Simulations of a molecular cloud falling into single and binary Supermassive Black Holes

PhD Thesis Project by Felipe Garrido Goicović

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1 Scientific Context

The idea that Supermassive Black Holes (SMBHs) reside in the centers of (at least) the more massive galaxies is currently well established (Richstone et al., 1998). These supermassive objects gain mass in an active phase of accretion, during which they are observed as Active Galactic Nuclei (AGNs), because of the large amount of energy that is released from them. Various correlations over the past decade have been found between the mass of SMBHs ($M_{\rm BH}$) and the properties of their host galaxies, e.g., the velocity dispersion (σ) of the galaxy's bulge (Ferrarese and Merritt, 2000) and the mass of the galaxy's bulge (Häring and Rix, 2004). These results indicate that accreting SMBHs play a key role in the formation and evolution of galaxies (see for instance Di Matteo et al., 2005).

On the other hand, according to our current structure formation paradigm, galaxies often interact and merge following the hierarchical growth of their parent dark matter halos. Then, in the aftermath of a major galaxy merger, it is expected that the resultant merged galaxy will contain a pair of SMBHs. Dynamical interaction with stars and gas drive the SMBHs towards the center of the new galaxy on short time scales (Milosavljević and Merritt, 2001), where they will form a black hole binary (BHB).

At large separations the BHs sink due to dynamical friction, but becomes inefficient when the enclosed stellar mass is the order of the binary mass; then three-body encounters will eject stars from the system shrinking the binary to separations of ~ 1 pc (Begelman et al., 1980). When the separation is sufficiently low ($\lesssim 10^{-3}$ pc) the gravitational radiation will efficiently extract angular momentum and energy from the binary and rapidly lead it to coalescence; gravitational waves emission can also be enhanced with high eccentricity. However, at parsec separations there are too few star scatterings to keep hardening the binary at time scales within a Hubble time; this is called the "last parsec problem" (Yu, 2002). Observationally, there are only few binary candidates, which could imply that they likely merge fast, although observing in this regime is very challenging.

A possible mechanism that can still drive the SMBHs to lower separations is the interaction with gas. When two galaxies merge there are large amounts of gas funnelled to the center of the remnant (Mayer et al., 2007). This gas is more efficient on absorbing the angular momentum of the binary than stars, and can bring the BHs to parsec distances. Several authors have investigated the interaction with gas orbiting in a prograde disc just outside the binary (Armitage and Natarajan, 2005; Cuadra et al., 2009; Lodato et al., 2009). This process is very inefficient for higher binary masses and typically takes longer than a Hubble time before coalescence. Cuadra et al. (2009) showed that this makes the orbit of the binary decay at a rate $\dot{a} \sim -\text{few} \times 10^{-5} a_0 \Omega_0$, where Ω_0 is the angular frequency and a_0 the semimajor axis of the orbit. Then, the time scale for a binary with mass of $10^7 M_\odot$ and semimajor axis of 1 pc is $\sim 10^{10}$ yrs. This will produce binaries that spend most time at ~ 0.01 pc, which can be really hard to observe. They also propose for higher binary masses that fragmentation of the disc can produce stars and still shrink the orbit by ejecting them from the system, although at a slower pace.

Recent work by Nixon et al. (2011a,b, 2013) has shown that a retrograde or counter-aligned circumbinary disc interact much strongly with the binary, due to the absence of resonant gravitational torques. For prograde discs these torques act to hold the material away from the BHs, reducing considerably the accretion. They found that the timescale for eccentricity growth is $e/\dot{e} \sim M_2/\dot{M}$, where M_2 is the mass of the secondary BH and $\dot{M}$ the inflow rate through the circumbinary disc. Nixon (2012) also study a circumbinary disc that forms with a random inclination angle θ to the binary, and shows that for typical disc parameters a misaligned circumbinary disc is likely to wholly coalign or counteralign with the binary plane. Then, a chaotic accretion event on to an SMBH binary will therefore result in a coplanar circumbinary disc that is either prograde or retrograde with respect to the binary plane, where the latter is more efficient on shrinking the orbit of the binary.

Here in my thesis I am investigating the possible mechanism that produce such circumbinary discs with a single accretion event.

2 Motivation and Goals

During a galaxy merger it is expected that the angular momentum of the large scale ($\sim$ kpc) gas and the SMBH binary are somewhat aligned, as shown in various simulation (e.g. Escala et al., 2005; Dotti et al., 2006). However, the highly turbulent nature of the nuclear component (Mayer et al., 2007) can produce accretion events without any strong preferential orientation within the influence radius of the SMBH or the binary. This is known as chaotic accretion scenario (King and Pringle, 2006).

For instance, the numerical model developed by Hobbs et al. (2011) showed that supersonic turbulence in gas at relatively large distances of a SMBH can produce "ballistic" accretion, where the high density zones travel through the ambient gas almost unaffected by hydrodynamical drag, reaching the influence radius of the BH. The large spread in angular momentum achieved with turbulence randomize the direction of the accretion events.

As explained before, one possible answer for the last parsec problem is the interaction with a circumbinary disc, either aligned or counter-aligned. However, the exact mechanism that would produce such discs is still unclear. Numerical studies (Bonnell and Rice, 2008; Hobbs and Nayakshin, 2009; Mapelli et al., 2012; Lucas et al., 2013), attempting to explain the unusual distribution of stars orbiting our Galaxy's SMBH, have shown that portions of infalling gas can be captured by a BH to form an eccentric disc that eventually fragments to form stars. Although the characteristics of the gas clouds are quite different, there is a key parameter present on each of these simulations: the near radial infall of material.

