Dynamic simulations analysis of merging galaxy clusters

Pedro Henrique Rocha de Andrade[a], Ana Cecilia Soja (advisor)[a]

[a] *Instituto Federal Fluminense - Campus Bom Jesus do Itabapoana - RJ*

March, 2023

Abstract

Cluster galaxy collisions are extreme events in the Universe whose study, among other factors, allows for an understanding of the nature of dark matter based on its behavior during the collision. Given the impossibility of direct observation of parameters such as the relative velocity of the components and their evolution over time, one of the strategies used to study this type of phenomenon is the analysis of dynamic simulations. This project aims to evaluate the accuracy of one of these simulations regarding the differentiation between the various temporal passages of the objects in interaction through the center of the collision. To do so, public data and programming knowledge were used. The results indicated good efficiency of the dynamic analysis, but with a tendency to return systematically lower values than the correct ones, which needs to be further analyzed. The methodology used proved to be feasible for this type of analysis and should be expanded to simulations of different collision scenarios.

1. Introduction

The Universe and its mysteries have fascinated humanity since the beginning of time. Questions such as where did we come from? Where are we going? Did the Universe have a beginning? Will the Universe have an end? Are there other worlds like ours or are we unique in the Cosmos? have guided generations of scientists and remain unanswered.

Despite this, centuries of careful observation and analysis have provided us with many discoveries. Today, for example, we know what stars are made of and the physical processes that allow them to shine (nuclear fusion in their cores).

The main tool for these studies is light [6]. It allows us to understand celestial objects deeply, as it carries a lot of information. One of the most important properties of light is that it travels at a constant speed of approximately 300,000 km/s. Based on this information, we define the unit of distance called light-year (LY), which is the distance that light travels in one year ($9.46 \times 10^{12} km$) [1] and serves as a reference value for other distances. One consequence of this concept is that when we look at the sky, we are necessarily observing events that happened in the past, since information takes time to reach us. The farther the object, the longer it takes for the light to reach us.

Another piece of information that light carries is about the nature of the source that generated it. This is possible through spectroscopy, a technique that separates a beam of light into different wavelengths according to its intensity [5]. Figure 1 shows an absorption spectrum as an example, where the light emitted by a source was absorbed by atoms present in the gas that was in the path between the source and the observer. In the example, the black absorption lines indicate the presence of the chemical element sodium (Na). This is how spectra can help us understand what stars are made of, as they carry these "signatures" of the interaction of light with the chemical elements present in their path.

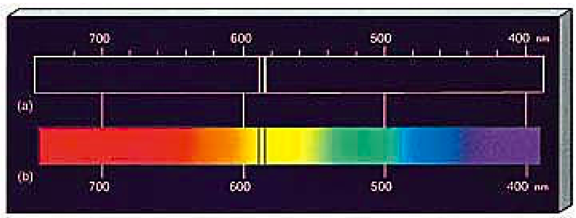

Figure 1: Example of an absorption spectrum Source: [5].

Spectra also help us understand the distance of objects and the evolution of the Universe itself. Relative motion between the source and the observer can cause shifts in the position of the lines, which is known as the Doppler effect. If the shift of a spectral line occurs to the right (increasing the wavelength), we call this effect redshift, indicating that the object is moving away from us. Blueshift is the opposite, i.e., the spectral shift of light to

[1] Knowing that there are 3.15×10^7 seconds in a year and that the speed of light is $3 \times 10^5 km/s$, we calculate the distance that light travels in a vacuum.

the left, decreasing the wavelength, indicating that the object is approaching. To symbolize the shift, we use the letter **z**, and from the variation of the wavelength by the emitted wavelength, we have the percentage value of **z**.

The study of redshift gained importance thanks to the work of the famous American astronomer Edwin Hubble (1889 – 1953), who, by analyzing spectra of distant galaxies, discovered that the farther they were, the faster they were moving away from us. This indicates that the Universe is expanding, which brings us closer to an answer to one of the fundamental questions (where did we come from?): if the Universe is expanding, it is possible that everything was once close together, having started in a big explosion.

