N-body Simulation of a Binary Dwarf Galaxy Infall

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The infall of a binary dwarf galaxy merger in the Milky Way's stellar halo was investigated using N-body simulations. A binary dwarf galaxy with 80000 bodies and a mass of 10^9 solar masses was generated in a null potential using Milkyway@home and its initial parameters were adjusted in mwahpy. Three sets of initial parameters were tried. The binary dwarf was run in a Milky Way potential for three Gyr. A tidal stream is observed to have formed from the second set of parameters. One of the dwarf galaxies has been entirely disrupted, while one is still being disrupted. The rotation direction of the binary dwarf didn't influence whether a tidal stream formed but did affect the characteristics of the observed stream. The formation of a tidal stream from a binary dwarf galaxy could allow for observed tidal streams to be modelled using a binary dwarf galaxy infall.

Introduction

The Milky Way has been studied for hundreds of years to determine its mass, structure and how it has evolved. The Milky Way is made up of several components; the bulge, the disk, and the stellar halo. The bulge is a very dense cluster of stars located at the center of the Milky Way where there is both an old population of stars and a younger population, which indicates recent star formation. The disk contains star clusters, interstellar gas and dust, and regions with active star formation. The disk stars orbit around the galactic center along the galactic plane and contains the spiral arms of the Milky Way. The stellar halo is located beyond the disk at very large distances from the galactic center. Only about one percent of the mass of the Milky Way is contained in the stellar halo. The halo also has nearly no net rotation, meaning the stars don't have uniform orbits. Stars in the halo are generally very old; due to this old age, understanding the processes which led to the formation of the stellar halo is key in unravelling the evolutionary history of the Milky Way. The halo is primarily where the Milky interacts with celestial objects such as dwarf galaxies.

Several dozen dwarf galaxies are known to orbit the Milky Way. As these satellite galaxies come too close to the Milky Way, the galaxy's gravitational potential pulls harder on the part of the satellite galaxy nearest to the galactic center, they are then pulled apart and stretched into thin strands that orbit around the Milky Way, this process is called tidal disruption (Newberg and Carlin, 2016). The tidal disruption of these dwarf galaxies leads to the formation of significant density substructure in the halo, called tidal streams.

Tidal streams reveal information about the nature of the galaxy's evolution and stellar halo. Studying the present-day configuration of the Milky Way can be used to develop theories about the formation of the Milky Way and the early universe. The Milky Way halo is primarily built up by accretion events, which is when the Milky Way takes on mass from a dwarf galaxy. Remnants of dwarf galaxy mergers are presumed to make up a majority of the mass of the stellar halo. Recently, it has become apparent that the Milky Way is made up of at least one major merger event (Helmi, 2020). However, there is debate over whether there was one ancient massive merger event, where a massive dwarf galaxy collided with the Milky Way billions of years ago or several smaller dwarf galaxy mergers built up the halo (Belokurov et al., 2018; Helmi et al., 2018; Donlon et al., 2019, 2020).

Most literature describes single dwarf galaxy mergers, where one dwarf galaxy collides with the Milky Way and forms a tidal stream in the halo. Single dwarf galaxy mergers have been used to model many significant substructures in the Milky Way halo, such as the formation of the Orphan-Chenab stream and other tidal streams (Mendelsohn et al. 2022). However, there is substructure in the halo that hasn't been explained by a single dwarf galaxy merger. For example, a second stream has been observed alongside the Sagittarius tidal stream (Koposov et al. 2018). The mechanism for this formation is currently unknown. There have been several theories about this structure including, the interaction of the Sagittarius dSph with the dark matter halo, and that the Sagittarius dSph was once a part of a binary galactic system, similar to the Large Magellanic and Small Magellanic Clouds.

One possible solution could be using two gravitationally bound dwarf galaxies, a binary dwarf galaxy, to model the observed substructure that hasn't been able to be explained by a traditional single dwarf galaxy merger. Additionally, modeling substructure with a binary dwarf could provide substantial evidence in favor of the several smaller merger events theory and provide information about the accretion history of the Milky Way.

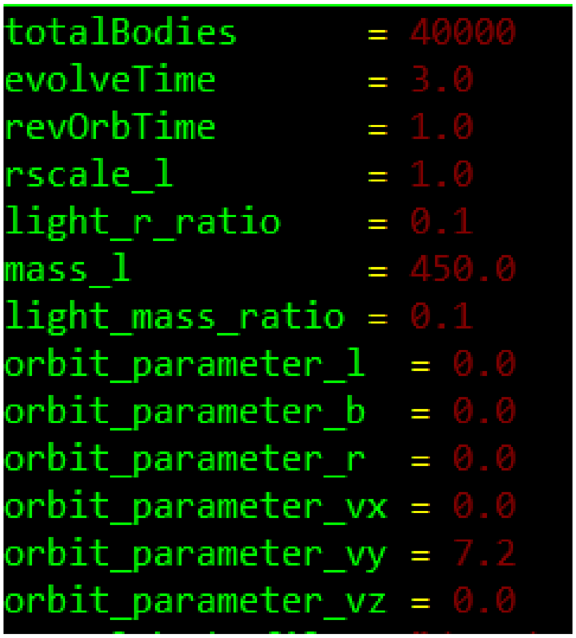
I propose to model a binary dwarf galaxy merger using N-body simulations. I will look at the observed outcome of the binary dwarf galaxy merger to see if a tidal stream forms, and how changing the initial parameters, such as the starting position of the binary dwarf and the internal parameters of the dwarf galaxies, affects the observed outcomes.

