Time variability of low angular momentum accretion flows around black hole

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We present the relativistic 2D and 3D GRMHD simulation of axisymmetric, inviscid, hydrodynamic accretion flows in a fixed Kerr black hole gravitational field. The flow is having low angular momentum with respect to Keplerian one. A relativistic fluid where its bulk velocity is comparable to the speed of light, flowing in the accretion disk very close to the horizon should be described by adiabatic index: $4/3 < \gamma < 5/3$. The time dependent evolution of shock position and respective effect on mass accretion rate and oscillation frequency with varying adiabatic index has been studied. Here we present some of the results for adiabatic index $= 1.4$ in a 2D and 3D model.

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1. Introduction

Observations show the emission of hard and soft photons at high energies (X-ray or gamma ray) in the spectrum of black hole accretion flows [1]. These hard photons are observed at very high frequency which implies that they are produced close to black hole horizon. As the quality and quantity of the high-energy observations improved over the years, evidence mounted showing that photons must be created in a hot, tenuous, advection dominated region called the corona. This corona, boiling violently above the comparatively cool disk, is very close to the event horizon of the black hole. The observed spectrum of the black hole accretion flows is in reality partly coming from the quasi spherical low angular momentum flow component. Sub-Keplerian accretion disk with possible multitransonic flow has now been discussed in much details over the past few decades.

It is well known that matter very far from black hole having negligible speed i.e less speed than the local sound speed has to fall into the black hole with the speed of light to satisfy causality condition. Thus the transonic mode of accretion is the most viable scenario as the flow must cross sonic points in order to turn from subsonic to supersonic [4] [3] [2].

Inviscid flow of infalling matter, rotating with low angular momentum, feels the centrifugal barrier near the horizon for a while as the centrifugal force \(1/r^3\) increases rapidly compared to the gravitational force (which goes as \(1/r^2\)) as the distance \(r\) decreases. This initially slows down the matter typically through a shock transition, and matter piles up, eventually making a possible density jump before entering the black hole supersonically.

The general outcome of all the past analysis of the inviscid accretion models in general relativistic regime with relativistic EoS shows that the transonic, radiative, and thermodynamic behaviour of the flow are strongly related to its composition. Adiabatic index gives away the information about microphysics of the flow and thus different values of \(\gamma\) correspond to different types of astrophysical objects or different phases of astrophysical activity. The temperature range for advective accretion flow is \(10^6 K < T < 10^{11} K\) which shows that same value of \(\gamma\) is not able to explain whole scenario. In reality, adiabatic index must have a value in between 4/3 and 5/3. For example, weakly active galaxies, such as Sgr A, usually studied using a polytropic EoS with \(\gamma\) around 5/3, because these flows are believed to be radiatively inefficient and gas pressure dominated. The other scenario could be imagined of GRBs which are a blend of electron-positron pairs, nucleons, photons and neutrinos [12] where the accretion flow is radiation pressure dominated, and requires a relativistic EoS with \(\gamma = 4/3\). Also, even smaller values of adiabatic index, close to isothermal value of 1.0, may be relevant to the systems like the proto-planetary and proto-galactic disks.

Among the parameters determining the sonic points and shock position in the transonic solution, adiabatic index also seems to play a crucial role in determining the formation of standing or oscillating shocks [2]. The oscillations of these shock fronts depend upon the physical properties of the matter and may give an explanation for the observed quasi periodic oscillations in black hole X-ray light curves.

In former work [9], the numerical studies of quasi-spherical transonic accretion and time-dependent evolution of the shock position were for the first time addressed in a fully General Relativistic scheme. This is why the results obtained were not only qualitatively, but also quantitatively...
relevant for the observation of realistic sources, where the GR effects cannot be neglected in the closest vicinity of the black holes. That work however was limited to the choice of a fixed parameter, namely the adiabatic index of $\gamma = 4/3$. In the recent work [14], we explored other values of $\gamma$ to study the role of adiabatic index in producing different pattern of shock evolution. Here we present the follow-up of [14] by extending our simulation in 3-Dimension for few models.

