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Tori sequences as remnants of multiple accreting periods of Kerr SMBHs

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ABSTRACT

Super-massive black holes (SMBHs) hosted in active galactic nuclei (AGNs) can be characterized by multi-accreting periods as the attractors interact with the environment during their life-time. These multi-accretion episodes should leave traces in the matter orbiting the attractor. Counterrotating and even misaligned structures orbiting around the SMBHs would be consequences of these episodes. Our task in this work is to consider situations where such accretions occur and to trace their remnants represented by several toroidal accreting fluids, corotating or counterrotating relative to the central Kerr attractor, and created in various regimes during the evolution of matter configurations around SMBHs. We focus particularly on the emergence of matter instabilities, i.e., tori collisions, accretion onto the central Kerr black hole, or creation of jet-like structures (proto-jets). Each orbiting configuration is governed by the general relativistic hydrodynamic Boyer condition of equilibrium configurations of rotating perfect fluid. We prove that sequences of configurations and hot points, where an instability occurs, characterize the Kerr SMBHs, depending mainly on their spin–mass ratios. The occurrence of tori accretion or collision are strongly constrained by the fluid rotation with respect to the central black hole and the relative rotation with respect to each other. Our investigation provides characteristic of attractors where traces of multi-accreting episodes can be found and observed.

1. Introduction

Galactic cores and active galactic nuclei (**AGNs**) provide a rich scenario to observe super-massive black holes (**SMBHs**) interacting with their galactic environments. There are several observational evidences supporting the existence of such objects in AGNs. To cite two of most recent studies on **SMBHs** in their host galaxies, we point out the analysis in Tadhunter et al. (2017) exploring the link between galaxy collisions and super-massive black hole feeding, while in Regan et al. (2017) the link between galaxy collapse and rapid **SMBHs** formation is faced. Both these studies show the existence of an intense and strong relation between the galaxy dynamics and its super-massive guest, especially in the accretion processes characterizing the strong attractors. It can be expected that, during their life-time, **SMBHs** would be influenced by the galaxy dynamics due to a series of multi-accreting episodes as a consequence of interaction with the galactic environment made up by stars and dusts. These activities may leave traces in the form of matter remnants orbiting the central attractor.

Chaotical, discontinuous accretion episodes can produce sequences of orbiting toroidal structures with strongly different features as, for example, different rotation orientations with respect to the central Kerr **BH** where corotating and counterrotating accretion stages can be mixed (Dyda et al., 2015; Alig et al., 2013; Carmona-Loaiza et al., 2015; Lovelace and Chou, 1996; Gafton et al., 2015), or disks strongly misaligned with respect to the central **SMBH** spin may appear (Nixon et al., 2013; Dogan et al., 2015; Bonnerot et al., 2016; Aly et al., 2015). Eventually, the scenario envisaged by these studies raises a series of issues and indications about the different stages of the attractor accretion periods binding it on its intrinsic rotation. Motivated by these facts, in this work we investigate structured toroidal disks, so called ringed accretion disks (**RAD**), which may be formed during several accretion regimes occurred in the lifetime of non-isolated Kerr **BHs**. These configurations were first introduced in Pugliese and Montani (2015) and then detailed in Pugliese and Stuchlík (2015, 2016). They feature a system made up by several axis-symmetrical matter configurations orbiting in the equatorial plane of a single central

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Kerr **BH**. Evidences of these special configurations are expected to be found in the associated X-ray spectra emission in **AGNs**.

The phenomenology associated with these toroidal complex structures may be indeed very wide. This new complex scenario enables to re-interpret the phenomena analyzed so far in the single-torus framework. Observational evidence is expected by the spectral features of **AGNs** X-ray emission shape, due to X-ray obscuration and absorption by one of the tori, providing therefore a fingerprint of the tori as a radially stratified emission profile (Karas and Sochora, 2010; Sochora et al., 2011; Schee and Stuchlik, 2009). Relatively indistinct excesses of the relativistically broadened emission-line components were predicted in different works, arising in a well-confined radial distance in the accretion structure originating by a series of episodic accretion events. Furthermore, the radially oscillating tori can be related to the high-frequency quasi periodic oscillations (QPOs) observed in non-thermal X-ray emission from compact objects. More generally, instabilities of such configurations, we expect, may reveal crucial significance for the high energy astrophysics related especially to accretion onto **BH**, and the extremely energetic phenomena occurring in quasars and **AGNs** that could be observable by the planned X-ray observatory ATHENA.[1]

