Extension Report
DAAD PhD Scholarship

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Contents

1 Report

Since my arrival in Germany to the present day it has been almost one year. This time can be split-up into two periods. The first four months, from 06.15 to 09.15, correspond to the German course in Berlin. Finally, the second period, from 10.15 to 04.16, correspond to my arrival in Heidelberg for starting my PhD.

Regarding the first period, there is not much academic progress to report on as I was focused on learning German. The only two exceptions perhaps were a first-author paper I published in 08.15 (Bustamante & Forero-Romero, 2015) [1] and an invited talk I gave at AIP (Leibniz-Institut für Astrophysik Potsdam) about the paper. Nevertheless, all the results reported in this work were already developed during my studies in Colombia and the activities during my stay in Berlin were limited to corrections of referee reports.

For the second period there are several things to report on. These can be split-up in 3 categories: general, corresponding to activities such as taking lectures and seminars, getting the admission to the university, etc. Major project, which is related to the main project I am developing with my supervisor, and finally, a minor project developed with a postdoc of the group.

1.1 General

After my arrival in Heidelberg, the first step was to enrol to the University as a PhD student, however the assessment emitted by the HGFSP office (Heidelberg Graduate School of Fundamental Physics) was to take preparatory studies before being admitted as PhD student (this was because I do not hold a master's degree), which means I had to take two core lectures of the master. Nevertheless, this assessment was out of date as it corresponds to my old application in 2013. Since then, I had taken 1 semester of master studies in Colombia and published a first-author paper. Unfortunately, I had not brought documents to prove this, so I had to wait for someone to bring them to me from Colombia. In the meantime, it was decided by my Thesis Committee that I should take one of the core lectures during the first semester, so I decided to take Theoretical Astrophysics.
At the end of the semester, I finally got the documents, so I immediately submitted them to the HGFSP office and one week later I was officially admitted as a PhD student in the University of Heidelberg. It is worth mentioning that I also finished the lecture, which included homework and a final examination.

Although the astronomy PhD program is officially hosted by the HGFSP, the associated activities are organized by the MPIA (Max Planck Institute for Astronomy) within the framework of the IMPRS program (International Max Planck Research School), which is a structured program, and for that reason, there are several activities that the student members are re-

[1] `http://mnras.oxfordjournals.org/content/453/1/497`

quired to participate in. Among these activities are the IMPRS literature seminar and the first-year student retreat. The seminar corresponds to a weekly session where every student must give a short talk about an assigned research paper. In my case, I attended this seminar during the first semester and also gave a talk about diffusive shock acceleration[2]. About the first-year retreat, it consists of a social integration for new PhD students and a visit to some astronomy institute in some city out of Germany. The last retreat took place on 13.04.16 (four days) in Budapest, Hungary, where we visited the Konkoly Observatory.

1.2 Major Project

The initial project I submitted in 2014 for the application to the scholarship was about the study of the gaseous cosmic web in the context of the state-of-art hydrodynamical simulations using AREPO code (Springel, 2010) (e.g. Illustris simulation[3]). However, after my arrival in Heidelberg and during my first meeting with my supervisor, it was decided to change the focus of the main project to study dynamical friction of supermassive black holes in the centres of galaxies in order to make predictions of gravitational-wave emissions in a cosmological context. The main reason for this decision was that black hole physics was going to become a very trendy topic in the light of the forthcoming gravitational wave experiments (e.g. LIGO [4]), and robust predictions are going to be needed from theoretical and numerical models. Nowadays, with the confirmed discovery of gravitational waves by the LIGO team, the change of course proved to be a very wise judgement.
With the new project already defined, I proceeded to compile and read references about the topic, and, along with my supervisor, to write a new research proposal to be submitted to the DAAD (this document is attached in the appendices).

In the first two months, I was focused on comprehending the process of dynamical friction and how it operates in the context of galaxy dynamics. This was an important step because this process drives the orbital decay of supermassive black holes, specially after a galaxy merger, where two or more black holes coalesce after emitting a burst of gravitational waves. For the purpose of understanding this process, I developed some scripts in python and a small N-body code[5] to study how numerical resolution effects influence the trajectory of a massive body embedded in some background medium composed of slightly lighter particles, which is indeed a fair approximation to the real problem faced when simulating supermassive black holes in galaxies.

Once this initial stage was successfully done, I moved on to use the hydrodynamic code AREPO to simulate isolated galaxies and merger events (see figure 1), which, although yet simplistic, were closer to the original problem that we want to solve. The objective with this exercise was to get familiar with the code and understand the problems with the current

[2] https://www.youtube.com/watch?v=L7OVGV6XJ0k
[3] http://www.illustris-project.org/
[4] Laser Interferometer Gravitational-Wave Observatory, https://www.ligo.caltech.edu/
[5] https://github.com/sbustamante/N-body

treatment of supermassive black holes (Springel et al., 2005), where their position are glued to the potential minimum of the galaxy. This approach has proven to be numerically stable, yet unrealistic.

