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Tidal Mass Transfer from Close Encounters between MW and M31

Aidan J. Nakhleh[1]

[1] *University of Arizona*

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ABSTRACT

The Milky Way Galaxy (MW) and The Andromeda Galaxy (M31) are predicted to undergo several close encounters, and eventually merge together, allowing for potential mass transfer between the two galaxies in the process. This potential mass transfer can influence the structure of each respective galaxy, and influence the rate of star formation and spiral-like structures of each galaxy, influencing each galaxy's respective evolution before their final merger. We are quantifying mass transfer by tracking disk particles inside and outside each galaxy's Jacobi radius at certain times, as well as calculating particles with total energies above zero (free) and below zero (bound). This quantification is important to gain estimates for what fractions of the disk will transfer away from one galaxy, and the tracking is important to see where these particles will move to, thus assessing the accuracy of our energy predictions. We have found that no mass transfer occurs until ~ 5.8 Gyr, and despite $\sim 3\%$ of each galaxy's disk having positive energy, dynamical friction and extra dark matter mass hinder the ability of the particles to escape and transfer elsewhere. This is important because we need energy calculations need to be more refined, and there may be less mass transfer than expected between these two tightly interacting bodies.

Keywords: Major Merger – Hernquist Profile – Gravitationally Bound – Jacobi Radius – Spiral Galaxy

1. INTRODUCTION

When galaxies interact with each other gravitationally, dynamical effects alter their structures. Specifically, tidal forces that are brief but very strong distort the outer parts of the interacting disk-shaped galaxies. These distortions take on different forms, and have differing effects on the resulting galactic evolution after the interaction. Some of these effects include satellite formation, star formation and quenching, mass transfer between galaxies, and ejection of material from the entire system.

These dynamical effects impact kinetic properties of the galaxy, the total mass of the galaxy, and the distribution of different matter within and around the galaxy. These changes can influence the rate of star formation, mass, density, and luminosity profiles, and even the existence of satellites, all influencing the evolutionary track and categorization of the galaxies affected during the merger.

The two main characteristics formed during gravitational interaction are galactic tails and bridges. Both of these are formed from tidal forces acting on the outer parts of galactic disks when they interact with each other (Toomre & Toomre (1972)). If conditions are right, some disk material can gain a large velocity kick, and begins to move away from its host galaxy in a thin tail. If there is enough of a kick, the tail can become unbound and escape the system, otherwise it returns back to the system and can connect with either of the two galaxies, or form a separate satellite. Another distortion is the tidal bridge, which features outer disk material of the two galaxies forming a tight line from galactic center to galactic center. This bridge allows for very direct, albeit brief, mass transfer. If the bridge is rich in gas, and it falls to the center of the companion galaxy, a process called AGN feedback can occur, which influences galactic growth and the process of quenching (Ji et al. (2014)). Conversely, in the process of tail creation the velocity kick can induce shock waves which can trigger star formation as well (Barnes (2004)). The theories of shock induced star formation and density dependent star formation are coupled together by broader dynamics induced during galaxy encounters, so while shock induced star formation does seem to exist, it is not unified yet, and cannot predict star formation properly before the interaction occurs (Barnes (2004)). Additionally, many of these mergers have been modelled using N-body simulations with gravity as the only contributing force. To obtain a more complete model of how these tails affect star

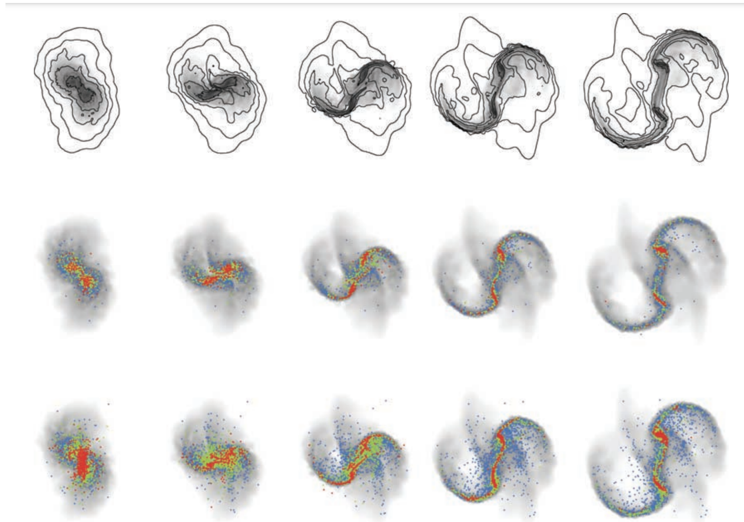


Figure 1: From Barnes (2004), detailing simulation of the Mice Galaxies (NGC 4676) and their dynamical evolution. This figure tracks star forming regions at different time units using a color coded tagging method. The top row involves contours of gas densities, the second and third rows detail star formation regions through points as they evolve over time. I wish to tag my particles of interest similarly, but instead particles that are part of the tidal bridges and tails in MW and M31.