2. Initial Conditions

To study the accretion flow of non-viscous matter, we start with the polytropic equation of state: $p = K \rho^\gamma$ where $\gamma$ is the adiabatic index, $p$ is the gas pressure and $\rho$ is the gas density. The details of the initial conditions prescription is given in [9], [13] and [14].

Unlike for a thin disc, here we assume the quasi-spherical distribution of the gas, provided by constant specific angular momentum $\lambda$ [10]. Such a distribution of matter is possible to be formed instead of an evaporated Keplerian accretion disc.

A transonic flow of matter makes a jump from supersonic to subsonic region at certain position, which is called shock ($r_s$) [11]. The region from shock to inner sonic point is defined as the post shock region, which basically acts as CENBOL (CENtrifugal force dominated BOundary Layer) region. The increase in density across the shock is described by compression ratio, $R_{\text{comp}} = \rho_+/\rho_-$ where $\rho_+$ is post-shock density and $\rho_-$ is pre shock density. The initial conditions that we use here to study the $\gamma$ dependence of the sonic surface are similar to those used in previous work [13]. The rotation, i.e. the angular momentum of the flow has been prescribed according to the relation

$$\lambda = \lambda^{eq} \sin^2 \theta, \quad (2.1)$$

where $\theta = \pi/2$ and $\lambda^{eq}$ is the angular momentum in the equatorial plane. The definition of angular momentum goes as usual, $\lambda = u^\theta$. Our initial state does not correspond to the stationary state, because that is derived for quasi-spherical distribution of gas with constant angular momentum in the pseudo-Newtonian potential. However, as we scale angular momentum according to relation (2.1) and we are in the general relativistic regime, the resulting configuration is not the solution of the stationary time-independent equations. Hence, it is expected that at the beginning of the simulation during a transient time, the flow adjust itself into the appropriate profile.

2.1 Transonic accretion:

A transonic flow of matter consists of three real critical points. The initial subsonic flow enters through the outer boundary and becomes supersonic at the outer sonic point, which in our case coincides with the outer critical point. Then it may jump from the supersonic branch of solution to the subsonic one at the point, which is called shock($r_s$) [11]. The region from shock to inner critical point i.e inner sonic point is being defined as the post shock region, which basically acts as CENBOL region. We get two values for velocity gradient at critical point, which are obtained as real and opposite to each other. This shows that the nature of the critical points are saddle type [14]. The models are parameterized by the value of the specific angular momentum $\lambda$, polytropic exponent $\gamma$ and the energy $\varepsilon$, which set the critical point position $r_c^{in}$, $r_s$, $r_c^{out}$ [15].
2.2 Time evolution:

The model in 2D has been evolved till $t_{final} = 10^6[M]$ and the final time of evolution for model in 3D is till $t_{final} = 10^4[M]$. The inner mass accretion rate has been calculated as in [16]:

$$M(r,t) = \int \rho u' \sqrt{-g} d\theta d\phi$$ (2.2)

3. Numerical setup

The quasi spherical, slightly rotating flow in all the models in our simulations, starts with the initial condition prescribing the critical point and the velocity gradient at the critical point derived in [13]. The model parameters i.e the specific energy ($\varepsilon$), specific angular momentum ($\lambda$), adiabatic index ($\gamma$), spin of black hole (a) and distribution of angular momentum are chosen in the initial condition, which set the properties of the flow. The evolution of non-magnetized gas (as assumed in our initial conditions) is simulated with the HARM package supplied with a few modifications (see [9] and [14]). HARM (high-accuracy relativistic magnetohydrodynamics), is a conservative, shock-capturing scheme for evolving the equations of general relativistic MHD [17].