The simulation of Bonnell and Rice (2008) shows a spherical, turbulent cloud falling with a very low impact parameter ($\sim$0.1 pc) onto a one million solar masses BH. Assuming that these accretion events are common in centers of galaxies, I want to investigate what differences will produce the presence of a binary instead of a single SMBH, particularly if it is possible to produce circumbinary discs given different orientations between the orbital angular momentum of the cloud and the binary. Also, I want to investigate the impact of magnetized accretion on similar events.

The specific goals of my thesis are:

1. Model the hydrodynamical evolution of a molecular gas cloud as it approaches and is partially captured for single and binary SMBHs.
2. Measure the alignment of the gas with the binaries depending on the initial relative orientations of the angular momentum vectors.
3. Follow the evolution of the gas trapped by the BH(s), modeling its possible fragmentation and star formation.
4. Quantify the evolution of the binary orbit as the result of the interaction with the cloud.
5. Determine possible observational signatures that can help to find BHB with observations.
6. Repeat the previous points but using Magneto-Hydrodynamic (MHD) simulations, measuring the effect of the different configurations for the magnetic field.

3 Work Plan

Here I present the list of the main activities to perform along the work of my thesis. The time estimated for the simulations is based on the work done during this year (first point in the list). It is important to clarify that all the times marked as Computing Time (**CT**) correspond to the period where the simulations are running, and then gives time to advance with other tasks.

- 2013:

1. Read and understand the simulation developed by Bonnell and Rice (2008), in particular, the initial conditions for the cloud.

   Time $\approx$ 3 weeks.
2. Write a code that generates a turbulent velocity field to a spherical, uniform distribution of particles that will represent the cloud.

   Time $\approx$ 2 months.
3. Modify the SPH code GADGET-3:
   - Simple accretion: sink particles accrete every particle within certain radius.
   - Thermodynamics: change Equation of State (EoS) according to density.

   Time $\approx$ 1.5 months.
4. Model the evolution of the infalling cloud onto single and binary SMBHs. In the case of the binaries, three different initial configurations according to the relative angular momentum direction of the cloud and the BHs.

   Time $\approx$ 4 months (**CT**).
5. Analyze the outputs of the simulations, concentrating on the angular momentum direction of the gas particles and identify structures around each BH and/or the binary.

   Time $\approx$ 2 months.

- 2014-1:
  1. Present my results on the X annual meeting of the Chilean Astronomical Society (SOCHIAS)
  2. Publish the first results of the structures formed and the gas alignment around the binaries for the different initial configurations.

     Time $\approx$ 1 month.
  3. Explore the parameter space, to study the dependence of my results with:
     - Turbulence.
     - Thermodynamics.
     - Binary mass and mass ratio.
     - Binary separation and eccentricity.
     - Impact parameter of the cloud.
     - Size, mass and form of the cloud.

     Time $\approx$ 4 month (**CT**).
  4. Modify the code to save the information of the accreted particles. Time $\approx$ 1 week.
  5. Use the output of the accreted particles to determine its torque contribution, and the evolution of the BHs spin.

     Time $\approx$ 1 month.

- 2014-2:
  1. Present my results on the IAU Symposium "Star Clusters and Black Holes in Galaxies across Cosmic Time", Beijing, China.
  2. Modify the code to improve the accuracy on the computation of the gravitational forces on the SMBHs by adding directly the contribution of each particle, instead of using the tree approximation.

     Time $\approx$ 1 month.
  3. Run again some of the configurations to measure the binary orbit evolution produced by the interaction with the gas.

     Time $\approx$ 4 months (**CT**).
  4. Determine the possible observational signatures that each gas structure will produce.
     - Shift of spectral lines.
     - Luminosity/accretion variability.

    - Spectral energy distribution.

   Time ≈ 2 months.

5. Investigate the implications of spin misalignment (between each BH or with their orbit) on the SMBH population due to non-isotropic emission of gravitational waves.

   Time ≈ 1 month.

6. Publish the new results.

   Time ≈ 1 month.

- 2015-1:

  1. Run the same configurations as before, including MHD effects.

- 2015-2:

  1. Write the final report of the thesis.

4 Collaborations

During the development of my thesis I will work with two astrophysicists, both located in Potsdam, Germany. Dr. Alberto Sesana (Albert Einstein Institute) is an expert on SMBH binaries, in particular on models of binary formation within galaxies and the evolution of their orientation; he will help me to study the alignment of the material and gravitational waves emission. On the other hand, Dr. Federico Stasyszyn (Leibniz-Institut für Astrophysik) develops MHD simulations applied on cosmology, galaxies and star formation; he will assist me with the development of an MHD code that can model the evolution of a cloud/SMBHs system.

I already have funds to visit Germany for 3 months during 2014, and also I have applied for a Chile-Germany exchange project with CONICYT that can fund a two-month trip for me (probably during 2015), and short trips to all the researchers involved with this project: J. Cuadra, N. Padilla, F. Stasyszyn and A. Sesana.

In addition, Dr. Alex Dunhill recently has arrived at the IA to work as a post-doctoral researcher. One of the topics of his PhD thesis is the formation of prograde and retrograde circumbinary discs as the result of a single cloud infall with a large impact parameter. We will collaborate to complement our research and extend the scope of our conclusions.

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