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GRMHD simulations of hard to soft state transition in X-ray binaries

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Abstract. Black hole binaries (BHBs) undergo state transitions during which their spectral and timing properties change dramatically. The nature of these state transitions is a long-standing open question. One leading idea is that they are associated with modulations in the mass accretion rate $\dot{M}$ which affect the amount of radiative cooling in the accretion flow. The goal of this project is to address the nature of state transitions in BHBs, by performing global 3D GRMHD simulations of accretion flows around stellar mass black holes (BH), incorporating the radiative cooling self-consistently in the dynamics through the bremsstrahlung, synchrotron and inverse Compton processes. We will use a state-of-the-art GPU-accelerated code and quantify how the inner radius of the thin disk and the properties of the hot corona (e.g. size and temperature) are related to the fundamental system properties such as $\dot{M}$ and BH spin. Along the way, we will compare our results with BHB observations.

Resumo. Binárias de buracos negros (BHBs) exibem transições de estados nas quais suas propriedades espectrais e temporais mudam drasticamente. A natureza dessas transições de estados é uma questão longínqua em aberto. Uma ideia principal é que elas estão associadas com modulações na taxa de acreção de massa $\dot{M}$ que afeta a quantidade de radiação de resfriamento no fluxo de acreção. O objetivo desse projeto é abordar a natureza das transições de estados em BHBs, desenvolvendo simulações 3D GRMHD de fluxos de acreção ao redor de buracos negros de massa estelar (BN), incorporando a radiação de resfriamento auto consistentemente na dinâmica através dos processos de bremsstrahlung, síncroton e Compton inverso. Usaremos um código GPU-acelerado de última geração, quantificando como a geometria (H/R, raio de truncamento) e fator de advecção dependem de $\dot{M}$, da topologia magnética e do spin do BN. Durante o percurso, nós compararemos nossos resultados com observações de BHBs. .

Keywords. Black hole physics – Magnetohydrodynamics (MHD) – X-rays: binaries

1. Introduction

In general, we can categorize a black hole into one of the two categories: a Supermassive Black Hole or a Stellar Mass Black Hole. A supermassive blackhole is usually found in the center of galaxies. Unlike stellar mass black holes, they were not formed in the evolution of massive stars and their formation history is still under study. They are usually very massive reaching millions or billions of solar masses. Stellar mass black holes are born in the latest phases of a star's evolutionary process due to the death of the star as a supernova remnant. They are usually found in different parts inside the galaxies.

Because the matter falls toward the black hole with some angular momentum, it will not fall in a straight line, but rather spin around before being accreted, forming a disk of matter rotating around the black hole. This matter will not spin in the same orbit, but rather spiral inwards. For this to happen, it is necessary a mechanism to withdraw the gas's angular momentum. Nowadays, it is believed that the mechanism responsible is the magnetorotational instability (MRI), which arises from magnetohydrodynamics (MHD) physics. As the matter from the disk loses energy and gets close to the black hole, radiation is emitted by the disk, being the main source for detecting them. Radiative losses will have an impact in the dynamics and properties of the accretion disk and plays a major role in the evolution of the system.

Black holes X-ray binaries (BHBs) are systems composed of a black hole and a companion star and have been identified to have two different spectral states throughout it's lifetime, the hard state and the soft state. The hard state is characterized by a hot, geometrically thick and optically thin accretion disk, while the soft state can be described by a geometrically thin and optically thick disk. When compared to supermassive black holes, the stellar mass ones have a much shorter dynamical timescale, in a way that it's possible to see BH X-ray binaries alternate between both states in periods of weeks. Radiative losses seem to be the main cause of state switching, allowing the transition from the hard state to the soft state.

The transient state is still under study, mainly in the way in which radiative cooling occurs. It is extremely important to characterize the functions responsible for this process. We will consider three different types of cooling, through bremmstrahlung radiation, synchrotron radiation and comptonized synchrotron.

This project aims to study the cooling of this systems, simulating black holes in the general relativity magnetohydrodynamics (GRMHD) regime. For this purpose, we'll use the code H-AMR (Liska et al. 2019), which is a GPU-accelerated 3D GRMHD code that has shown great results.

2. Radiative Cooling implementation in GRMHD code

`H-AMR` is a GRMHD code derived from HARMPI code, which derives from HARM2D code (Gammie et al. 2003; Noble et al. 2006). `H-AMR` uses a finite volume shock-capturing, Godunov-based HLLE scheme. It is assumed that the radiative cooling has a major role in the state transition. The aim of this research is to implement radiative cooling into the code using a simplified prescription that describes bremmstrahlung, synchrotron and comptonized synchrotron radiation (Esin et al. 1996). In this prescription, the radiative cooling depends on three parameters: Magnetic field value, electronic temperature and electronic density.