3.1 Grid setup:

The inner and outer radius of the computational grid $R_{in}$ and $R_{out}$ are set as $0.2[M]$ and $50000[M]$. The resolution for model in 2D and 3D has been chosen as $[384 \times 256 \times 1]$ and $[384 \times 256 \times 92]$ in radial, polar and azimuthal direction respectively.

4. Results

The different behaviour of transonic flow corresponding to different parameter set has been presented and discussed in extension in [14]. Here in addition to those results, we present two models G6 and I4.

Here Model G6 is a 3D model similar to the 2D model, D6 with parameters [$\gamma = 1.4, \lambda = 3.6[M], \varepsilon = 0.0001$] from [14]. In model G6, the flow has been followed in phi direction as well with 92 grid points. 3D simulations are more realistic than 2D simulations but due to the axially symmetric nature of the Kerr metric, the results in 2D and 3D models are similar to each other here. Another model I4 is a 2D model with similar parameters as 2D model H4 [$\gamma = 1.4, \lambda = 3.6[M], \varepsilon = 0.0001, \text{spin}(a) = 0.1$] from [14] but with higher spin (a = 0.8).

Figure 1 shows the cartesian plots for 3D model G6, where the spherical Boyer Linquidst coordinates $(r, \theta, \phi)$ have been transformed to X,Y, Z as:

$$X = r \sin(\theta) \cos(\phi)$$ (4.1)
$$Y = r \sin(\theta) \sin(\phi)$$ (4.2)
$$Z = r \cos(\theta)$$ (4.3)

The figure panel consist of of four quantities plotted in X and Z direction namely density, Mach number, angular momentum and radial velocity in clockwise direction.
Mach number is a dimensionless quantity which is the ratio of local flow velocity w.r.t local sound speed and thus it tells us about how fast or slow the matter is going. When radial velocity of matter is more than sound speed, it travels supersonically and hence shown here in red color. Similarly matter moving subsonically has been represented as blue color in Mach number plots. The growth of shock bubble can be seen in different time slices. It has been observed in 2D model D6 that shock bubble was having both vertical and horizontal oscillation during evolution of the flow (see [14]). The oscillation of the shock bubble in 2D model D6 was observed around $t \sim 10^5[M]$ which is longer time than the $t_{final}$ for 3D model G6 i.e $10^4[M]$. Thus here in model G6 only the growth of the shock bubble has been followed. In Figure 1, the scale in X and Z axis has been enlarged in time snapshots placed in 2nd row to show the expansion of shock bubble.

![Figure 1: Density, Mach number, angular velocity and radial velocity profile for a model with $\gamma = 1.4, \lambda = 3.6[M], \varepsilon = 0.0001$ from 3D model G6 at four different time snapshots.](image)

Figure 2 and 3 are the polar plots from the similar 3D model G6. These are depicting Mach number and density of the flow respectively from three different angles at two different time. The Mach distribution in second panel in Figure 2 can be seen completely subsonic near the black hole at $\theta = 90^\circ$ as it is not possible to see the supersonic inflow from polar sides on the equator slice. When viewed from slant angles, such as $\theta = 45^\circ$ and $\theta = 145^\circ$, the supersonic flow through the corners of the shock bubble can be seen. For longer runs, the oscillations in radial direction are expected to be seen more clearly in $r-\phi$ plots as the size of subsonic part will vary if seen from $\theta = 45^\circ$ and $\theta = 145^\circ$ at same time. Density distribution in polar plots in Figure 3 can be seen...
as maximum for $\theta = 90^\circ$ i.e on equator and almost similar profile for $\theta = 45^\circ$ and $\theta = 145^\circ$ similar as seen in 2D models. Hence our results from 3D model G6 till $t = 10^4 [M]$ is similar to that from 2D simulations till this very time. Investing more longer computational hours will show us more accurate oscillation position of shock bubble. This will also help us to acquire more accurate estimation of oscillation frequencies and thus to have better comparison with observed QPOs (Quasi Periodic Oscillations).