Methodology

N-body simulations are used to represent the movement of a dynamical system of particles under the influence of forces. These simulations have been used to model few-body systems like a star system, as well as large scale structures, such as dwarf galaxies. For this study, the particles represent the stars in the binary dwarf galaxy. N-body simulations determine the forces on each particle in the simulation, in this case the gravitational potential of the Milky Way. Based on these forces it will calculate the movement of each particle.

Milkyway@home (MWAH) will be used to run the N-body simulations (Mendelsohn et al. 2020). MWAH is a distributed volunteer supercomputer that utilizes spare computing power from volunteers to run simulations. It is designed to create accurate 3-D models of the Milky

Way and tidal streams in the stellar halo. A work unit will be given to MWAH containing the initial parameters of the dwarf galaxy, such as the total number of particles, evolve time, mass, and the orbital parameters, which are shown in Figure 1. The outputs of the simulations provided by MWAH will be analyzed and adjusted in a supplementary Python package called mwahpy, which can be found at https://github.com/thomasdonlon/mwahpy.



```
totalBodies        = 40000
evolveTime         = 3.0
revOrbTime         = 1.0
rscale_l           = 1.0
light_r_ratio      = 0.1
mass_l             = 450.0
light_mass_ratio = 0.1
orbit_parameter_l   = 0.0
orbit_parameter_b   = 0.0
orbit_parameter_r   = 0.0
orbit_parameter_vx = 0.0
orbit_parameter_vy = 7.2
orbit_parameter_vz = 0.0
```

Figure 1. Example workload for MWAH.

MWAH can’t generate a binary dwarf, so a single dwarf galaxy was generated in MWAH in a null potential, meaning it will experience no gravitational forces from the Milky Way. The dwarf galaxy will be placed at the origin with initial parameters of 40000 total bodies, a mass of 10^9 solar masses, and a y-component velocity of 7.2 km/s, determined by equation 1.

$$v = \sqrt{\frac{GM}{2R}} \qquad 1)$$

The binary dwarf galaxy will have a radius of five kpc, so the dwarf galaxy must be shifted to the correct x positions, in mwahpy. A copy of this dwarf galaxy will be generated in mwahpy and rotated π radians around the z axis. The two dwarfs will be placed on a circular orbit. Next, the binary dwarf galaxy will be run in a null potential for three Gyr to check that the system is on a stable orbit and won't collapse in on itself. A scatter plot of the x and y positions will be generated to check that the system is stable.

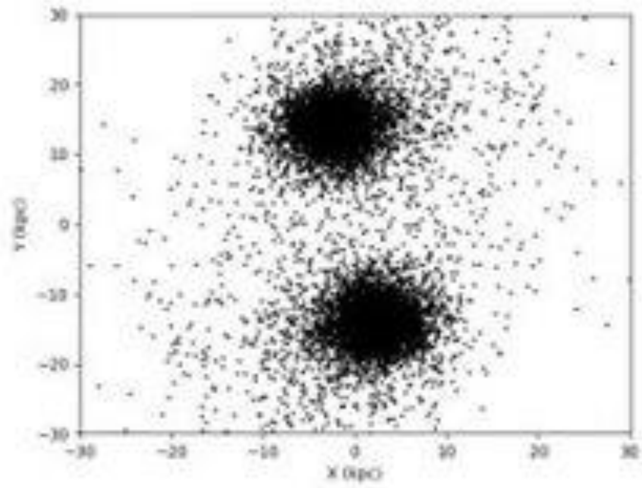


Figure 2. Plot of x and y positions of the binary dwarf galaxy.

The binary dwarf will then be run in a Milky Way potential for three Gyr, with data being collected every two hundred million years to see how the stream evolves over time. Three initial conditions will be tried: x=25 kpc, y=0 kpc, z=25 kpc, and zero velocity will be added, x=25 kpc, y=0 kpc, z=25kpc, vx=150 km/s, vy=150 km/s, vz=0 km/s, and x=0 kpc, y=0 kpc, z=30 kpc, vx=200 km/s, vy=0 kpc, vz=0 kpc. The third set of initial parameters are similar to the orbit of the Sagittarius dwarf galaxy.