formation, AGN feedback, and gas physics, these N body simulations will need to include hydrodynamics and smaller scale interactions at the sub-grid level (Privon et al. (2013)), and the computational costs need to be reduced for the calculations to be feasible. Mass transfer between systems can potentially influence AGN feedback from an N-body perspective that is not easily quantifiable a priori. If, during a close encounter, matter transfers from a host galaxy to a companion galaxy, and that mass travels to the center of the companion galaxy, it has the potential to ignite / accelerate the AGN accretion rate, which can enhance AGN feedback by a certain amount. Additionally, the process of quenching/acceleration of star formation rates after galaxy mergers appears unclear. If a region of a galaxy that is rich in dust happens to transfer through a tidal tail away from the host galaxy to the companion or off to infinity, star formation rates will certainly decrease. If this gas rich matter lands in the companion galaxy, the star formation rate of this companion galaxy will similarly increase. Investigating the regions where mass transfer takes place and investigating the presence of dust in that region will help to probe the parameters of quenching and star formation during galaxy mergers.

2. THIS PROJECT

In this paper, I will explore the mass transfer between the Milky Way and Andromeda galaxies when they interact. Specifically, I will be seeing how much mass flows from one to another, and where that mass flows to. This flow can suggest to us whether AGN feedback is a significant feature, and how star formation may begin or end. I will also consider mass shed from either system off to infinity when the galaxies perform a close flyby. This paper investigates the mass transfer of disk material, which is some of the most observable material, and thus useful to understand. The flow of disk matter is also best observed through these tidal tails and bridges. In order to determine which material undergoes mass transfer, we will need to study the potential and kinetic energies of different particles as the galaxies undergo close encounters. If the kinetic energy of a particle exceeds the gravitational potential energy of the host galaxy, it will in theory have achieved transfer, either to the other galaxy or off to infinity.

This project will help to answer the questions of AGN feedback and potential quenching or increase in star formation, based on where the particles undergoing mass transfer come from and arrive at. If particles coming from the spiral arm of one galaxy end up escaping the system entirely, or end up in the center of the companion galaxy, then the first galaxy may undergo some quenching, and the second galaxy may feature some AGN feedback, for example.

In general, the rate of star formation can help astronomers gauge the age of a galaxy. However if two young galaxies merge early and extreme quenching takes place, astronomers will see a lower rate of star formation and assume the pair of galaxies are older than they really are. This affects the categorizations astronomers use to gain a sense of consistency when seeing many different kinds of galaxies. Additionally, mass transfer can influence AGN feedback, which affects the amount of energy the surrounding gaseous medium has, which in turn affects galactic evolution differently than if the AGN feedback had not taken place.

3. METHODOLOGY

To probe the question of mass transfer between M31 and MW during their future close encounters, we utilize the set of simulations created by Van der Marel et al. (2012) that study how MW and M31 interact over time. This is an N-body simulation, which calculates the mutual gravitational forces between a large number of particles N on each other. In order to do so, numerical techniques must be applied to the initial conditions of a collection of particles, and advanced through time.

As this simulation is advanced forwards in time, every particle composing the system is considered, with each particle having a position in Cartesian space with the origin centered on the Milky Way center position at time 0. Additionally, every particle has a velocity vector, broken into its x,y, and z components. A respective galaxy is composed of three types of particles: bulge particles, disk particles, and dark matter halo particles, so every particle also has this composition label on top of its kinetic properties. I am going to analyze these particles to determine if they transfer from one galaxy to another, or escape the entire system entirely. I will use widely accepted profiles and boundary values to help ease the computational burden of calculating the potential energies and kinetic energies for many particles, so I can accurately assess mass transfer efficiently. To get an idea of which particles are prone to mass transfer, I will first calculate if they

