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Analyzing stellar stream dynamics: *N*-body simulations and analytical potentials.

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Abstract. Understanding the dynamics of tidal interactions between galaxies is crucial for comprehending galaxy evolution.This study aims to compare an analytical model with *N*-body simulations to discern the differences and limitations of the analytical approach in modeling dynamics from tidal interactions. The focus is on the orbital evolution of a satellite galaxy interacting with a Milky Way-like galaxy, particularly a satellite galaxy with a mass of $1 \times 10^9 M_\odot$. Initial conditions were set for both galaxies, implementing the analytical model using Gala, and conducting *N*-body simulations via Gadget. Preliminary results show a close agreement between the analytical model and *N*-body simulations for orbits with an initial radius of 70 kpc over a 3 Gyr period. However, for orbits starting at 30 kpc, the analytical model reveals deviations of 8% for circular orbits and 18% for eccentric orbits, indicating limitations in capturing the complex dynamics of tidal interactions at closer ranges.

Resumo. Compreender a dinâmica das interações de maré entre galáxias é essencial para entender a evolução estrutural das galáxias.Este estudo tem como objetivo comparar um modelo analítico com simulações de *N*-corpos para discernir as diferenças e limitações da abordagem analítica na modelagem da dinâmica das interações de maré. O foco está na evolução orbital de uma galáxia satélite interagindo com uma galáxia semelhante à Via Láctea, especificamente uma galáxia satélite com massa de $1 \times 10^9 M_\odot$. As condições iniciais foram estabelecidas para ambas as galáxias, implementando o modelo analítico usando Gala e realizando simulações de *N*-corpos através do Gadget. Resultados preliminares indicam uma concordância próxima entre o modelo analítico e as simulações de *N*-corpos para órbitas com um raio inicial de 70 kpc num período de 3 Gyr. No entanto, para órbitas com início em 30 kpc, o modelo analítico mostra uma divergência de 8% para órbitas circulares e de 18% para órbitas excêntricas, revelando limitações na captura da dinâmica complexa das interações de maré em distâncias mais curtas.

Keywords. Galaxy: kinematics and dynamics – Galaxies: star clusters: general

1. Introduction

Understanding the dynamics and evolution of galaxies, particularly the Milky Way, and the role of tidal interactions in shaping their structures has been a subject of immense interest in astrophysics. The advent of the Gaia satellite, with its observations and precise astrometric data, has significantly contributed to our knowledge of the Milky Way, enabling the mapping of stellar streams. This research focuses on investigating the dynamics and effects of tidal streams resulting from tidal interactions between a disk galaxy and a satellite galaxy. The study employs a combination of *N*-body simulations and analytical models (Price-Whelan et al. 2017) to compare and analyze the accuracy and limitations of each approach.

2. Methods

The initial conditions for the simulations were generated using Galstep (Ruggiero & Lima Neto 2017), incorporating components such as a stellar disk, a dark matter halo, and a stellar bulge. *N*-body simulations were performed using the Gadget-4 code (Springel et al. 2021), while the analytical models were constructed using the Gala package (Price-Whelan et al. 2017), applying the same parameters. The results from the simulations were compared with the analytical models to assess their accuracy and limitations. Using the Hernquist density profile (Hernquist 1990) for the halo, as given by Equation 1, with $a_\mathrm{h} = 47$ kpc and the halo mass $M_\mathrm{h} = 1 \times 10^{11} M_\odot$.

$$\rho(r) = \frac{M_\mathrm{h}}{2\pi} \frac{a_\mathrm{h}}{r} \frac{1}{(r + a_\mathrm{h})^3} \tag{1}$$

Similarly, we applied the Hernquist density profile for the bulge, as per Equation 1, but with different parameters $a_\mathrm{b} = 1.5$ kpc and $M_\mathrm{b} = 9 \times 10^9 M_\odot$. For the disk, we used the Miyamoto Nagai 3 density profile (Smith et al. 2015), as described in Equation 2, with values $a_\mathrm{d} = 3.5$ kpc, $b_\mathrm{d} = 0.7$ kpc and $M_\mathrm{d} = 5 \times 10^{10} M_\odot$.

$$\rho(R, z) = \frac{M_\mathrm{d} b_\mathrm{d}^2 [a_\mathrm{d} R^2 + (a_\mathrm{d} + 3\sqrt{z^2 + b_\mathrm{d}^2})(a_\mathrm{d} + \sqrt{z^2 + b_\mathrm{d}^2})^2]}{4\pi [R^2 + (a_\mathrm{d} + \sqrt{z^2 + b_\mathrm{d}^2})^2]^{\frac{5}{2}} (z^2 + b_\mathrm{d}^2)^{\frac{3}{2}}} \tag{2}$$

The satellite galaxy was placed in a polar orbit for these simulations. A series of 6 simulations were conducted: 3 with circular orbits at their respective circular velocities, and 3 with eccentric orbits, with initial velocities set at 70% of the circular velocity for the gravitational potential. The trajectories of these orbits over the 3 Gyr period are presented in Figure 1 for circular orbits and shown in Figure 2 for eccentric orbits.

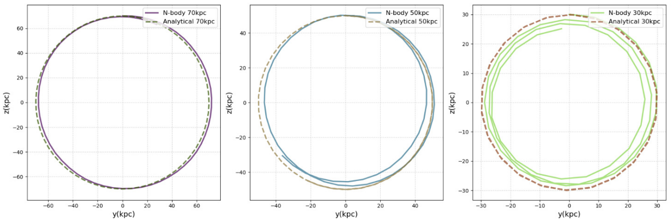

Figure 1. Comparison of circular orbits from 70 kpc to 30 kpc.

