# USING NUMERICAL N-BODY SIMULATIONS AND THE FOF ALGORITHM TO ANALYZE THE COLLISION OF THE YOUNG MILKY WAY WITH ANOTHER DISK GALAXY

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**ABSTRACT**

This report encompasses the use of GADGET-2, a computer program for N-body simulation and smoothed-particle hydrodynamics (SPH), to analyze the collision of the Milky Way and a smaller disk galaxy 10 billion years ago. The product of this collision is present-day dwarf galaxies. The simulation is based on a mass ratio of 4 to 1 for the colliding galaxies, with one million particles in each one, and an impact parameter of 6 kpc, for a parabolic orbit. The results demonstrate the effect of tidal forces between the galaxies as the smaller galaxy is destroyed by the impact. The debris of the destruction precedes to orbit the parent galaxy in a perpendicular plane similar to the spatial distribution shown by the satellite galaxies of the Milky Way.

## 1 Introduction

The study of Dwarf Galaxies is of great importance. This is primarily because of the inconsistency between the predictions given by the cosmological model of cold dark matter and what has been acquired through observational data. The model predicts a much higher number of galaxies than what has been recorded by observations [1]. Further reason lies in their relevance to the formation of larger galaxies like the Milky Way. As seen in figure 1, it is thought that our version of the Milky Way was formed after a cosmic collision approximately 10 billion years ago in which Gaia-Enceladus, a dwarf galaxy, crashed into a primitive Milky Way (Milky Way Progenitor) [2]. In addition, it has been shown that the Milky Ways dwarf satellite galaxies are in a very particular distribution because they are orbiting our galaxy in an anisotropic way, forming a plane almost perpendicular to it in the form of a disk [3]. The disagreement between the cosmological model and the observations suggests that the cosmological model has not taken into account the cannibalization of the satellite galaxies into larger galaxies. Thus studies of dwarf galaxies are important to address this disparity between the model and observations.

The anisotropic distribution of our satellite galaxies was first found in the so-called 11 "classical" dwarf galaxies. They were the first ones discovered because of their proximity to the Milky Way. With respect to them, it was found that they are orbiting our galaxy organized in a virtual disk-like structure as seen in figure 2, inclined approximately 88° to the plane of the Milky Way, i.e., the so-called disk of classical satellites (DoS) is oriented almost perpendicular to our galaxy. Then, new galaxies were discovered, among them a new type called ultra-faint dwarf galaxies, [Leo IV, Her, CVn II, CBe, etc] characterized by very low stellar density and luminosity. These newly found ultra-faint dwarfs were shown to have a spatial distribution very similar to that shown by the classical satellites [4]. These galaxies respond to a spatial structure susceptible to be adjusted to the same plane as the brightest "classical" galaxies, thus corroborating the anisotropy of the spatial distribution and, in turn, generating more interest in it. Given the above, the purpose of this work was to simulate the collision of two galaxies, one of them the young Milky Way with another disk galaxy of lower mass in order to demonstrate whether it is possible that such a collision could generate debris resulting from tidal forces that lead to the formation of small structures spatially distributed in a similar way to the disk of satellites of the Milky Way.

Figure 1: Two spiral galaxies, NGC 2207 and IC 2163 colliding with one another. As the two galaxies slowly tear each other apart, their stars are pulled by “tidal forces,” eventually forming a long cord of stars that will form a smooth, sharp curve around the galaxy. Evidence of this type of collision, known as a "shell structure," was recently found in the Milky Way, remnants of a collision that happened nearly 3 billion years ago. (Image credit: Debra Meloy Elmegreen (Vassar College) and the Hubble Heritage Team (AURA/STScI/NASA)

