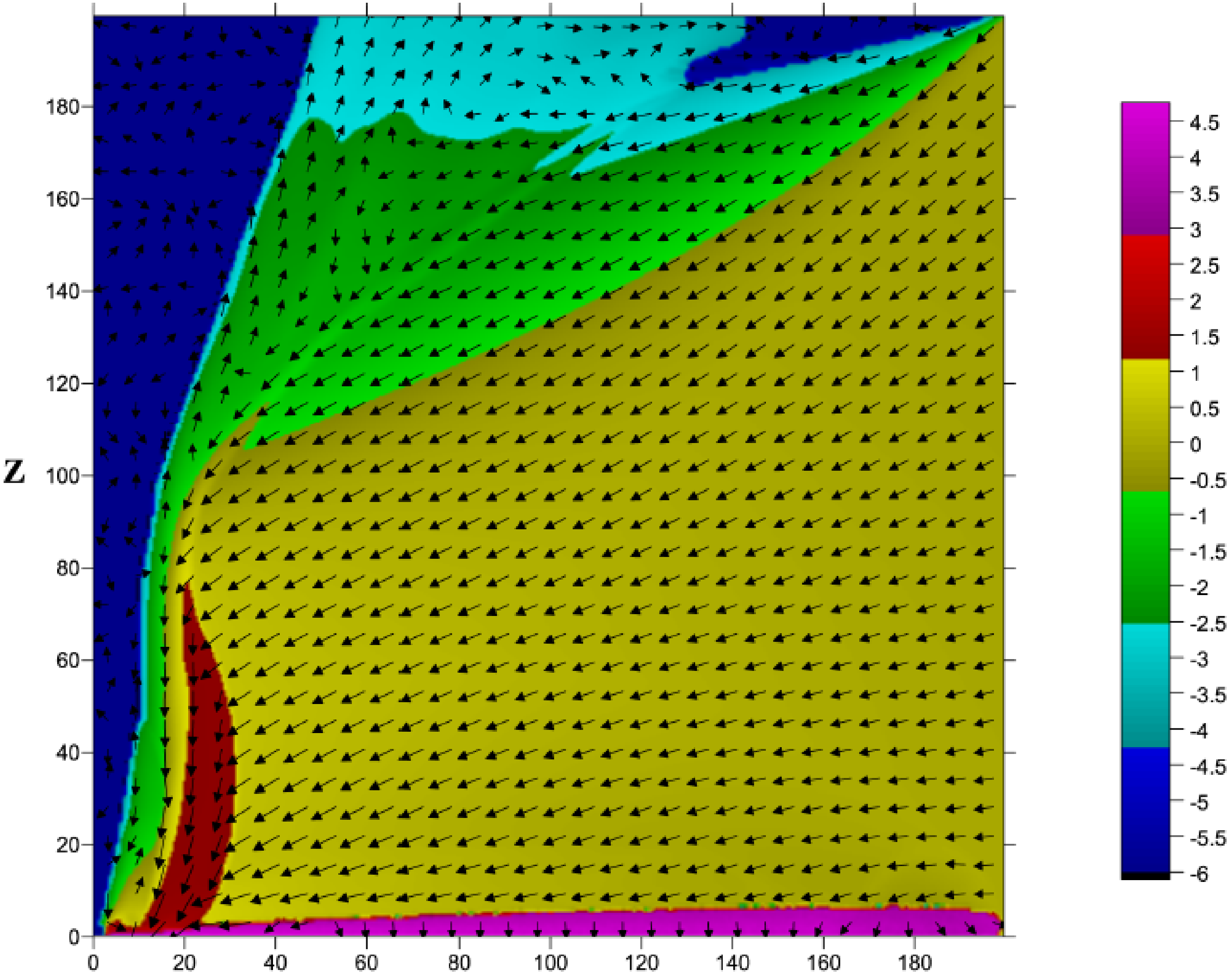
Case ID	$\mathcal{E}$	λ	$\dot{M}$	α
C1	0.001	1.70	2.0	0.012
C2	0.001	1.70	1.5	0.012
C3	0.001	1.70	1.0	0.012
C4	0.001	1.70	0.5	0.012
C5	0.001	1.95	2.0	0.012

Specific angular momentum distribution for case C1 (2 Edd.)

