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Transonic structure of slowly rotating accretion flows with shocks around black holes

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Abstract. We present recent results of the studies of low angular momentum accretion of matter onto Schwarzschild black hole using fully relativistic numerical simulations. We compare the resulting 2D structure of transonic flows with results of 1D pseudo-Newtonian computations of non-magnetized flow. The research has observable consequences on black holes on the whole mass scale, in particular it is related to the time-scale and shape of luminosity flares in Sgr A* or to the evolution of QPO frequency during outbursts of microquasars.

Keywords. accretion, accretion disks, hydrodynamics, shock waves, X-rays: binaries

1. Introduction

With the growing number of available X-ray data especially from the dedicated X-ray satellites, the complicated behaviour of the microquasars during their outbursts have been spotted. It has been realized, that the accretion through the simple Shakura-Sunyaev accretion disc is not able to explain different phenomena occurring in the those sources, e.g. quasiperiodic oscillations (QPOs) and flares or the spectral and timing properties of the lightcurves. Hence, different models were proposed to describe such behaviour.

Usually, in those models, two different components of the accretion flow are present, namely the cold Keplerian disc and a hot corona, which are responsible for different timing properties in soft and hard X-rays. However, the origin and geometry of the hot component are still under debate and different ideas have been set in the literature. Because of the short timescales in the hard X-ray component, the hot flow should exhibit high radial velocities and fast inflow. Therefore, the reasonable expectation is that it has a low value of angular momentum.

The flows with constant low angular momentum have been studied theoretically and the authors showed the possibility of standing shock appearance for certain subspace of the parameter space, for which there exist two different solutions going through the inner sonic point located very close to the black hole and the outer sonic point located far away from the central region (for discussion about low angular momentum flows see (Chakrabarti & Titarchuk, 1995) and references therein). The dependence of the shock location, which connects the two branches of solution, and shock strength on the parameters, especially on the angular momentum λ, energy ϵ and adiabatic index γ of the flow, leads to the possible movement and oscillations of the shock front with changing properties of the inflowing matter. Because at the shock front the dissipation processes

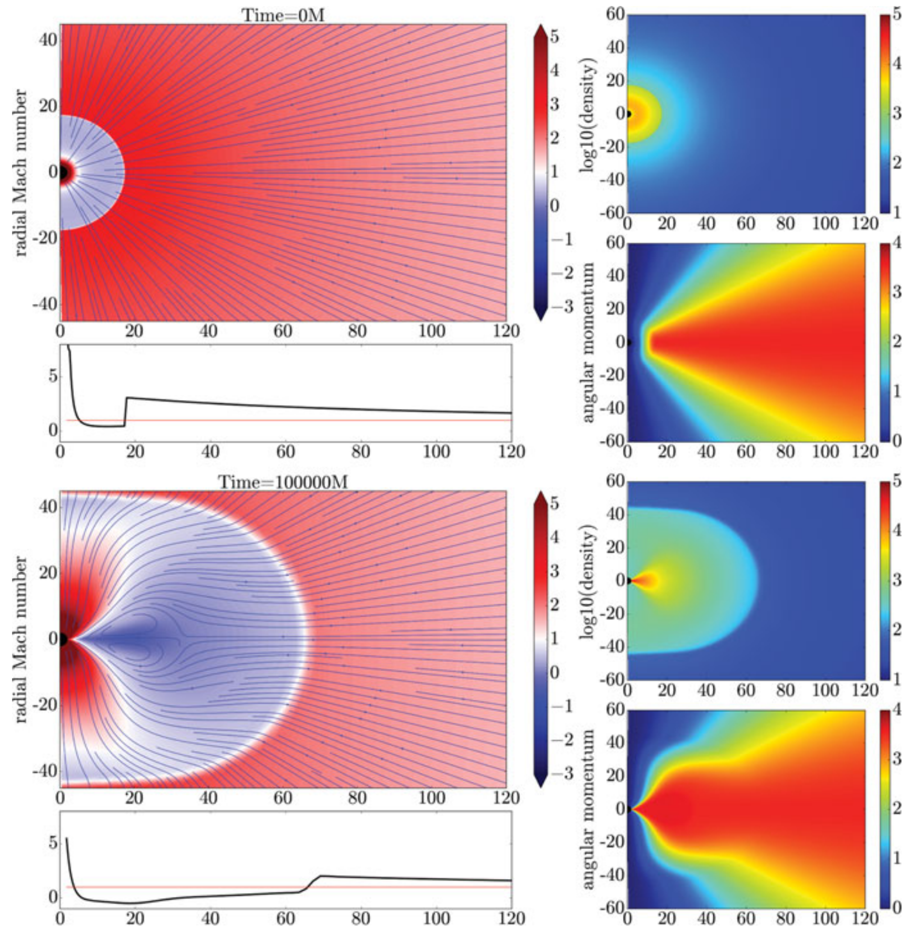

Figure 1. Top set of four panels: zoom of the initial conditions for simulation ($\lambda_{\max} = 3.54M, \epsilon = 0.0025, \gamma = 4/3,\ r_s^{\text{in}} = 14M$) – radial Mach number $\mathcal{M}$ and its equatorial profile on the left, and density ρ and angular momentum λ on the right. The x and y axes are measured in M, as well as λ, ρ is given in arbitrary units and $\mathcal{M}$ is dimensionless. Bottom set of four panels: the same for $t = 100\,000M$.