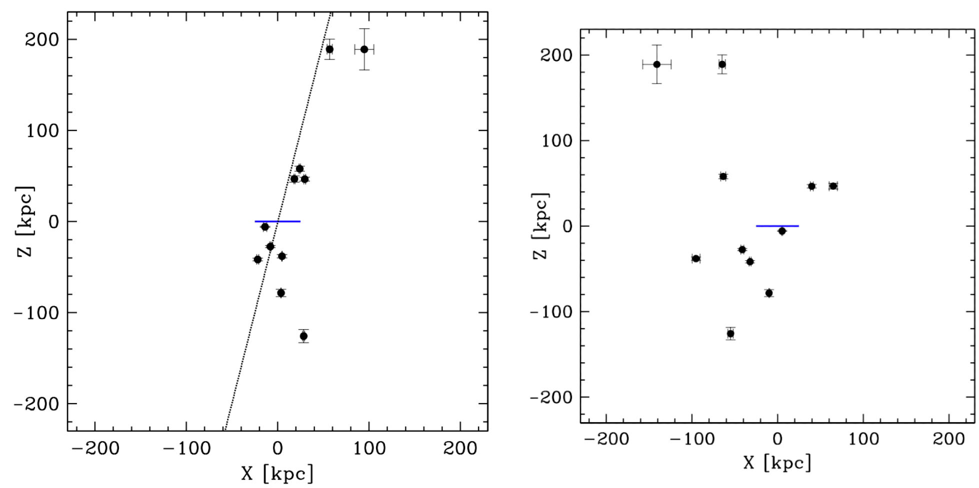


Figure 2: On the left table, the position of the innermost 11 Milky Way satellites is viewed from a point located at infinity and $l$ = 167°.91. The Milky Way disk is indicated by the horizontal line -25 $\leq X$/pc $\leq$ 25, and the centre of the coordinate system lies at the Galactic centre. The dashed line marks the fitted plane for $N$ = 11 seen edge-on in this projection. The table on the right is the left viewed from $l$ = 77°.91. The fitted plane here is seen face-on. (Credit: Christian M. Boily (University of Strasbourg)

## 2 Scenario and Initial Conditions for Collision

In these tests, a scenario was considered where approximately 10 Gyr ago, the Milky Way collided with another disk galaxy four times smaller. The simulations were performed using a numerical N-body simulation code called GADGET2 to perform the collision of the galaxies. Gadget-2 was used as opposed to other applications as its TreeSPH code is capable of following a collisionless fluid with the N-body method, and an ideal gas by means of smoothed particle hydrodynamics (SPH). Furthermore, its SPH conserves energy and entropy in regions that are without dissipation while allowing for adaptable smoothing lengths as well as the capability to be computed with a hierarchical multipole expansion for gravitational forces which can be applied in the form of a TreePM algorithm [5].

Using the code, the galaxies were constructed using one component for the disk and one for the halo. The halo has a Hernquist-type density distribution [6] and for the disk, an exponential disk model was used with each galaxy being composed of one million particles. With respect to the geometry of the collision, parabolic orbits were used, since, from previous work, it is known that such orbits are more efficient with regard to the generation of bridges and tidal tails [7], with the purpose of achieving an off-center collision where the less massive galaxy makes several close passes and loses material, before colliding directly with the other. The galaxies rotate prograde with respect to the orbit, with an initial