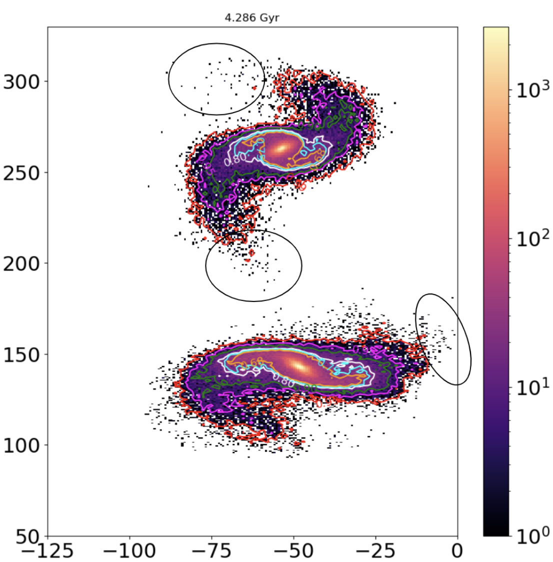


Figure 2: Snapshot of disk particles in MW (top) and M31 (bottom) galaxies through a 2D density contour histogram, recently completing a close encounter 4.286 Gyr from today, with circled regions of potential mass transfer in black ellipses. Instead of selecting every single particle to check if mass transfer is possible, we select particles based on unique locations where mass transfer is more likely to take place. Specifically, we will analyze if these particles are within their host Galaxy's Jacobi radius, and whether their kinetic energies are greater than or less than their gravitational potential as predicted by the analytic Hernquist potential energy profile.

are within the Jacobi radius of the host galaxy. The Jacobi radius for a satellite is the minimum radius of the satellite travelling in circular motion around an isothermal sphere to be gravitationally bound to the host. In general,

$$R_j = r(\frac{M_{sat}}{2 * M_{host}(< r)})^{1/3} \tag{1}$$

Where r represents the center of mass separation between the two galaxies. Therefore for the host galaxy we only want to include matter enclosed within the radius of the center of mass separation, while for the satellite galaxy we want to include all of the matter composing the galaxy, since all of it will contribute to binding the particle to the satellite.

Any particles lying outside of this calculated Jacobi radius of the satellite galaxy may undergo mass transfer, so I will check their potential energies with kinetic energies to get a definite result. In order to check their potential energies, I will utilize the analytic gravitational potential as predicted by the Hernquist dark matter halo profile Hernquist (1990), as well as the gravitational potentials from the bulge and disk. Specifically, for the Hernquist profile,

$$\Phi = -GM_{tot}/(r+a) \tag{2}$$

Where Φ is the gravitational potential, M_{tot} is the mass of the galaxy's total halo or bulge component, r is the radius away from the center of mass of the galaxy, and a is the scale factor of the galaxy (empirically determined by comparing the actual mass profile to the analytic Hernquist mass profile). We also want to include the potential from the disk component, by using the analytical Miyamoto-Nagai potential for a disk Miyamoto & Nagai (1975). This potential goes as

$$\begin{aligned} \Phi &= \frac{-GM_{disk}}{\sqrt{R^2+B^2}} \\ R^2 &= x^2+y^2 \\ B &= r_d + \sqrt{z^2+z_d^2} \end{aligned} \tag{3}$$

Where r_d is the galaxy's disk scale length, and z_d is the galaxy's disk scale height. Both of these are determined empirically. This is a convenient equation because our particles are already in x,y,z coordinates so they plug nicely into Equation 3. Lastly, for a full energy calculation we need the kinetic energy of the particle, relative to the center of mass of its host galaxy.

$$KE = \frac{1}{2}m((v_x - v_{x,COM})^2 + (v_y - v_{y,COM})^2 + (v_z - v_{z,COM})^2) \tag{4}$$

Where $v_{x,COM}, v_{y,COM}, v_{z,COM}$ are the x,y, and z components of the host galaxy's center of mass velocity. This is how we determine the relative kinetic energy of the particle to its host galaxy for the calculation.

Therefore, the total energy of a given particle relative to its host mass is

$$E_{tot} = m(\frac{1}{2}v_{rel}^2 + \Phi_{bulge}(r) + \Phi_{halo}(r) + \Phi_{disk}(r)) \tag{5}$$