The above presents in a summarized way some of the knowledge that can be constructed from the analysis of the light that we capture from stars. However, the Universe is not made up only of luminous objects such as stars (or galaxies, which are made up of stars). In fact, a good portion of the Universe (25%) is made up of a type of matter that we do not know: dark matter [4]. Dark matter would be a different type of matter from what we know precisely because it does not emit light. Its only interaction occurs through the force of gravity and it can only be noticed on large scales (such as galaxies and clusters of galaxies).

Since the first hypotheses of its existence in the 1930s, astronomers have been developing tools and alternatives to understand what dark matter is, what it is made of, and its relevance to the Universe. As it is not possible to collect a sample of this matter, nor observe it directly (as it is dark and does not emit any type of light) or even manufacture it on Earth, the possibilities of study are limited to analyzing its interaction with other objects.

One of the most promising fields in this regard is the study of galaxy clusters in collision. These events are interesting because galaxy clusters are very large structures (the largest in the Universe, with masses billions and billions of times greater than the Sun), where normal matter and dark matter have similar relevance. When they collide, in events that are known as the most energetic in the Universe, these components separate, each interacting in a different way. By analyzing how dark matter behaves, it is possible to develop hypotheses about its nature. An example of a galaxy cluster collision is the Bullet Cluster (Figure 2), which is named because it looks like a shot. In the image, it is possible to see in different colors how the components of the cluster behave differently: galaxies, made of normal matter, pass through more easily than gas (also made of normal matter), while dark matter seems to follow the behavior of galaxies but not exactly, suggesting that physical phenomena not yet known may be happening there.

Figure 2: Image of the Bullet Cluster, two clusters that have collided. Dark matter is represented as blue, while gas is represented as red. In the image, we see that each component (gas, galaxies, and dark matter) seems to behave differently. Fonte: [9]

Given the context, the main objective of this work is to contribute to the study of dark matter using galaxy clusters. The project is part of the CNPq pre-scientific initiation program and has been awarded a Junior Scientific Initiation scholarship in the *Edital 94/2022 – Processo de Seleção de Projetos de Pesquisa e de Estudantes Bolsistas de Iniciação Científica (PIBIC – CNPq) e de Iniciação Científica Júnior (ICJ – CNPq)* at the Instituto Federal Fluminense. Thus, the secondary objective of the work is to provide, through the study of Astronomy, a scientific development environment for the young researcher, applying practical knowledge he acquired throughout his technical training.

2. Methodology

Currently, scientific work is very specialized, usually carried out by large research groups where each member is responsible for a part of the study, in which they delve deeper than the others.

Inserted in this context of collaboration, a key word for the development of large-scale astronomy observations, this work focuses on the analysis of only one important parameter for the study of colliding galaxy clusters: the time elapsed between the collision and the current observation of the object. This parameter is of special importance because it helps to understand at what moment of the collision the clusters are in (are they about to collide? have they already collided and will collide again?), so being certain of its accuracy is essential for the study of the components of the clusters in general.

One of the most commonly used methods for measuring the collision time is the one developed by Dawson et al. in 2013 [2]. They used the statistical Monte Carlo method to estimate the age from relatively simple observational parameters (relative masses, redshift, and projected separation). The code used was written in the Python programming language and is available for public use [2].

Therefore, in order to fulfill the objective of contributing to the science of merging galaxy clusters, we propose to analyze the accuracy of the collision time measurement using Dawson's method [2]. For this purpose, we used their code in controlled situations to verify its efficiency.

Since it is not possible to conduct real experiments that reproduce what is happening in space, an alternative for the study of astronomical phenomena is the use of computer simulations. These simulations "create" artificial universes where all parameters are well known. Thus, by studying the data from this "fake" universe, we can verify if our analysis is correct.