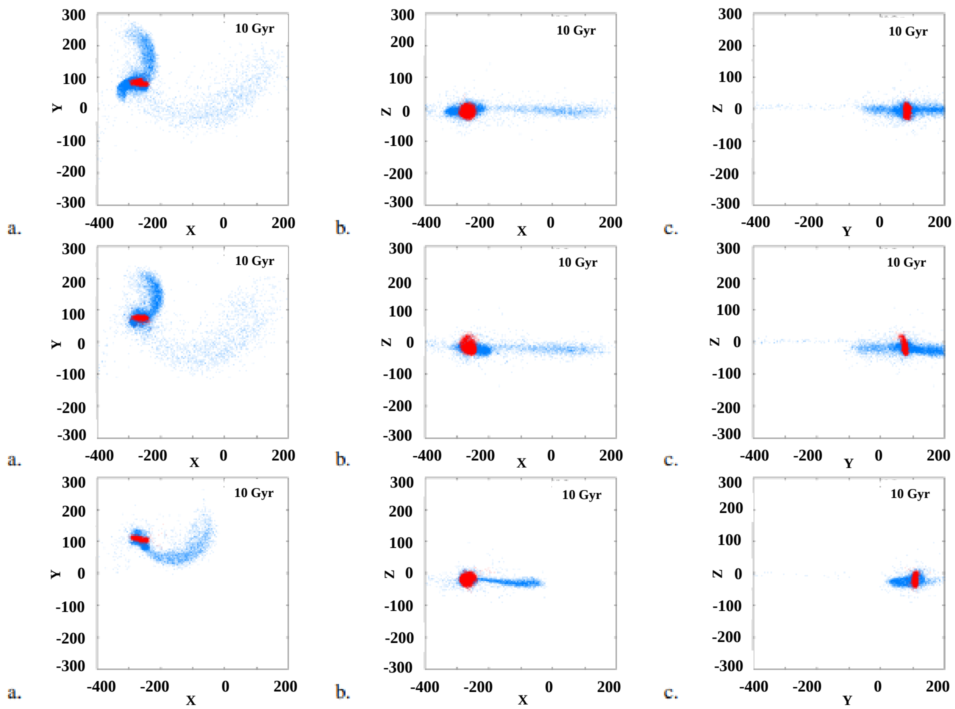


Figure 3: The red points represent the disk and the blue points represents the halo and the outer parts of the galaxy.

distance between them of approximately 200kpc. The galaxies are positioned so that their planes are perpendicular to each other, to promote the generation of tidal debris perpendicular to the parent galaxy.

Since what is sought is an organization of debris almost perpendicular to the disk of the parent galaxy, it is necessary to define the appropriate impact parameter, which allows such a distribution. For this reason, several simulations were carried out with $10^5$ particles in each galaxy to find a range for the fixed parameter and thus be able to perform the simulation with a million particles and shorten the simulation time. A range between 6, 6.5, and 7 kpc was tested as seen in figure 3 with each row of a, b, and c respectively representing the result of the simulation for 100 thousand particles. All three planes were in units of kpc, with each parameter arranged according to the order already mentioned.

As can be seen in the last two rows for parameters of 6.5 and 7 kpc, the mother galaxy is closely accompanied by a small remnant galaxy that fails to be completely destroyed. As this is not supported by cosmological observations, it is decided to perform the simulation with a million particles for an impact parameter of 6 kpc. As can be seen in the graphs of the first row, it is possible to obtain the total destruction of the less massive galaxy and also have debris distributed more perpendicular to the mother galaxy. Looking at the results obtained for the simulation of a million particles with the chosen impact parameter of 6 kpc cited above, it is shown how the less massive galaxy makes a few very close passes to the parent galaxy leaving each of them orbiting material due to the tidal forces generated by the more massive galaxy. On the third pass, the remnant collides for the last time and is completely destroyed. With the data from this last simulation, I found clumps of particles in the tidal debris left by the collision in order to analyze their spatial distribution and compare it with observations over the Milky Way. For this purpose, a code called Friends of Friends (FoF) was used under certain initial conditions, which allowed me to find several groups of particles that could be fitted to a plane whose inclination with respect to the plane of the Milky Way was 85°, i.e., the plane of the groups found for this simulation is almost perpendicular to the plane of the Milky Way.

## 3 Conclusion and Results

Using GADGET-2, I simulated the collision of two disk galaxies with a mass ratio of 4 to 1, starting with a few particles in order to find a range for the impact parameter and found a range between 6, 6.5, and 7 kpc. Observing the results for the 6.5 and 7 kpc parameters, it was concluded that they were not adequate, since they left a small remnant galaxy very close to the mother galaxy, which does not agree with observations, and therefore the parameter to use in the simulation with a million particles is 6 kpc. With respect to the simulation for a million particles, it was found that due to tidal forces, the galaxy with the lowest mass manages to make a pair of pericentric passes around the most massive one, losing particles in each of them, and then collides directly with the parent galaxy before entirely dissolving itself.

After concluding those results, particles were found using the Friends-of-Friends (FoF) grouping algorithm. In order for accurate data to be measured, the FoF depends on two linking lengths (LLs), plane-of-sky and line-of-sight (LOS), normalized to the mean nearest neighbor separation of field galaxies [8]. Once the two LLs were managed, I found groups of particles from the debris of the collision, which are shown to be distributed almost perpendicular to the plane of the Milky Way. It is found that the number of clumps found near the Milky Way is very large and there is a deformation of the disk of the parent galaxy with each pericentric passage of the lower mass galaxy. I only saw a similarity with the observations with respect to the perpendicularity in the distribution of the groups found, but for future work, different mass ratios can be tested for approximation.

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