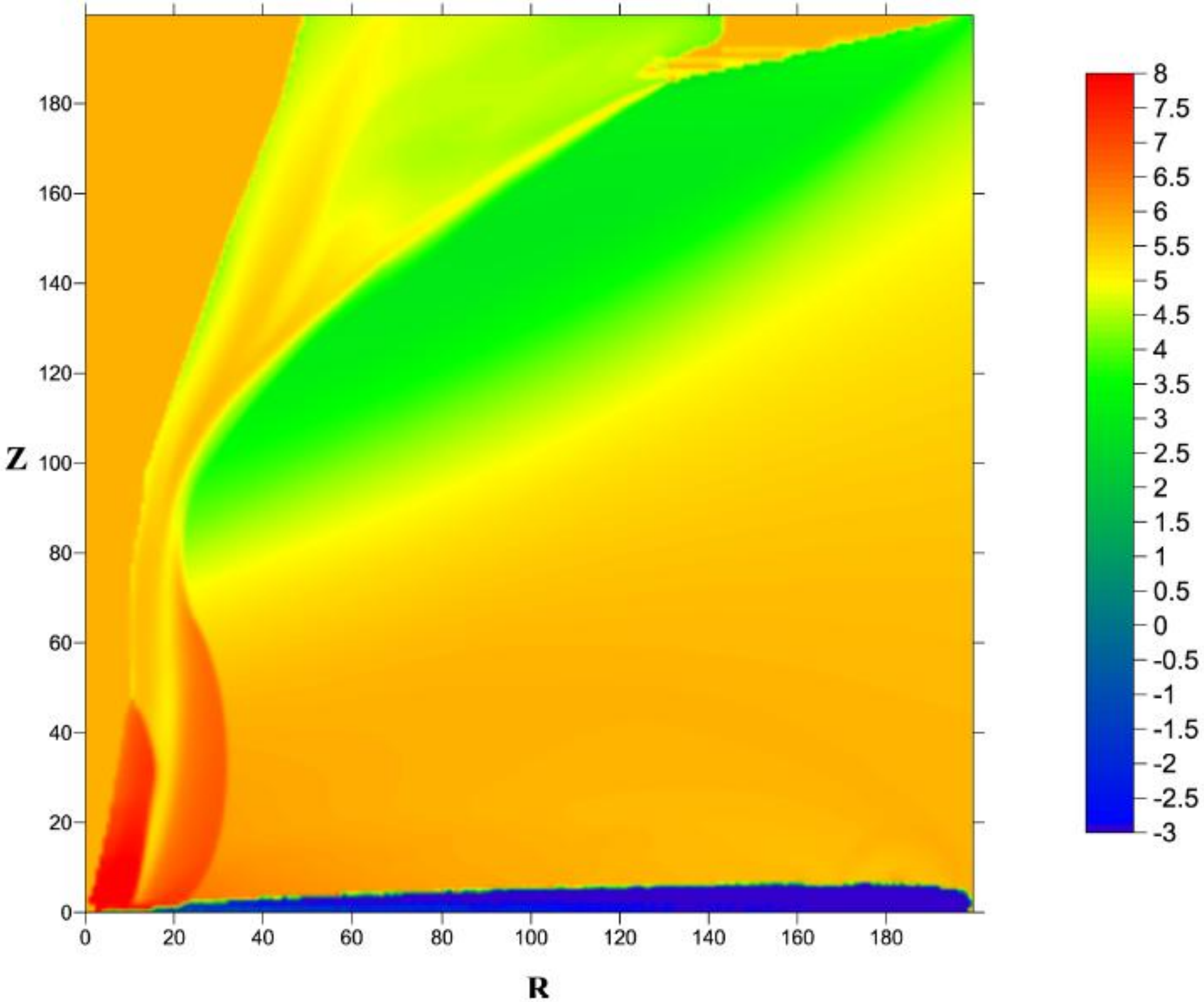


- The simulated specific angular momentum distribution throughout r-z plane for case C1.
- In the frame of sub-Keplerian matter, the Keplerian disc behaves as an obstacle. This causes the formation of a wake at the tip of the outer edge of simulated Keplerian flow.
- Here it is demonstrated that a Keplerian disc forms not by removal, but by redistribution of injected angular momentum.

Density and velocity distributions in log scale for case C1(2 Edd.)



Temperature in keV in log scale for case C1 (2 Edd.)



- The most prominent features are the formation of a TCAF.
- For higher viscosity, the flow has a Keplerian distribution near the equatorial region.
- A Keplerian disc is formed out of sub-Keplerian matter by redistributing angular momentum, unlike other works involving condensation of matter from a corona to a cool, optically thick disc (Taam et al. 2008).
- Simulated Keplerian disc is automatically truncated at R around 15 Schwarzschild radii and a CENBOL is produced in between the Keplerian disc and the horizon.