release energy in form of radiation, the movement of the shock front can have observational effects, such as QPOs with changing frequency. The propagating oscillatory shock (POS) has been used to explain the rise and decline of the low frequency QPO in several microquasars during their outburst (Nandi *et al.* 2012), however, there the behaviour of the shock (the shock strength and the shock front velocity) was inferred as a fit to the observational data. As such, this phenomenological model lacks the explanation of the shock appearance and motion.

We are interested in the appearance of the shock front and its movement in low angular momentum flows. In (Suková & Janiuk, 2015) we showed that the steady 1D solution of the slowly rotating flow is achieved in the corresponding 1D pseudo-newtonian hydrodynamical simulations with the code ZEUS. We found the shock front stable for lower angular momentum and oscillating around the theoretical position of the shock for higher values of angular momentum. We also observed the recurring formation and disappearance (very fast accretion) of the shock front when the angular momentum of the incoming matter was changed periodically.

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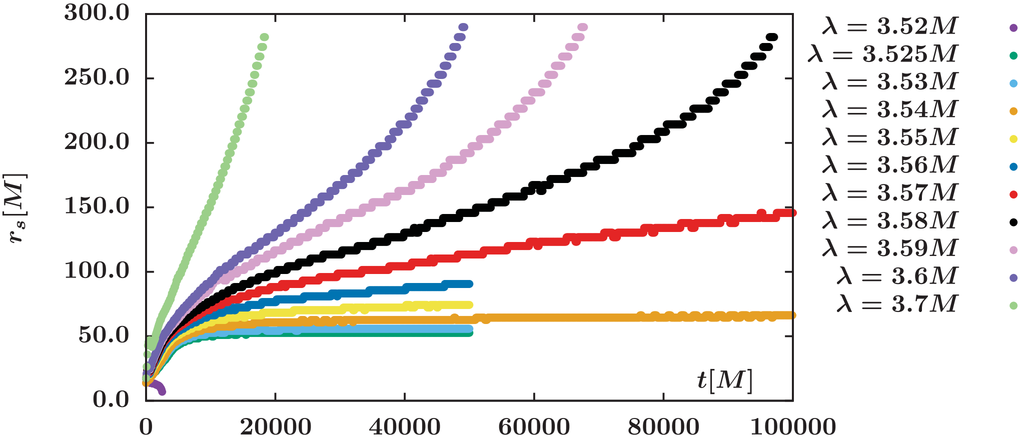

Figure 2. Time dependence of the location of the shock front in the equatorial plane for different λ. Other parameters are kept constant ($\epsilon = 0.0025, \gamma = 4/3$).

2. Numerical setup and initial conditions

Here, we study the behaviour of the shock in the framework of general relativity. For that purpose we use the code HARM, which has been equipped by 3D capabilities and MPI interface (Tchekhovskoy, Narayan & McKinney, 2011; and references therein). Our goal is to find out, if the 1D results can be generalised to realistic flows on the black holes, in particular, if there exist a stationary solution with standing shock or a solution with oscillating shock in higher dimension. Because we will use the cylindrically symmetric initial conditions, it is sufficient to compute 2D slice with constant ϕ. We use logarithmic grid in r with $r_{\rm out} = 20\,000M$ and the resolution is 256 x 128.

In (Suková, Charzyński & Janiuk, 2016) we showed, that if we start with the Bondi initial conditions for density ρ, pressure p and inward radial velocity u^r, which is modified by additional slow rotation given by a nonzero ϕ component to the four-velocity of the gas in the outer region according to $u^\phi = \frac{\lambda}{r^2}\sin^2\theta$, then the solution converges to the outer branch of solution, the so called "bondi-like" accretion. There, the sonic point lies far away from the center and the properties of the flow are similar to the Bondi solution, modulated by the centrifugal barrier close to the horizon.