The simulation chosen for this work was the one by ZuHone et al. in 2017 [10]. It is interesting because it has high resolution and nine different sample groups. The samples are divided according to the ratio between the masses of the clusters involved in the collision and the impact parameter, which quantifies the distance between the centers of the clusters. For mass ratios, there are three possibilities: 1:1 (the clusters have the same mass), 1:3 (one of the clusters has three times more mass than the other), and 1:10 (one of the clusters has ten times more mass than the other). The impact parameter is divided between 0, 500, and 1000 kpc [3]. The combination between them gives rise to the nine subgroups. In this work, we chose to initially analyze only the simulations that defined an impact parameter of 0kpc, indicating that the collision occurred in the plane of the sky.

Therefore, the work consists of applying Dawson's code [2] to the simulated data from ZuHone [10], verifying the correspondence between them. For better organization, we have separated the necessary steps for the completion of the work, presented below:

1. Familiarization with the problem and Astronomy concepts;
2. Compilation and understanding of Dawson's method and code;
3. Obtaining and understanding ZuHone's data;
4. Application of Dawson's method to each of the available simulations;

The results obtained for each stage so far are presented in more detail in the next section.

3. First Results

3.1. Step 1: Familiarization with the problem and astronomy concepts

This first step was essential for achieving the secondary goal of the work, which is scientific initiation through basic research in astronomy.

The study began with material on astronomy dissemination, such as the book *"À Luz das Estrelas"* [6]. This material is aimed at the general public and introduces fundamental concepts for scientific research on the universe in an easy-to-understand language. In this study, we followed the pedagogical order proposed by the book, from the closest (Solar System) to the farthest (galaxies).

The first learning was about the concept of parallax, which is an ancient trigonometric method for distance determination. In summary, parallax is the apparent change in the position of an object relative to an observer in different positions. There are two types of parallax: geocentric and heliocentric. Geocentric parallax (Diurnal) is used to measure distances from the observation of the object's displacement from two points on Earth; it is an old method that uses triangulation. It uses the Earth's diameter as a basis for calculations. Heliocentric parallax (Annual) is used to measure the distance of stars. It is done in two moments, with a 6-month interval, due to the translation movement of the Earth around the Sun. This knowledge is fundamental because it is the first way to measure distance, and all others (such as light-years and parsec) are based on it.

The next step was to understand a little more about stars. Stars are formed in galaxies from the dust that remains in them. Formed from a cloud of gas, they become protostars, where they begin to fuse hydrogen into helium in their core, performing the phenomenon known as nucleosynthesis. In their formation, they have a certain amount of hydrogen in the core that will be burned until the end of their life cycle. During their life cycle, their core will be active and constantly undergoing nuclear fusion.

When the star is transforming hydrogen into helium in its core, we say that it is in the Main Sequence. In it, we have Yellow and Blue type stars; the yellow ones are stars with mass less than 10

[2] The code in question is available at https://github.com/MCTwo/MCMAC.

[3] kpc is a distance measure equivalent to 1000 pc. The *parsec* is defined as having a parallax of 1 arcsecond, which is equivalent to 3.26 light years.

$M_{\odot}$ [4] and the blue ones with mass greater than 10 $M_{\odot}$. The mass of the star defines how its evolution will be. The smaller ones (yellow) tend to evolve into Red Giant, such as the Sun; later, it implodes into a Planetary Nebula, finally becoming a White Dwarf. The blue ones are larger and known as giants. They evolve into Red Supergiant and, over time, the core burns various chemical elements until it cannot burn iron; the star explodes in a supernova, one of the most energetic events we currently know. Depending on the remaining mass of the iron core after its explosion, it can become a Neutron Star or a Black Hole.

Stars can be classified into classes, according to their decomposed light spectrum. The classification can be in 7 different classes, represented by the letters **OBAFGKM**, where **O** are hot and **M** are cool[5]. Each of the letters is divided as follows:

- O – Blue
- B – Blue-White
- A – White
- F – Yellow-White
- G – Yellow (Sun)
- K – Orange
- M – Red

At the end of their life cycle, stars can become one of three options, according to their mass:

- White Dwarfs: It is the result after the star becomes a planetary nebula.
- Neutron Stars: when the nucleus (Fe) after the Supernova explosion is between 2 and 3 solar masses.
- Black Hole: when the nucleus (Fe) after the Supernova explosion is larger than 3 solar masses.