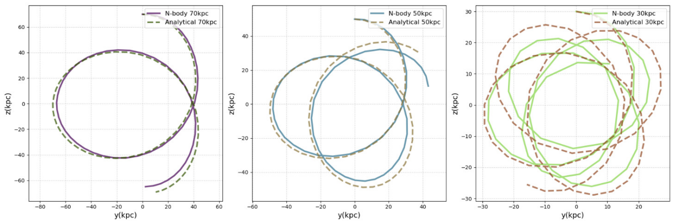

Figure 2. Comparison of eccentric orbits from 70 kpc to 30 kpc.

Additionally, Figure 3, which showcases the galaxy generated with the satellite galaxy located 30 kpc away in orbit and its evolution over 3 Gyr with the respective circular velocity for the compound potential, should be mentioned:

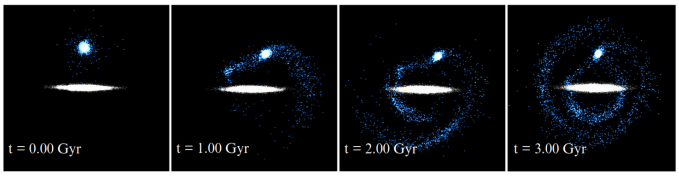

Figure 3. Four frames from one of the simulations showing the evolution over 3 Gyr.

3. Result

The study's results shed light on tidal stream effects in disk-satellite galaxy interactions. The *N*-body simulations, compared with analytical models, showed minor discrepancies for circular orbits at 70, 50, and 30 kpc, but these errors grew for eccentric orbits, particularly around 30 kpc where differences became notable after several Gyr. Conducted over a 3 Gyr period, the simulations revealed a significant error increase (up to 18% for eccentric orbits at 30 kpc), underscoring the challenges analytical models face in complex orbital scenarios. These insights are key to understanding analytical models limitations in depicting dynamic galactic systems.

Figure 4 illustrates the radial velocity for circular orbits, providing a detailed view of the velocity patterns and their consistency across different orbital distances. The radial velocity trends observed here are indicative of the gravitational influences at play and the relative stability of circular orbits under these conditions.

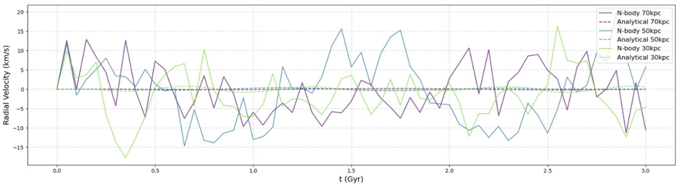

Figure 4. Radial velocity for circular orbits.

In Figure 5, the tangential velocity for circular orbits is displayed. This graph offers insight into the lateral motion of the satellite galaxy in its orbit, further underscoring the variances in orbital behavior at different radial distances.

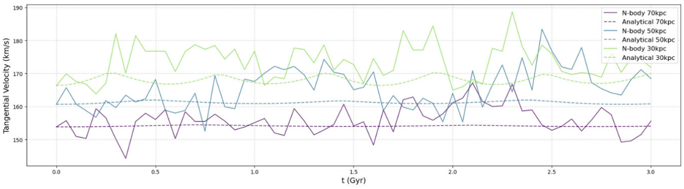

Figure 5. Tangential velocity for circular orbits.

The increasing divergence between the *N*-body simulations and analytical models for shorter orbital distances suggests that the simplifications inherent in the analytical calculations become more pronounced as the gravitational interactions intensify. This is further demonstrated in Figure 6, which depicts the radial velocity for eccentric orbits. The variability and complexity of these orbits are evident, reflecting the heightened challenges faced in modeling such trajectories.

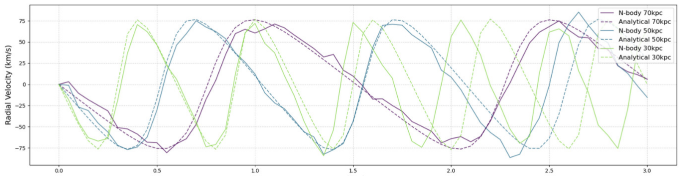

Figure 6. Radial velocity for eccentric orbits.

Lastly, Figure 7 presents the tangential velocity for eccentric orbits. This visualization is key to understanding the non-linear and irregular patterns that emerge in the movement of the satellite galaxy, especially in orbits with high eccentricity.

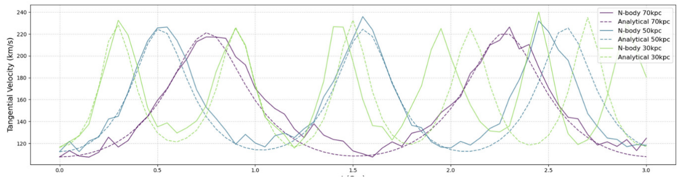

Figure 7. Tangential velocity for eccentric orbits.

4. Conclusion

The comparison between *N*-body simulations and analytical models yields valuable insights into the capabilities and limitations of each method. For orbits ranging from 70 kpc to 30 kpc, the analytical models exhibited a relatively minor error, in the order of 8% for circular orbits, suggesting their utility in predicting the system's dynamics under these specific conditions. However, discrepancies increased for eccentric orbits, escalating to a variation of 18% for those near 30 kpc after several Gyr. This increasing trend of error with decreasing orbital distance and rising eccentricity highlights the limitations of the models and underscores the need for more refined techniques to accurately capture the complex dynamics at these closer distances.

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