Boletim da Sociedade Astronômica Brasileira, **36**, no. 1, 172-173

Study of dark matter from n-body simulations

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Abstract. In this work, we study the main numerical methods for solving the n-body gravitational problem, presenting as an example a simulation that describes the collision of spiral galaxies, implemented using the GADGET-2 code. Given the absence of electromagnetic interactions of Dark Matter (DM), n-body simulations become an essential tool for its study. We explore this characteristic by performing a simulation of the large-scale structure of the Universe, aiming to extract the DM halos generated at the end of the program and compare their rotation curves with those observationally obtained for 19 nearby dwarf galaxies listed in the LITTLE THINGS catalog.

Resumo. Neste trabalho, estudamos os principais métodos numéricos para resolver o problema gravitacional de n-corpos, apresentando como exemplo uma simulação que descreve a colisão de galáxias espirais, implementada com o código GADGET-2. Dada a ausência de interações eletromagnéticas da Matéria Escura (DM), as simulações de n-corpos tornam-se uma ferramenta essencial para seu estudo. Exploramos essa característica realizando uma simulação da estrutura em larga escala do Universo, com o objetivo de extrair os halos de DM gerados ao final do programa e comparar suas curvas de rotação com as obtidas observacionalmente para 19 galáxias anãs próximas, listadas no catálogo LITTLE THINGS.

Keywords. dark matter – Methods: numerical – Methods: data analysis

1. Introduction

A widely accepted result in the scientific community today is that the primary constituent of the massive part of our Universe is an unknown component called Dark Matter (DM). Its presence accounts for 23% of the entire cosmos, as noted by Marcomini (2015), and the term originates from the absence of electromagnetic interactions between DM and the luminous content of the Universe, referred to as baryonic matter. Despite the accumulated evidence, the study of DM is still relatively recent and fundamentally relies on gravitational n-body simulations. This is because, given the absence of electromagnetic interactions, gravity is the main force acting on dark matter on a large scale. In this work, we performed n-body simulations related to galaxy collisions and the large-scale structure of the Universe. Additionally, we obtained the rotation curves of 19 nearby dwarf galaxies available in the LITTLE THINGS catalog and compared them with results available in the literature.

2. Methods

2.1. N-body simulations

N-body simulations are a numerical approach to solving the so-called “n-body problem,” which involves determining the temporal evolution of the trajectories of the components in a system composed of n massive particles interacting with each other. In simpler cases, the universal law of gravitation is used to determine the accelerations of each body, and numerical integration methods are applied to find their positions at each moment in time. In cosmological simulations, the systems are described by Einstein’s field equations. Additionally, baryonic matter can be included, for example, using the smoothed particle hydrodynamics (SPH) method.

Initially, we studied n-body simulations by implementing a code in Python. However, one of the main challenges in this type of simulation is optimizing the execution time of the codes. The simplest algorithm to solve the problem involves calculating the gravitational force pairwise between the bodies, which results in increasingly worse temporal performance as the number of bodies grows. This happens because, to update each particle, it is necessary to account for information from all others, leading to a computational cost of $O(N^2)$.

Due to this high computational cost, we opted to use GADGET-2, a program widely used in the literature for cosmological n-body simulations. GADGET-2 (GAlaxies with Dark matter and Gas intEracT) is a free and open-source code designed to simulate the formation of large-scale structures in the Universe. It employs a tree algorithm to compute particle accelerations, reducing the computational cost to $O(N \log N)$. Moreover, the program includes native parallelization, making it efficient for large-scale simulations.

To evaluate the performance of the programs, we conducted simulations with initial conditions describing the collision of two spiral galaxies, comparing the efficiency of our code with that of GADGET-2. For this, we executed the simulation multiple times, varying the number of bodies in each run and recording the corresponding execution time. The initial and final states of the simulation are illustrated in Figure 1.

In the study of DM, we used the GADGET-2 code to perform a low-resolution simulation of the large-scale structure of the Universe. This simulation employed 32^3 DM particles confined within a cubic box with an edge length of 50 h^{-1} Mpc, assuming a ΛCDM cosmological model. Similarly to the previous simulation, the initial and final states of the simulation are shown in Figure 2. The goal was to study the techniques required to perform a higher-resolution simulation, from which specific dark matter halos can be extracted.

2.2. LITTLE THINGS catalog

The next step of the work was to use the velocity fields available in the LITTLE THINGS catalog to extract the rotation curves of 19 nearby dwarf galaxies, comparing the results obtained with the data presented in Oh et al. (2015). Based on the rotation curves of the gaseous and stellar components, and using the expression

$$V_{total}^2 = V_{gas}^2 + \Upsilon_\star V_\star^2 + V_{halo}^2,$$

we also determined the rotation curves of the dark matter halos for each galaxy.