Results:

The first and third set of initial parameters didn’t form a tidal stream or other significant substructure, as demonstrated by Figure 3. The dwarf galaxies appear to collapse into one structure and don't orbit the galactic center on a uniform orbit. Both span large distances from the galactic center of up to 1000 kpc from the galactic center.

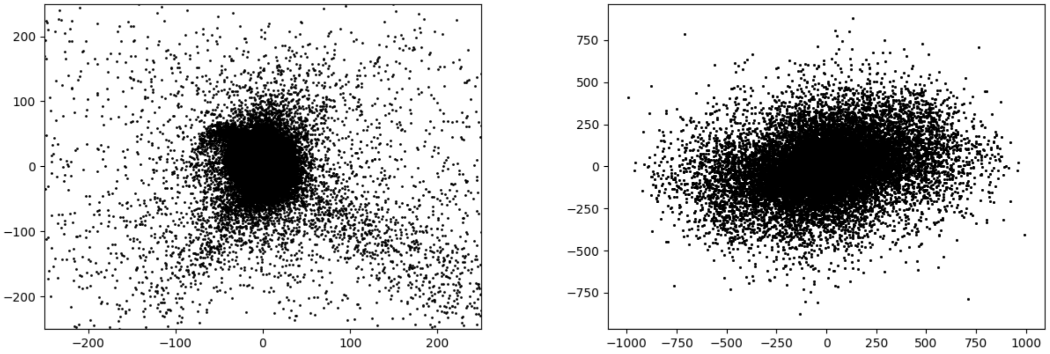


Figure 3. Plots of x and y positions of the first and third set of initial parameters.

The second set of initial parameters is observed to have formed a tidal stream, as seen in Figure 4. Notably, the stream is not continuous with a significant gap between the two dwarf galaxies at around 50 kpc, which separates the two dwarf galaxies. The dwarf galaxy colored in orange has been entirely disrupted and a smooth density gradient can be seen along this portion of the stream. However, the dwarf galaxy colored in blue is continuing to be disrupted, and the tidal tails and the core of the dwarf galaxy are still visible.

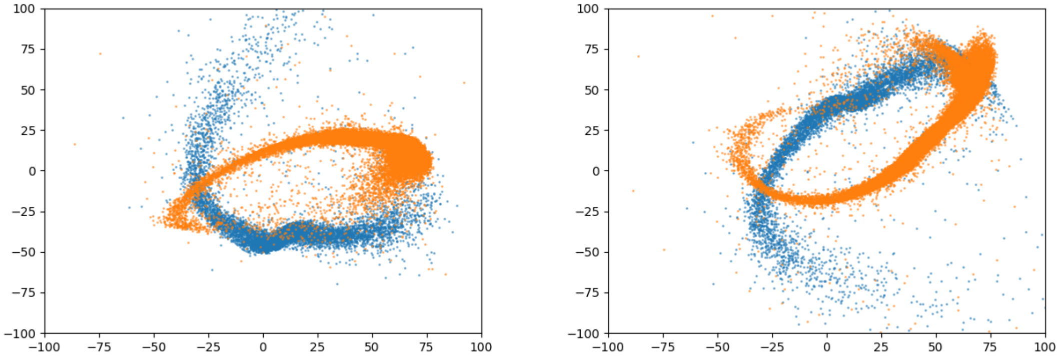


Figure 4. Plot of x and y and x and z positions of the second set of parameters. The blue and orange colors represent stars in each of the dwarf galaxies in the binary dwarf.

The velocity of the second set of parameters was negated to check if the rotation direction of the binary dwarf affected the stream. It can be seen in Figure 5, that the observed stream (which will be called stream two) is much thicker and doesn't reach as large of distances compared to stream one. There is a more consistent density gradient across the stream and there isn't a significant gap between the two dwarf galaxies.

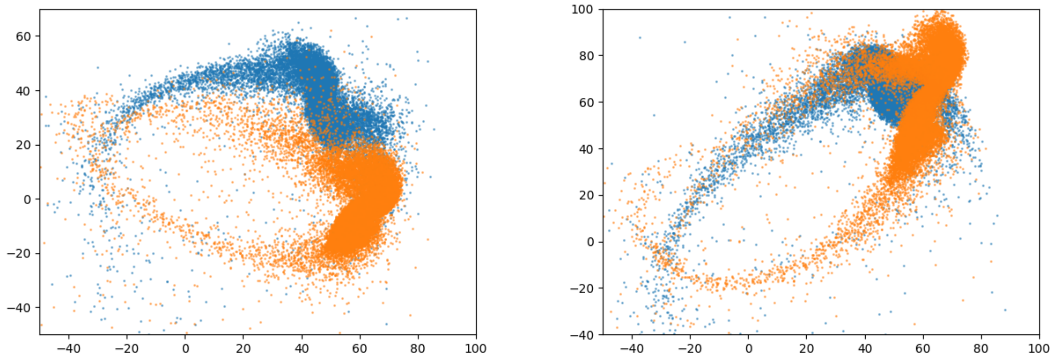


Figure 5. Plots of x and y and x and z positions of stream two.