Accretion rate and surface temperature of simulated Keplerian disc for C1,C2,C3,C4

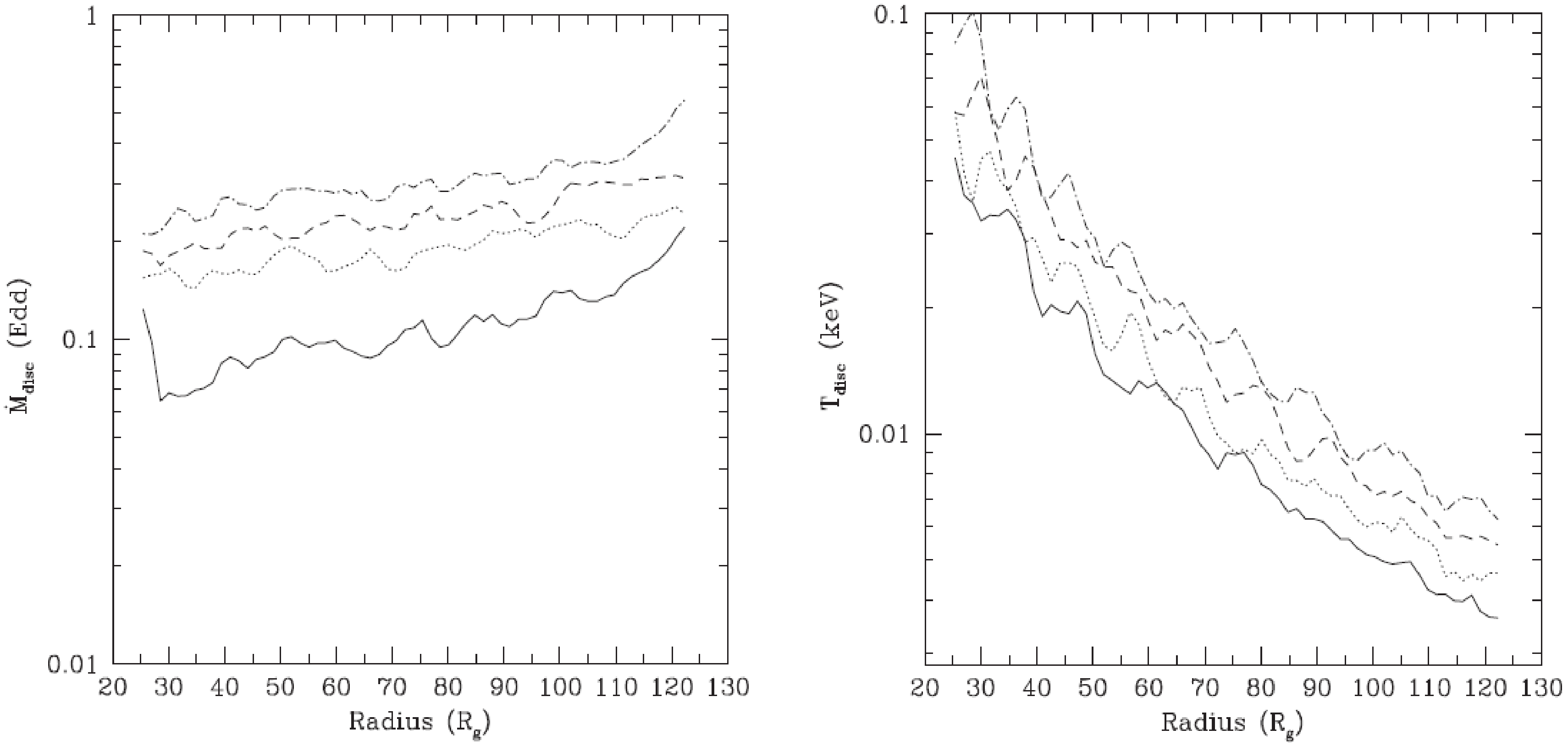


Figure 3. Changes in (a) accretion rate ($\dot{M}_{\rm disc}$) and (b) surface temperature of simulated Keplerian disc ($T_{\rm disc}(r)$) with change of injected accretion rate parameter $\dot{M}$ at $t = 95$ s. Here, $T_{\rm disc}(r)$ is in keV unit, ($\dot{M}_{\rm disc}$) is in Eddington rate unit and radius is in the Schwarzschild unit. For both the figures, from top to bottom, the curves are for C1, C2, C3 and C4, respectively. For details, see the text.