$$Q_{cool} \equiv Q_{cool}(B_{mag}, T_e, n_e) \qquad (1)$$

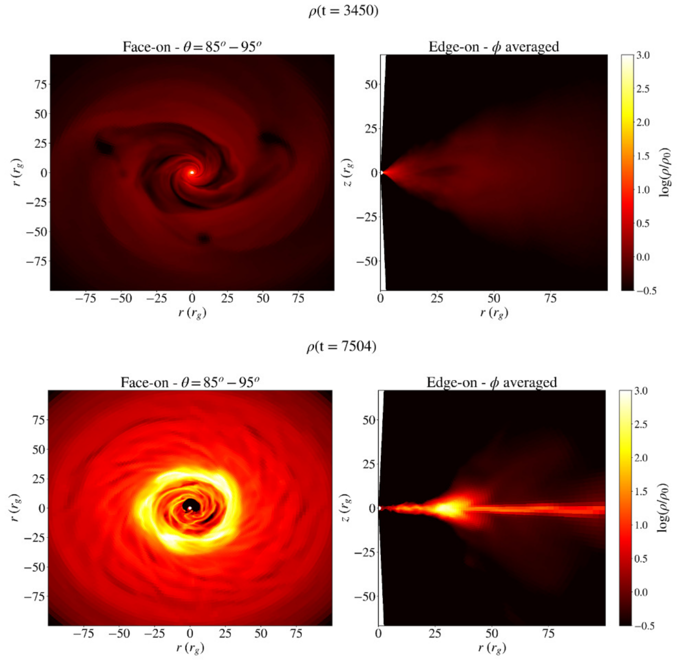

Figure 1. Comparison of the color maps of density for two distinct moments of the simulation, on top: $t = 3450t_g$, bottom: $t = 7504t_g$. The top image displays moments before the cooling activation, while the bottom shows moments afterwards.

This implementation was possible using a lookup table. This table was stored in the texture memory of the graphics processing unit (GPU), which is a read-only memory stored in cache that allows for a fast reading. The computational cost of this implementation of radiative cooling was negligible, allowing a cooling prescription addition without computation cost.

3. Resultados Preliminares: Colapso do disco

The main expected result is the collapse of the thick disk into a thin disk. This happens because when the temperature drops, the thermal pressure also drops, causing a self-gravity collapse of the disk. This can be seen in figure 1 The thin disk formed in our simulations agree with previous results found in other simulations (Wu et al. 2016; Das and Sharma 2013), such as the difference in density and electronic temperature between the RIAF and the thin disk. This difference can be seen in figure 2.

4. Expected Results

We plan to run the code for different accretion rates and establish a relation between the truncation radius of the disk and the distance of the black hole $\dot{M}(t) \times R_{tr}$. This has been done by a previous member of our group, although, the relation presented a contrast from the observational data by a factor of ≈ 4, as observed in figure 3. We believe this happened because the simulations were MHD instead of GRMHD and also had a simplified magnetic field prescription. We also plan to check the effects of the black hole spin and magnetic topology to the radiative cooling and truncation radius relation.

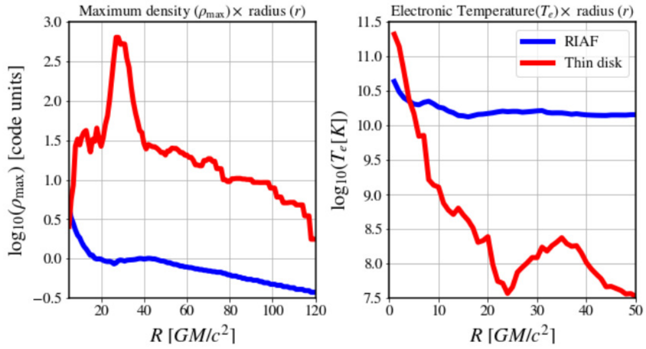

Figure 2. Left: Comparison of the density as a function of the radius before and after the collapse. Right: Comparison of the electronic temperature as a function of the radius before and after the collapse. The formation of a denser and colder disk is observed.

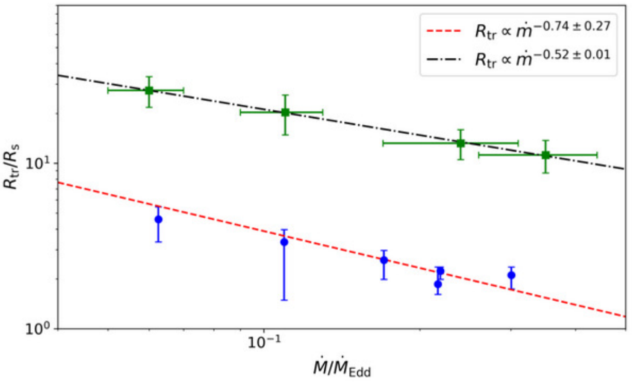

Figure 3. Relationship between the truncation radius and the distance to the black hole using the code `PLUTO` (green dots) and the observational data (García et al. 2015) for the X-ray binary GX 339-4. Nemmen et al. (in prep).

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