Understanding the process of evolution and classification of stars, as well as the most important parameters (color and mass), we moved on to the study of galaxies. For this, a more advanced didactic material was used, the book "Astronomia e Astrofísica" [8], which is aimed at undergraduate students in Astronomy. This was possible thanks to the familiarity with the subject provided by the first study.

Galaxies are huge celestial objects, gravitationally bound, formed basically by stars, matter in the form of gas and dust and a still not well-understood component, dark matter. Edwin Hubble in his studies on galaxies defined a sequence of galaxies, dividing them into three main groups:

- Elliptical (E): They have a spherical or elliptical shape. Formed mainly by elderly stars and born in an accelerated way, they are classified according to the degree of flattening, given by Hubble. They have less gas and less dust, so the formation of new stars is rare to happen.
- Spirals (S): Spiral galaxies can be defined with: nucleus, disk, halo, and arm (which give rise to arms). The letter **S** is used to classify them, from the English word Spiral. They are divided into 3 classes, Sa (large nucleus, small arm), Sb (intermediate) and Sc (small nucleus, large arm). They can also have bars (SBa, SBb, and SBc). Our Galaxy (Milky Way) and Andromeda (the closest galaxy to us) are examples of spiral galaxies.
- Irregular (I): They do not have a defined structure and, because they have a lot of gas in their formation, they have many young stars in formation. Visible examples are the Magellanic Clouds.

Figure 3 exemplifies the galaxy classification developed by Hubble and still used today.

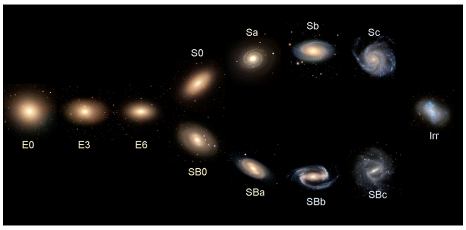

Figure 3: The Hubble sequence. On the right, we have elliptical galaxies and on the left spirals, divided between barred (below) and non-barred (above). Source: [1]

Finally, having understood what stars and galaxies are, we moved on to understanding what galaxy clusters are (an example of such an object can be seen in Figure 4). They can be understood as the largest gravitationally bound structures in the Universe [7], composed of galaxies, intracluster gas, and dark matter. Since each of the components has different characteristics, diverse techniques are used for their study. Galaxies are made up of stars

[4] $M_{\odot}$ is the symbol used to define solar mass, which is the mass of the Sun (approximately $2 \times 10^{30} kg$).

[5] The terms "cool" and "hot" are used here in relation to stars and not to the common concept of temperature. Thus, a cool star has around 3000K and a hot star, 10000K.

and mainly emit in the visible region, so optical telescopes and techniques such as spectroscopy are mainly used for their study. The gas mainly emits in the X-ray wavelength, so space telescopes are needed since this wavelength does not enter the Earth's atmosphere. Lastly, to study dark matter, techniques such as gravitational lensing are used, which is the study of the distortion of light as it passes through large objects (such as clusters). An example of the distortion caused by the gravitational lensing phenomenon can be seen in Figure 4.

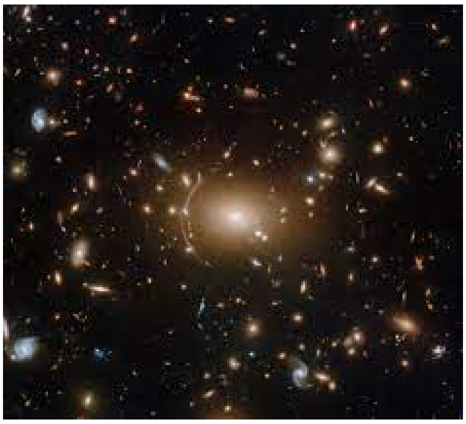

Figure 4: Image of the Abell 611 galaxy cluster obtained by the Hubble Space Telescope. In the image, it is possible to see the formation of gravitational arcs, which occur due to the distortion suffered by light passing through the cluster. Source:[3]

