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Faculty of Science

Course of:

Simulation and Modeling in Astrophysics

Project proposal: Where we are going: the fate of the Solar System after the Milky Way and Andromeda merger

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1 Abstract

Within the Local Group a macroscopic event is set to take place in the future: given that the Andromeda Galaxy is moving towards the Milky Way, the two galaxies will not be able to avoid the collision and the final merger. This immediately raises a question: at the end of such an event, what will happen to the Solar System? To get an answer our research will focus on simulating such a collision and merger using the AMUSE software, with the goal to unravel the fate of the Solar System. Additionally, we will take into consideration the intergalactic medium and follow the dynamical evolution of the two super massive Black Holes centered in both galaxies.

2 Project description

The future evolution of the Solar System is a fascinating problem, on which we already have some insight: the Sun will evolve into a Red Giant, probably including the inner planets into its expanding envelope. Although what will happen after this phase remains an open problem. To shed some light on the future we need to consider the Sun as a member of the Milky Way (MW) and our Galaxy as a member of the Local Group. The MW and the Andromeda Galaxy (M31) are the two most massive members of the Local Group that, according to recent simulations (see Cox and Loeb [1], van der Marel et al. [2] and Schiavi et al. [3]) and observational measurements (see van der Marel et al. [4]), are likely to experience a merger event in $\approx 5\,Gyr$.

The fate of our System after the merger is yet an unsolved problem that we will address in this project with the help of the AMUSE software (see Portegies Zwart and McMillan [5], Portegies Zwart et al. [6], Pelupessy et al. [7] and Portegies Zwart et al. [8]). Using this tool we will first model both the MW and M31, then set the galaxies in motion and monitor their evolution during the merger event, following closely the Solar System and its closer stars. To improve the past simulation we will add to the model the intergalactic medium (IGM), which could have an important role in the merger due to friction. Furthermore we will also monitor the evolution of the super massive Black Holes (SMBH) that lie at the center of both galaxies. We will answer the following questions:

- How do the starting conditions of the simulation, as relative velocity and orientation, and the presence of the IGM affect the dynamical evolution of the merger?
- What is the statistical likelihood of our Solar System to remain bound to the newly formed galaxy after the merger? If that is the case, what will be its position?
- What will be the final separation of the two SMBHs?

The simulations will be done with the implementation of a gravitational and hydrodynamics module within the AMUSE framework. We will put a substantial effort into the research of the specific N-body gravity and hydrodynamic solvers best suited for our problem. These modules will be used to build and evolve the galaxy models and to simulate the IGM. The galaxy models will feature bulge, bar, disk and halo, with focus on reproducing the spiral arms. The Solar System will be indirectly tracked by defining a region around its current position in the galactic plane and monitoring the evolution of the stars in this region. Data-analysis should then be able to show the probability of different end scenarios for the Solar System: it could undergo a change in its coordinate in the galactic plane (closer or further to the center) or it could become unbound and be ejected from the resulting galaxy.

To obtain meaningful results we will carefully choose the initial conditions of our simulation. First we will need a detailed model of MW and M31 (our goal is to use an improved version of the one used in Cox and Loeb [1]) and a model of the IGM (for the radius and density profile see Lehner et al. [9]). We will refer to Raychaudhury and Lynden-Bell [10] to get initial separation and galactic spin vectors. However no general agreement has been reached for the value of the velocity vector of M31, in the past several values have been proposed (see van der Marel et al. [4], Salomon et al. [11] and van der Marel et al. [2]) in a range that spans from $\approx 10\,km/s$ to $\approx 10^2\,km/s$. Given this wide uncertainty our simulations will be run taking into consideration several values from the range of possible M31 velocity vectors.

Much has already been studied in earlier works. In Cox and Loeb [1] the dynamic evolution of the Solar System during the merger has been studied as well as the separation between the galaxies during the merger. However we can bring improvements on this work: new estimates on M31 velocity and mass distribution are available (see Sohn, Anderson, and van der Marel [12] and van der Marel et al. [13]) while other initial conditions were used in the past (see Klypin, Zhao, and Somerville [14]). Newer papers have used these improved measurements to study the dynamics of the MW-M31 system (see van der Marel et al. [4]) and the effect of the relative velocity on the separation (see Schiavi et al. [3]). Nonetheless neither of these works focuses on the fate of our System or take the IGM into account. Lehner et al. [9] present new measurements and a description of the circumgalactic medium of M31.

Our results should be able to give us more insight into the MW-M31 merger event. The focus on the Solar System could provide some insight on the rate of ejected stars during such an event. By using more recently estimated dynamical initial conditions our results can be compared to Cox and Loeb [1], van der Marel et al. [4] and Schiavi et al. [3]. The inclusion of the IGM can improve our understanding on the future of the Local Group and more in general of merging galaxies dynamics.

To make sure that our simulations will finish running in a reasonable time we will gradually increase the amount of simulated particles. In the case that the model will turn out to be too slow to simulate we will scale it down in some of its components. Both gravitational N-body interactions and hydrodynamic turbulence present a chaotic behaviour: small changes in the initial conditions lead to macroscopic changes in the results, that in some cases can also diverge. Numerical effects such as RNG-seeding and floating-point roundoff can cause infinitesimal variations that will propagate in our chaotic system (see Keller et al. [15]). To take these uncertainties into account, we will run the simulations multiple times with the same initial conditions.

2.1 Resources

Initial simulations will be done on a smaller scale, modelling the galaxies with a limited number of particles (i.e. stars), so our own devices can be used to perform test runs. Once made sure our code works as intended, we will increase the accuracy of our models adding a larger number of particles. From this point onwards, to run the final simulations, we will have to rely on the ALICE High Performance Computing facility provided by Leiden University[1].

2.2 Expected results and possible developments

We expect to produce meaningful data that will answer the questions presented at the beginning of Section 2. To derive the final results we will present plots and animations showing the evolution of the merger while highlighting the Solar System, as well as a plot of the SMBH separation as a function of time. These results will be reproduced for different relative M31 velocities and taking into account the presence (or absence) of the IGM.

Numerous developments can extend the scope of the project in the future. To achieve an even more refined description of the merger, other members of the Local Group can be taken into consideration (van der Marel et al. [4] suggest that M33 will play an active role in the merger) while factor in the cosmological expansion. The spatial resolution of the simulations can also be increased to study the SMBH binary that will form at the end of the event.

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