3. Results

In Figure 3, we highlight the difference in execution times between our implemented code and the GADGET-2 program, demonstrating the superior efficiency of the latter. In Figure 4, we present the rotation curves for the dwarf galaxy DDO 154, including contributions from the gaseous and stellar components, as well as the dark matter halo.

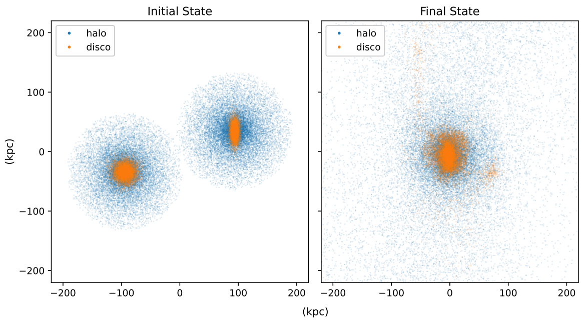

Figure 1. Initial state of a system consisting of two spiral galaxies on a collision course.

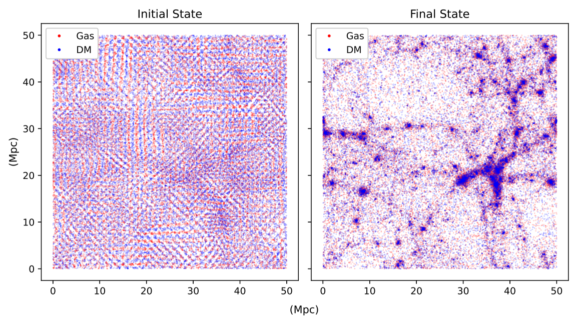

Figure 2. Initial and final states of a low-resolution simulation of the large-scale structure of the Universe with ΛCDM cosmology.

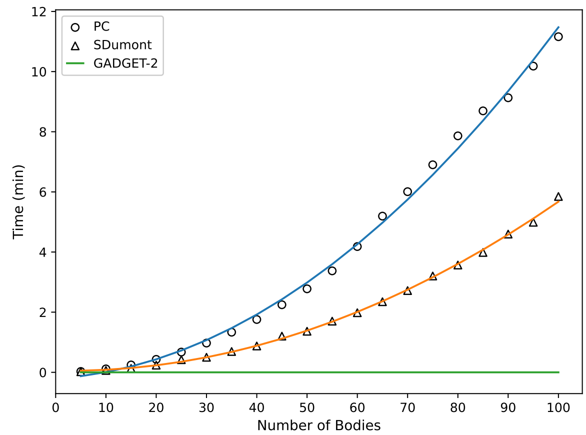

Figure 3. Simulation performed with GADGET-2 on a personal computer, along with the custom code implemented in this research executed on both the same computer and the Santos Dumont supercluster.

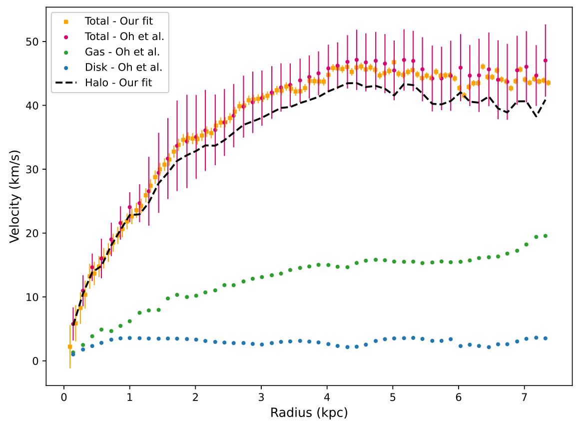

Figure 4. Rotation curves for the dwarf galaxy DDO 154. The dashed line represents the velocity distribution as a function of radius for the dark matter halo.

4. Conclusions

We presented a study on the numerical solution of the n-body problem. Additionally, we extracted rotation curves associated with the dark matter halos of dwarf galaxies using the LITTLE THINGS catalog. Future steps for this work could include conducting higher-resolution simulations to extract dark matter halos. These halos could then be directly compared with the data obtained from the LITTLE THINGS catalog, enabling a more in-depth analysis of the properties of dark matter in dwarf galaxies.

Acknowledgements. To FAPESP for granting the undergraduate scientific research scholarship and for the financial support of this research through process No. 2023/05909-9. To the National Laboratory for Scientific Computing (LNCC) for providing the computational resources of the Santos Dumont supercluster, which allowed for further discussions and analyses in this work.

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