3.2. *Step 2: Compiling and understanding Dawson's method and code*

After completing the study of fundamental concepts, the next step was the analysis of the dynamic code of Dawson [2]. Before compiling the code properly, it was necessary to understand how it works. The first step was to install and test the necessary libraries, as shown in Figure 5. These libraries are public and easy to use/install.

```
from __future__ import division
import numpy
import scipy.integrate
import pickle
import profiles
import time
import sys
import cosmo
```

Figure 5: Summary of Python libraries required for the use of Dawson's code. Source: [2]

Next, we sought to understand the constants defined by the code (Figure 6). It became clear that they are known quantities of nature, such as the Universal Gravitation Constant ($G = 6.67 \times 10^{-11} Nm^2/kg^2$) written in units more appropriate for the context of galaxy clusters (in terms of Mpc, for example), and unit conversions, such as from **kg** to **Mpc** and degrees to radians.

```
# Constants and conversions
G = 4.3*10**(-9) #newton's constant in units of Mpc*(km/s)**2 / M_sun
c = 3e5 #speed of light km/s
sinGyr = 31556926.*10**9 # s in a Giga-year
kginMsun = 1.98892*10**30 # kg in a solar mass
kminMpc = 3.08568025*10**19 # km in a Megaparsec
minMpc = 3.08568025*10**22 # m in a Megaparsec
r2d = 180/numpy.pi # radians to degrees conversion factor
```

Figure 6: Summary of the constants required for the use of Dawson's code. Source: [2]

The code has several functions, which return the desired information based on the input parameters. Firstly, the code was tested using the data from the Bullet Cluster available in [2], with masses of $1.5 \times 10^{14} M_\odot$ and $1.5 \times 10^{15} M_\odot$ and a projected distance of 720 kpc. The result for the time was consistent with the original work, showing that the compilation was correct.

The main function of interest (MCEngine) has several parameters. The main values provided as input to the program are "Nmc", which is the number of desired user samples, "M1", which is the mass of the first cluster, "M2" of the second, both in units of solar masses. "Z" represents the redshifts of each cluster and "dproj" is the projected distance, given in Mpc. This function generates random parameters according to the statistical method and calculates the kinematics of the cluster merger.

Initially, tests were carried out in the program with a small number of samples (1, 10, 100) up to 10,000, which would be ideal to obtain more accuracy when running the program.

Thus, the next step was to understand the data from the [10] catalog so that the code could be used with it.

3.3. *Step 3: Obtaining and Understanding the ZuHone Data*

The data from the ZuHone simulation was separated according to the input parameters already discussed in Section 2. As each file contains a lot of information, it was decided to download one file to test the methodology. The chosen file was for a mass ratio of 1:1 and an impact parameter of 0 kpc, with a size of 10 GB on disk.

Each simulation set contains files (tables) with the various simulated parameters.

Thus, the challenge was to read each of the files of interest and organize their data into tables that could be analyzed by the catalog, i.e., that related the parameters to time. This was successfully done for the first catalog of the selection and was applied to the others. The results obtained are shown in Figure 7, where the simulated collision pattern is seen. The simulation begins when there is maximum separation between the clusters until the moment of minimum separation (indicated by the black vertical line in the graphs). Then there is a new maximum separation, this time smaller than the first due to the loss of energy in the collision, followed by a new approach, and so on. The values of the collision instants are shown in Table 1.