Angular momentum vs orbital energy plots were created for both streams, as shown in Figures 6 and 7. As a dwarf galaxy orbits around the Milky Way, their positions and velocities will change. There are quantities that don’t change such as angular momentum and orbital energy. These quantities are used to think of the stream in terms of its orbit rather than its positions and velocities. Orbital energy is related to how far a star can get from the galactic center. Angular momentum represents how quickly a star spins around the Milky Way. Although, these quantities aren’t supposed to change over time, due to interactions between the particles in the simulation, there are small changes in energy and angular momentum. These changes can reveal information about the stream.

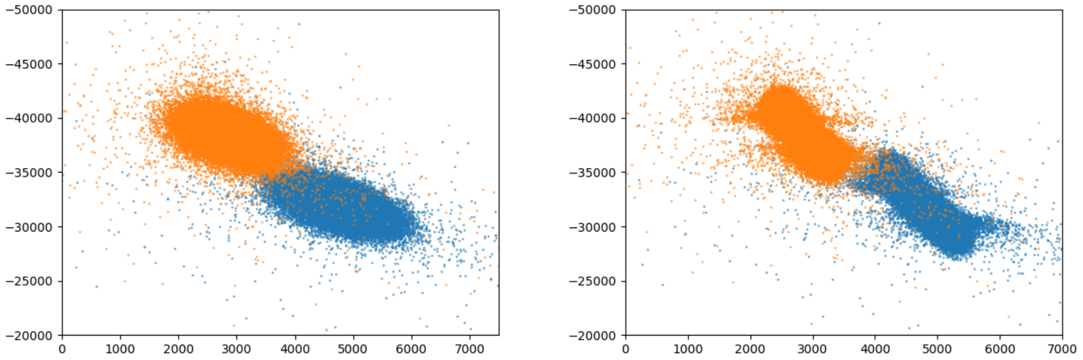


Figure 6: Angular momentum vs. orbital energy plots for stream one at the beginning and end of the simulation.

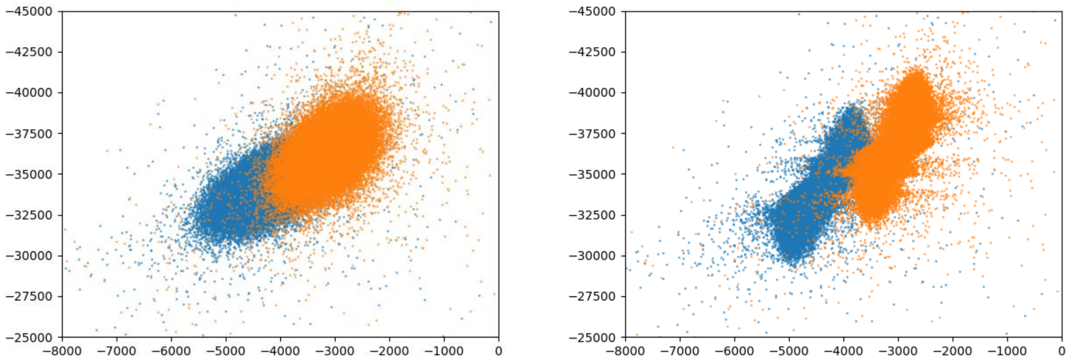


Figure 7: Angular momentum vs. orbital energy plots for stream two at the beginning and end of the simulation.

Conclusion:

Three initial parameters were tried. A binary dwarf galaxy has been shown to form a tidal stream in a Milky Way potential. A binary dwarf with initial parameters, x=25 kpc, y=0 kpc, z=25kpc, vx=150 km/s, vy=150 km/s, vz=0 km/s is observed to form a tidal stream. The formation of a tidal stream is correlated to the starting position of the binary dwarf relative to the galactic plane and its initial velocity. One of the dwarf galaxies has been entirely disrupted while the tidal tails and galactic core are still visible in the other. Also, a significant gap can be seen around 50 kpc from the galactic center. This will be notable when trying to use a binary dwarf to model observed tidal streams in the stellar halo.

The rotation direction of the binary dwarf was checked by negating the velocity value. It was observed that a tidal stream still formed from this adjusted stream, however there were significant differences in the structure of this stream. The stream reached smaller x and y positions, and there was no gap between the binary dwarfs. This stream is more consistent with observed streams in the halo and could indicate that the rotation direction of the binary dwarf galaxy will be significant in modelling tidal streams in the halo.

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