- Unlike standard thin disc model where mass accretion rate is assumed to be constant at all radius for a given case, mass accretion rate of simulated Keplerian disc appears to be radial dependent. This has important implications in disc model fitting of observed data as pointed out in Dutta & Chakrabarti (2010).

Disc and halo rates for case C3(1 Edd.)

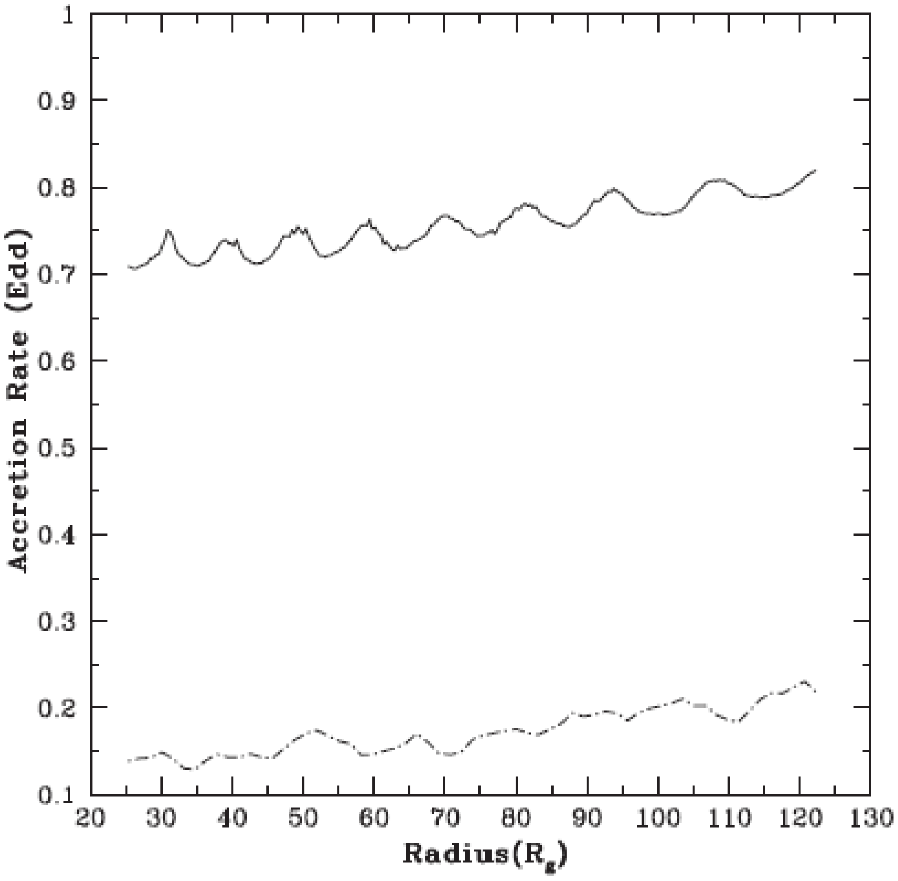


Figure 4. Comparison of the disc rate $\dot{M}_{\rm disc}$ and halo rate $\dot{M}_{\rm halo}$ along the radial direction in our simulation for the C3 case. Here, accretion rate is in units of the Eddington rate and the distance is in units of the Schwarzschild radius.

- For the case C3 (where mass injection rate at outer boundary is 1 mass Eddington rate), average disc rate varies around 0.15 while that of halo rate is 0.7. It is understandable that rest of the injected matter moves away from the system as an outflow.

Variation of shock location (2 Edd.)