$$t = 0[M]$$

![Mach number profile for a model G6 with $[\gamma = 1.4, \lambda = 3.6[M], \varepsilon = 0.0001]$ at two different time snapshots.](image)

$$t = 6700[M]$$

![Mach number profile for a model G6 with $[\gamma = 1.4, \lambda = 3.6[M], \varepsilon = 0.0001]$ at two different time snapshots.](image)

**Figure 2:** Mach number profile for a model G6 with $[\gamma = 1.4, \lambda = 3.6[M], \varepsilon = 0.0001]$ at two different time snapshots.

Figure 4 shows the mass accretion rate and the shock evolution with time for a model with $[\gamma = 1.4, \lambda = 3.6[M], \varepsilon = 0.0001, \text{spin}(a) = 0.8]$ from 2D simulation. This is similar to our model H4 from [14] but with higher spin i.e 0.8. Here we can see that our shock bubble expands over time through outer sonic point unlike our previous model where shock bubble had very nice oscillation for small spin of the black hole. This result is consistent with [9] where it has been shown that with higher spin it is required to have lower angular momentum of the flow so that the shock can oscillate. The mass accretion rate has been zoomed out in the inset in panel 1 of Figure 4 to show the accretion rate from only inner sonic point after the shock gets expanded through outer sonic point.

5. Astrophysical significance

Our results are important in connection to the observations of the low frequency QPO’s (LFQPO) in microquasars. Microquasars have been observed doing oscillations in range of few hundreds mHz up to few tens of Hz.
**Figure 3:** Density profile for a model G6 with $[\gamma = 1.4, \lambda = 3.6], \epsilon = 0.0001$ from 3D simulation at two different time snapshots.

**Figure 4:** Panel 1 shows the mass accretion rate for model I4 with $[\gamma = 1.4, \lambda = 3.6], \epsilon = 0.0001, \text{spin}(a) = 0.8$ and panel 2 shows the evolution of shock position with time.
These LFQPO’s have been observed in the frequency range of 0.05Hz - 10Hz in many x-ray binaries and microquasars such as GRO J1655-40, XTE J1118-480, XTE J1748-288, IGR J17091-3624 ([18], [19], [20], [21], [22]). We found that several models from our simulations show subtle and definitive shock front oscillations over time. The value of oscillation frequency obtained with our simulations is representative for the time variability found in the above microquasars. We get the estimated oscillation frequency range between 0.3Hz and 0.6Hz (from model D6), between 0.13Hz and 0.24Hz (from model H4), and between 4.8Hz and 8.6Hz (from model D3) (see [14] for details of these models).

Our frequency range fits broadly into the observed frequency of such sources. Our simulation results are also in good agreement with the frequency range (0.1Hz - 15Hz) observed in black hole system GRO J1655-40. This shows that our model could be a good explanation for LFQPO’s from these sources, under the assumption that the oscillations come from the inner parts of the adiabatic flow described with $\gamma = 1.4$ that accretes onto a spinning, or non-spinning black hole. Further investigation is needed to study in detail the range of spins of the Kerr black holes that is able to produce an oscillatory shock behaviour in the low angular momentum accretion flows. Finally, our investigations of the shock front oscillation may be relevant for some of the observed Active Galactic Nuclei. Here the observations are not as definitive as in the case of Galactic X-ray binaries, but the combined constraints from the energy spectrum and variability show that the soft excess is likely arising from the low-temperature Comptonization of the disc. This remains more or less constant on short time-scales, diluting the QPO and rapid variability seen in the power-law tail of the Seyfert galaxy RE J1034+396 [23]. Also, after careful modeling of the noise continuum, the $\sim 3.8$ hr QPO was found in the ultrasoft AGN candidate 2XMM J123103.2+110648 [24]. The tentative detection might suggest that the shock front in this AGN oscillates in several modes (equatorial, polar, azimuthal), as suggested by our results.

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