Therefore, another type of initial conditions has to be used, if the shock front† properties should be studied. We start with the simplest generalization of our 1D pseudo-newtonian model and we took the profile of density, pressure, and inward velocity given by the solution with $\lambda_{\rm max}, \epsilon, \gamma$ for each streamline with constant angle θ. However, we use the initial location of the shock $r_{\rm s}^{\rm in}$ (i.e. the location where we jump from the inner branch to the outer branch of solution) as a free parameter, in other words we initially glue the branches of the solution at a chosen radius, not necessarily the one given by the 1D solution. Moreover, we prescribe the angular momentum $\lambda = -u_\phi/u_t$ according to the relation $\lambda = \lambda_{\rm max}\sin^2\theta$, where $\theta = \pi/2$ in the equatorial plane, hence we decrease the rotation towards the axis to avoid diverging velocities close to the axis. It is obvious, that our initial state cannot correspond to the stationary state. We expect a short transient period at the beginning of the computation, during which the flow will retain the corresponding shape.

† The shock front is the surface, where the radial Mach number $\mathcal{M} = u^r/c_s$ jumps from supersonic ($\mathcal{M} > 1$) to subsonic ($\mathcal{M} < 1$) regime). Here u^r is the radial component of the four velocity in Boyer-Lindquist coordinates and $c_s = \gamma p/(\rho + \gamma p/(\gamma - 1))$ is the local sound speed.

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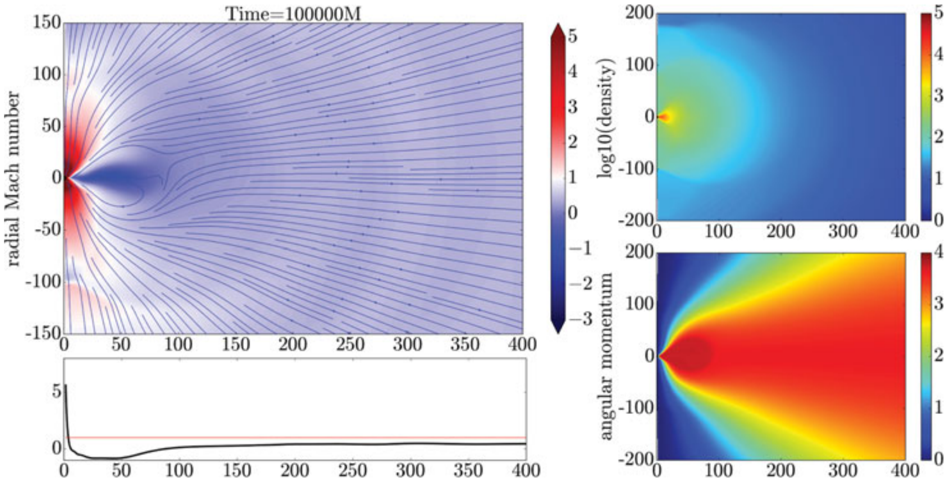

Figure 3. The same as in Fig. 1 for $\lambda = 3.6M$, $r_s^{in} = 18M$ and $t = 100\,000M$.

3. Results

For our study we have chosen the energy $\epsilon = 0.0025$ and the polytropic index $\gamma = 4/3$, while we are varying λ. Our 1D model predicts for this case the existence of shock solution for $\lambda \in (3.52 - 3.7)M$ with the shock locations $r_s \in (14 - 140)M$ and the outer sonic point location around 284M. The recent 2D simulations show, that for $\lambda_{max} = 3.52M, r_s^{in} = 14M$ the shock front is accreted onto the black hole. However, already for $\lambda_{max} = 3.525M, r_s^{in} = 18M$ the shock bubble grows and converges to stationary state with $r_s = 53M$, hence the position of the shock is much farther. The example of initial state and final converged state with $\lambda_{max} = 3.54M, r_s^{in} = 18M$ is given in Fig. 1.

With increasing angular momentum, the final shock location moves up and for $\lambda_{max} = 3.56 - 3.57M, r_s^{in} = 18M$ we do not obtain the converged state during our simulation time ($t_f = 50\,000M$ or $t_f = 100\,000M$ – see Fig. 2). For $\lambda_{max} \geqslant 3.58M$, the shock bubble grows so much, that it meets the outer sonic point and the shock front disappears. The example of such evolution is given in Fig. 3 for $\lambda_{max} = 3.6M, r_s^{in} = 18M$.

The presented set of simulations suggests, that the general relativistic 2D simulations put the shock front farther away from the black hole and so the interval of λ with stationary shock existence is smaller. We will continue our research with more detailed study of the shock behaviour depending on different initial geometries and on other important physical effects (spin of the black hole, magnetic field).

4. Acknowledgements

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References

Chakrabarti, S. & Titarchuk, L. G., 1995, *ApJ*, 455, 623
Nandi, A., Debnath, D., Mandal, S., & Chakrabarti, S. K., 2012, *A&A*, 542, A56
Suková, P., Charzyński, S., & Janiuk, A. 2016, *preprint arXiv:1602.07215*
Suková, P. & Janiuk, A. 2015, *Mon. Not. R. Astron. Soc.*, 447, 1565
Tchekhovskoy, A., Narayan, R., & McKinney, J. C. 2011, *Mon. Not. R. Astron. Soc.*, 418, L79