The investigation of these **RAD** configurations, however, is influences by significant methodological issues. The question of how to treat this scenario, and how to model the dynamics of toroidal sequences, is undoubtedly challenging. A major methodological challenge comes from the need to study different evolutive periods of the **BH** in its environment. Conveniently, we may consider following three periods of ringed accretion disk life: (*i*) formation of tori, (*ii*) the accretion periods onto the central Kerr attractor and (*iii*) the tori interaction (emergence of tori collisions). In the current analysis of dynamical one-torus system of both general relativistic hydrodynamic (GR-HD) and general relativistic magnetohydrodynamic (GR-MHD) set-ups, the geometrically thick disks considered in this work are often adopted as initial configurations for the analysis (Igumenshchev and Abramowicz, 2000; Fragile et al., 2007; De Villiers and Hawley, 2002; Porth et al., 2016; Shafee et al., 2008). We can therefore adopt an analogue approach for the investigation of the case of a central Kerr **BH** and several tori orbiting in its equatorial plane. However, in a dynamical process the timing problem of how to depict the different periods is definitely challenging, and requires a certain number of assumptions on the history of the **BH** in interaction with the environment. Therefore, fixing a minimum model set-up inevitably will focus the analysis on a single, very special situation. It would be necessary to fix: 1. the attractor through its dimensionless spin, 2. the accretion era we are willing to describe, and eventually, 3. number of tori, 4. fluid rotation law, 5. relative tori location, 6. location of the inner torus with respect to the attractor. The immediate approach would be to let the chance in the choice of a specific scenario which even in a rich variant of the model will provide necessarily only a partially focused description of one hypothetical model. The problem remains of how to fix, in such objectively complex scenario, the initial conditions of multi-tori orbiting a spinning **BH**.

In fact, recent results presented by Pugliese and Stuchlík (2017b, submitted for publication) show that it is not even immediate to choice the spin class for the central Kerr **BH**: the dimensionless spin of the Kerr black hole strongly constrains the possible couple of orbiting tori in number of orbiting tori, in location and relative range of variation for fluid specific angular momentum. In other words, to fix the initial data for a restricted dynamical scenario, one needs to have in advance the answer to the very question one firstly wants to address within the simulation.

[1] http://the-athena-x-ray-observatory.eu/.

In this respect, our analysis stands also as a guideline to this choice providing a detailed answer to these questions. Results found here will be the guide for the set-up of any more complex dynamical system. Moreover, we are able to trace some evolutive lines for an initial configuration of a system composed by an attractor and general n fluid configurations, corotating or counterrotating relative to the attractor, at any time of the system evolution, from the formation to the occurrence of accretion. Fixing an initial set up, and distinguishing a very restricted number of classes of configurations and attractors, we discuss the final state of a dynamical evolution from an initial configuration. There are few evolutive lines with different final states; the occurrence of these paths however will be finally established by a dynamical analysis. The set-up for the ringed accretion disk model was drew in Pugliese and Stuchlík (2015), while first proposal of these configurations was in Pugliese and Montani (2015). In Pugliese and Stuchlík (2015), constraints and discussion on perturbations were provided. Then in Pugliese and Stuchlík (2016) sequences of unstable configurations were discussed, the investigation was focused on the unstable phases of multi accreting toroidal structures. The paper Pugliese and Stuchlík (2017b) focused on the case of two tori as "seed" for larger configurations, and paper Pugliese and Stuchlík (submitted for publication) explicitly addressed collisions and energy release in colliding tori. In this article, we discuss the situation where several equilibrium and accreting or proto-jet (open critical) configurations are formed around a Kerr-**SMBH** in **AGN** environments. Here we take full advantage of the symmetry of the Kerr geometry, considering a stationary and axisymmetric, full general relativity (GR) model for a single thick accretion disk with a toroidal shape. Each torus is featured as an opaque (large optical depth) and super-Eddington (high matter accretion rates) disk model a radiation pressure supported accretion disk cooled by advection with low viscosity (Paczyński, 1980; Igumenshchev and Abramowicz, 2000; Fragile et al., 2007; De Villiers and Hawley, 2002; Porth et al., 2016). More precisely, the individual toroidal (thick disk) configurations are barotropic models where the effects of strong gravitational fields are dominant with respect to the dissipative ones and predominant to determine the unstable phases of the systems (Font and Daigne, 2002; Igumenshchev and Abramowicz, 2000; Abramowicz and Fragile, 2013; Pugliese and Montani, 2015; Paczyński, 1980; Kovar et al., 2016). As a consequence of this, during the evolution of dynamical processes, the functional form of the angular momentum and entropy distribution depends on the initial conditions of the system and on the details of the dissipative processes. The tori are governed by "Boyer's condition" of the analytic theory of equilibrium configurations of rotating perfect fluids (Boyer, 1965). The toroidal structures of orbiting barotropic perfect fluid are determined by an *effective potential* reflecting the spacetime geometry and the centrifugal force through the distribution of the specific angular momentum $\ell(r)$ of the orbiting fluid (Abramowicz et al., 1978, 1983, 1996, 2010; Abramowicz and Fragile, 2013; Stuchlik et al., 2005; Lei et al., 2008). The equipressure surfaces, K =constant, could be closed, determining equilibrium configurations, or open (related to protojets configurations; Pugliese and Stuchlík, 2016). The special case of cusped or critical equipotential surfaces allows for the accretion onto the central black hole (Paczyński, 1980). The outflow of matter through the cusp occurs due to an instability in the balance of the gravitational and inertial forces and the pressure gradients in the fluid, i.e., by the so called Paczynski mechanism of violation of mechanical equilibrium of the tori (Paczyński, 1980).

The plan of this article is as follows: Sec. 2 introduces the ringed accretion disk model: we discuss the main features of geometrically thick accretion disk orbiting a central Kerr **BH**, and we then proceed to consider the case of several tori orbiting in the equatorial plane of the central attractor. Concepts and notation