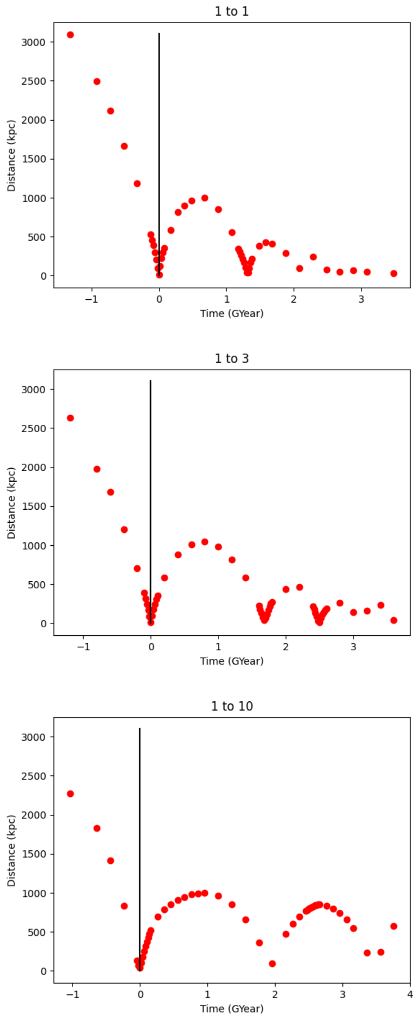

Figure 7: Plot of distance (Mpc) as a function of time (Gyr), where the black line represents approximately the moment of the first collision between the galaxy clusters. Source: [10]

Mass Ratio	Moments of the first collision (Ganos)
1:1	1.32
1:3	1.20
1:10	1.04

Table 1: The list of moments of the first collision identified in the sample of [10] is given for each of the presented mass ratios.

3.4. Step 4: Application of Dawson's method for each of the available simulations.

With the catalogs ready, the final step was to apply the code to each of the proposed scenarios. This means that for each of the points shown in Figure 7, the code presents a possible result for the time after the collision, obtained from 1000 Monte Carlo iterations. The error for the value was estimated from the np.quantile function. The results for each of the clusters are shown in Figure 8.

For a better interpretation of the results, it was decided to focus on the region of greatest interest, namely between the first collision and the subsequent maximum separation. It is worth noting that after this maximum separation, the code by [2] is no longer applicable, as its purpose is to determine the time elapsed after the first collision. The detailed results are shown in Figure 9.

The results shown in Figure 9 indicate that, within the uncertainties, the code from [2] is consistent with the simulated reality in the interval it proposes for all the analyzed scenarios (mass ratios 1:1, 1:3, and 1:10). However, there is a tendency for the main values to always be underestimated compared to the simulated data, a situation that needs to be analyzed in more depth.

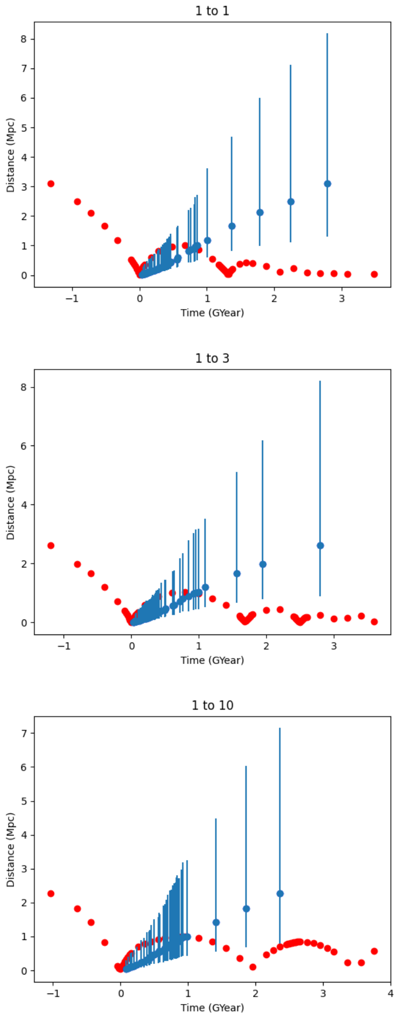

Figure 8: Comparative graph between simulation data (ZuHone) and analytical code (Dawson) for each mass range. In blue, Dawson, it is possible to see the margin of error in the separation (in Mpc) in relation to the red, ZuHone, which is the simulation. Source:[10]