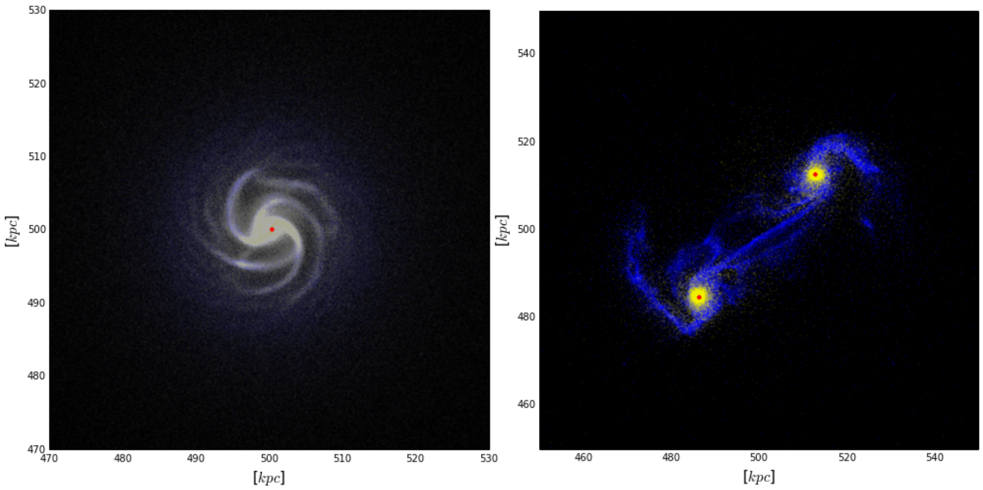

Figure 1: Left panel: isolated galaxy with a supermassive black hole in the centre (red dot). Right panel: a merger of two galaxies after a first passage. Two black holes are shown in the centre of each galaxy.

The last three months were dedicated to devise an improved treatment for the dynamical friction experienced by supermassive black holes in numerical simulations. In this regard, the main problem emerges when one tries to simulate a continuous stars and gas background using large sampling particles, with a size comparable to the black hole. This produces unrealistic orbits, where stochastic numerical heating prevails rather than a smooth decay as expected from dynamical friction driven trajectories. The described procedure is unfortunately necessary due to the limited computing power achieved by modern computers. That is the reason why sub-grid semi-analytic models are always required.

Several approaches have been proposed throughout the literature, namely glueing the position of the black hole to the potential minimum, as mentioned above. Using an improved version of the Chandrasekhar formula, where only the closer neighbour particles are used to compute the distribution function of the background (Tremmel et al., 2015). We also introduced and implemented (in AREPO) our own approach, where an effective drag force is estimated assuming an overdamped decay which follows the velocity of the potential minimum. Although this method is only partially physically motivated, it is indeed an effective way to yield decaying orbits, even for low resolutions.

During this time, I also devised a set of numerical experiments to test our approach. It consists of simulating a black hole particle embedded in an isolated dark matter halo that follows a Hernquist profile (Hernquist, 1990). This has two important advantages: firstly, this profile is stationary, meaning that there is not transient or numerical relaxation, and secondly, it has analytical profiles for the density, the potential and the velocity distribution function. Both features facilitate enormously comparison between numerical results and analytical predictions.

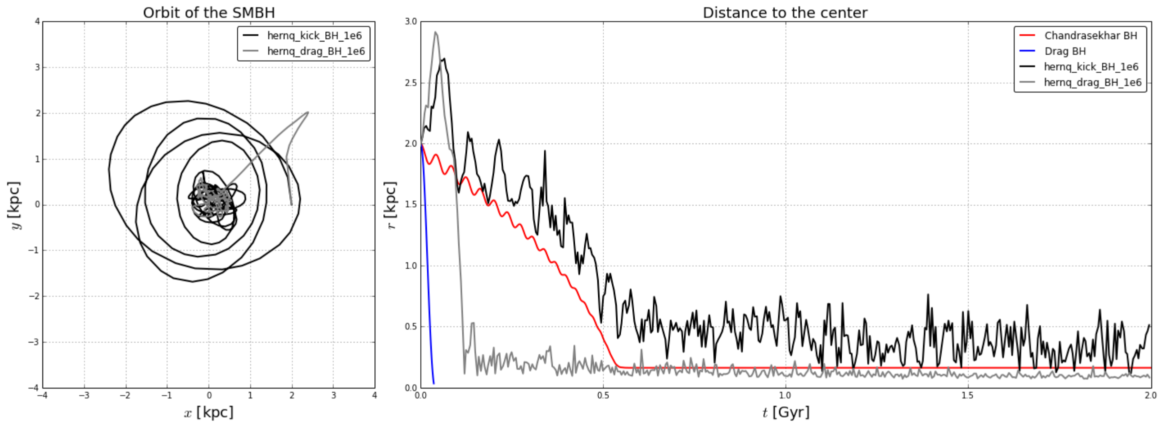

Figure 2: Left panel: numerical simulations of the decay of a supermassive black hole in a circular orbit, without using our approach (black line), and using it (grey line). Right panel: evolution of the radial component for the orbit of the black hole, using the numerical orbits (black and grey lines) and analytical integrations for a pure Chandrasekhar friction force (red line) and for a overdamped drag force (blue line).