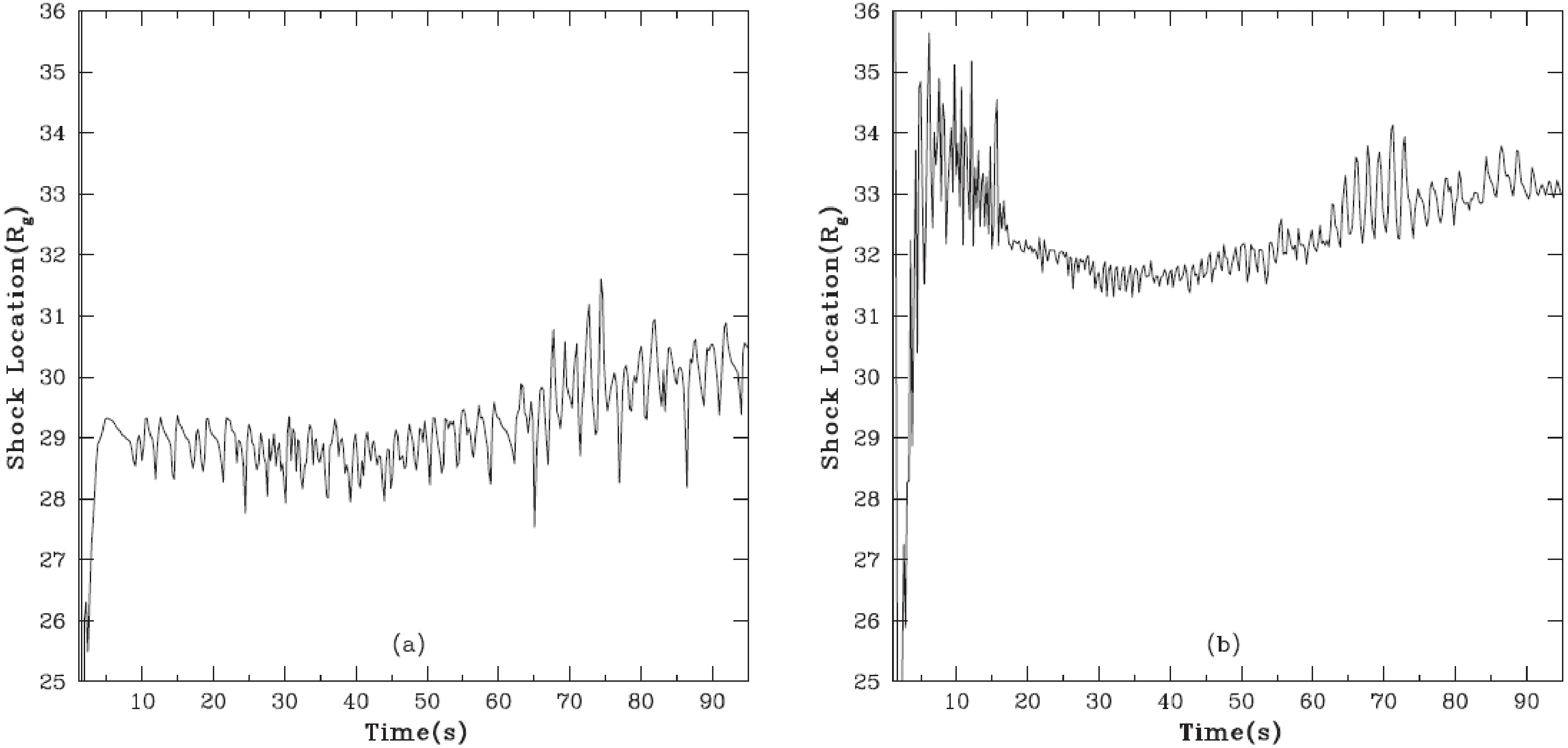


Figure 5. Variation of shock location with time (in seconds) when angular momentum is increased: (a) $\lambda = 1.7$ (C1), (b) 1.95 (C5).

- The shock oscillation can be the cause of quasi-periodic oscillations or QPOs (Molteni et al. 1996, Chakrabarti et al. 2004; Garain et al. 2014). The presence of oscillations in shock can be seen here as well.
- Mean shock location increases when the specific angular momentum is increased from 1.7 to 1.95 due to enhancement in centrifugal pressure as was explained theoretically in 1989 by Chakrabarti.

Temporal variations of luminosity (2 Edd.)