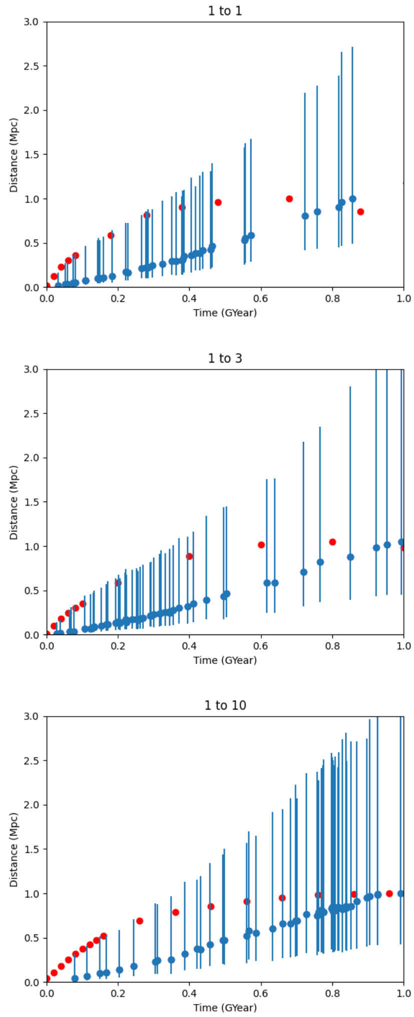

Figure 9: Graphs highlighting the interval of greatest interest, between the minimum and maximum separation points of the galaxy clusters. The blue bars represent the error margin for the time elapsed since the collision for the different scenarios.

4. Final Considerations

The main objective of the research - to contribute to the knowledge of dark matter through the study of cluster galaxy collisions - was successfully completed, demonstrating that the chosen method for analysis is feasible.

It was concluded that the code proposed by [2] has good reliability within the error intervals for situations with different mass ratios between the first collision and the separation. However, there was a tendency for the data to always be lower than the reality, which needs to be investigated more carefully by future work.

Given the feasibility of the method, the perspective is to apply it again to the other data sets of the simulation by [10], in this case, with impact parameters inclined relative to the plane of the sky.

The secondary objective - the training of a young researcher, the main focus of the CNPq's junior scientific initiation program - was fully achieved, as the author carried out basic research, fulfilling all the stages of developing a scientific work. The important role of Astronomy in this process is also highlighted, as its ability to fascinate people with its fundamental questions contributed to motivating the realization of this work.

References

[1] Y. Cui, Y. Xiang, K. Rong, R. Feris, and L. Cao, ≪A spatial-color layout feature for representing galaxy images≫, in Ieee winter conference on applications of computer vision (2014), pp. 213–219, 10.1109/WACV.2014.6836098.

[2] W. A. Dawson, ≪The dynamics of merging clusters: a monte carlo solution applied to the bullet and musket ball clusters≫, The Astrophysical Journal **772**, 131 (2013) 10.1088/0004-637X/772/2/131.

[3] B. Downer, *Hubble celebrates the spooky season with abell 611 — a cobweb of galaxies held together by a dark secret*, ESA, (2022) https://esahubble.org/news/heic2213/ (visited on 10/30/2022).

[4] M. de Fátima Oliveira Saraiva, *O conteúdo do universo*, UFRGS, (s.d) http://www.if.ufrgs.br/~fatima/ead/universo-atual.htm (visited on 08/02/2022).

[5] IF−UFRGS, *Espectroscopia*, UFRGS, (s.d) http://astro.if.ufrgs.br/rad/espec/espec.htm (visited on 07/18/2022).

[6] L. I. A. Prado, *À luz das Estrelas*, 1ed (DP A Editora LTDA, 2006), ISBN: 8574903051.

[7] A. C. Soja, *O Aglomerado de Galáxias RXC J1504 -0248*, 2011.

[8] K. de Souza Oliveira, *Astronomia e Astrofísica*, 4ed (Livraria da Física, 2017), ISBN: 8578614852.

[9] D. Vergano, *Astronomers spy bullet galaxy blasting through other galaxies*, National Geographic, (2015) https://www.nationalgeographic.com/adventure/article/150114-bullet-cluster-space-newton (visited on 08/02/2022).

[10] J. Zuhone, K. Kowalik, E. Öhman, E. Lau, and D. Nagai, ≪The galaxy cluster merger catalog: an online repository of mock observations from simulated galaxy cluster mergers≫, The Astrophysical Journal Supplement Series **234**, 4 (2017) 10.3847/1538-4365/aa99db.