It is shown in figure 2 the results of our numerical integration and the corresponding analytical predictions. It is worth noting that we were using a rather high resolution (1×10^6 particles), so it is expected that dynamical friction is accounted for at some extent. Indeed, a decay is observed for the case without an effective drag force and the orbit is close to the one predicted analytically using the Chandrasekhar formula with a correction for the maximum impact parameter (Just et al., 2011). In the case when the drag force is activated, the numerical result and the analytical prediction are different. However, the numerical orbit exhibits a faster decay and is less noisy once it gets close to the centre. Further study in this direction is necessary to fine tune our drag friction force to reproduce realistic decay times.

Finally, a last problem we are currently working on is related to tracking the trajectory of the potential minimum of a galaxy, which is an essential step for our approach as the drag force is precisely given from that frame of reference. The method currently in use consists of following the most bound particle. Nevertheless, due to numerical noise, this has shown to be numerically unstable, producing levels of noise comparable with the resolution effects that we want precisely to deal with. The alternative that is being now developed consists of fitting the potential field around the black hole using a least squares multidimensional minimization with the neighbour particles, which might offer a more stable solution for the potential minimum trajectory. Once this approach, along with the effective drag force, are working, our short-term plans are to run a cosmological simulation and write a first paper about the results.

1.3 Minor Project

Additionally, a minor project has been going on during the previous semester, which is being developed with a postdoc of the group at HITS (Martin Sparre). The goal of this project is to study the effect of minor mergers on the star formation rate of galaxies at different redshifts. This is important in the context of galaxy formation because high star formation rates in galaxies at high redshifts remain unexplained. So far, there are several hypothesis supporting this picture, namely, accretion of cold star forming gas through infalling filamentary flows which are able to cross trough the shock-heated regions around galaxies and penetrate towards the centre. A second hypothesis consists of major merger events, where tidal forces compress the gas and trigger star formation. Finally, we propose to study a third scenario, that is not exclusive with the other two, but offers an appealing alternative as minor merger events are very common and not as potentially destructive as major mergers.

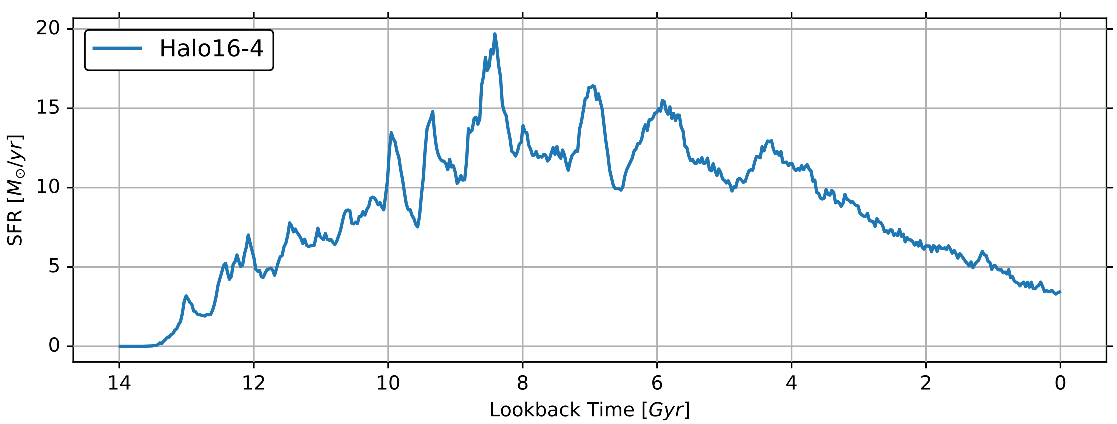

Figure 3: Star formation history for a galaxy in the Auriga project. The peaks are associated to star bursts induced by major or minor mergers.

For the purpose of this project, we use a set of zoom cosmological simulations (the Auriga project), where several galaxies have been simulated with very high resolutions from sub-boxes of the Illustris simulation (see more details in Grand et al. (2016))). So far, several analysis scripts have been developed using the library MergerZoomAnalysis[6] of Martin Sparre. For example, in figure 3 it is shown the star formation history of one of the simulated galaxies, where the peaks correspond to star bursts induced by minor or major mergers. My current objective is then to develop a method to track minor merger events and correlate them with star bursts in the star formation history.

[6] `https://bitbucket.org/martinsparre/mergerzoomanalysis`

8 Bibliography

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