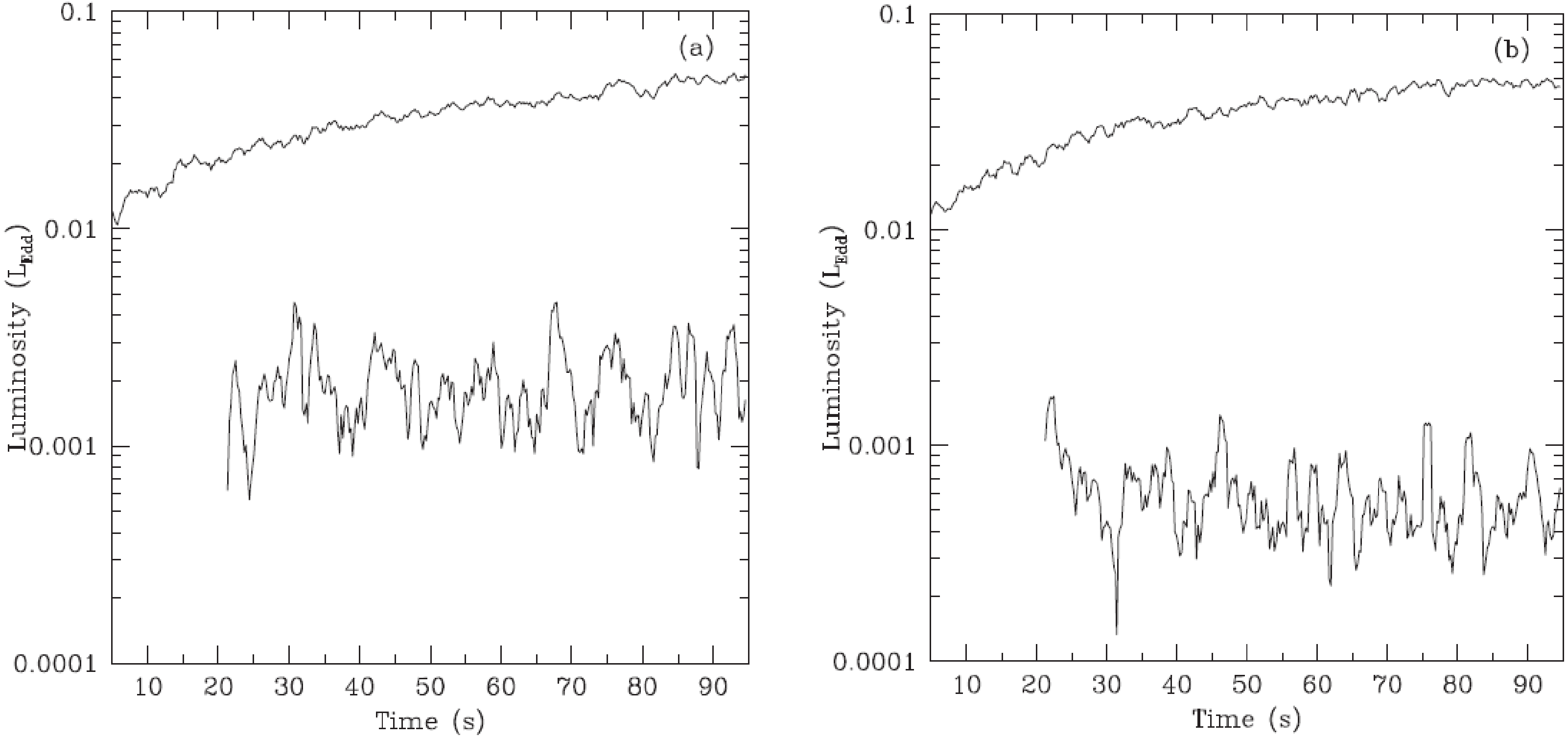


Figure 6. Temporal variations of luminosity for both hot sub-Keplerian flow and Keplerian disc are shown when angular momentum is increased: (a) $\lambda = 1.7$ (C1), (b) 1.95 (C5). In each of the figure, the top curve represents the hot flow while the bottom represents the Keplerian disc. Luminosity is in units of Eddington luminosity and time is in seconds. See text for details.

- Total luminosity of simulated TCAF is the sum of luminosity of Keplerian as well as sub-Keplerian components.
- In both the plots, top curve is for sub-Keplerian, hot flow whereas bottom curve is for Keplerian, cold disc.
- Because of large volume of the sub-Keplerian component, it luminosity is higher than that of Keplerian disc by a large factor. This difference would be reduced with increase in viscosity when more matter settles to the Keplerian component.

CONCLUSIONS

- A transonic flow splits into a standard disc in regions of high viscosity parameter (near the equatorial plane), while regions of lower viscosity and inefficiently cooling matter would remain advective above and below the Keplerian disc.
- The standard disc emitting blackbody can survive even when it is sandwiched between fast moving (but slow-rotating) sub-Keplerian flows above and below.

- The sub-Keplerian flow, due to inefficient loss of angular momentum ends up producing a centrifugal-pressure-dominated shock near the inner edge, “evaporating” (in fact, truncating) the Keplerian disc which behaves as Compton-cloud, responsible for producing the power-law component of emitted spectrum.

- CENBOL is also believed to be responsible for producing jets and outflows. Its oscillation is resposible for low-frequency QPOs.
- This work establishes the stability of TCAF solution beyond any doubt and TCAF can be safely used for fitting spectral and temporal properties.