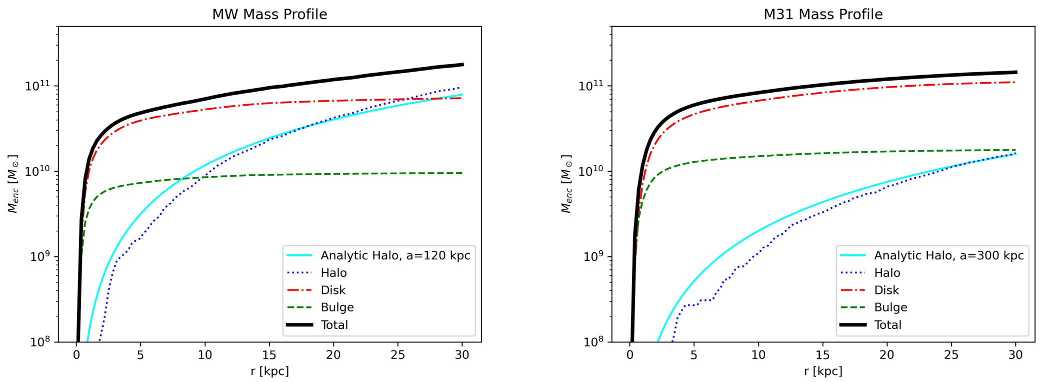
If a particle is outside of the Jacobi radius (i.e. $r > R_j$), and the particle's kinetic energy is greater than the absolute value of the potential energy (i.e. $E_{tot} > 0$), then it has certainly escaped the host galaxy. These particles will then be tagged and tracked through later snapshots to see if they end up in the companion galaxy, or if they escape the system entirely.

This tagging visualization can tell us whether transferred mass ends up in the spiral arm of the companion galaxy, the center of the companion galaxy, or outside of both systems. As discussed earlier, the location of the mass transferred particles is very important in determining processes such as star formation / quenching and AGN feedback, two processes critical to galaxy evolution.

A relatively small amount of mass transfer will occur between the two galaxy disks on the scale of the galaxy mass, but potentially large on the scale of stellar mass. This will be the case because Toomre & Toomre (1972) mentions, galactic bridges are very transient phenomena so there is not a lot of time for mass transfer to take place. These galaxies will also swing by each other multiple times before merging, which means there will be several opportunities for mass transfer to occur, which means mass can oscillate back and forth between the galaxies several times, reducing the net mass transfer. That being said, there can and probably will still be a profound effect on the mass close to the center of each galaxy. The formation of possible satellites and/or tidal tails that are stretched far away from the disks of the galaxies after they interact and eventually merge may be formed as well, according to existing theories of satellite formation. That being said, I believe that we will find quenching to be more dominant, because particles near gas rich locations that undergo mass transfer can either end up in the core of another galaxy (which contributes to AGN feedback but not star formation), or they may be ejected from the system entirely, which also results in galactic quenching.

4. RESULTS

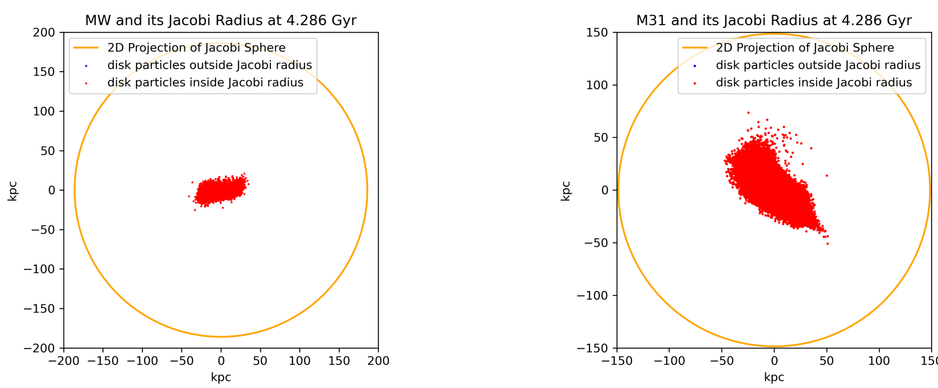
First, we need to see how well the analytic Hernquist mass profile holds up when the galaxies become deformed after a close encounter. To do so, we can calculate the predicted mass enclosed by the Hernquist model, and compare it to the actual enclosed mass, at different radii.



(a) (b)

Figure 3: Plot of MW's and M31's mass profiles with an analytic Hernquist profile to match the dark matter mass profile, at 4.286 Gyr. The fits are not extremely precise, but become more accurate at greater distances. Here, $a_{MW} \approx 120$ kpc, and $a_{M31} \approx 300$ kpc, which is important for the Hernquist profile and thus energy calculation.

Because these fits are still accurate, we can use the Hernquist profile for this first close encounter. This allows us to come up our Jacobi radius for each galaxy by means of equation 1. Doing so, we get that $R_{j,MW} = 185.95$ kpc, and $R_{j,M31} = 148.55$ kpc. We can project these Jacobi radii onto plots of the galaxies to see if any particles lie outside of the Jacobi radius.

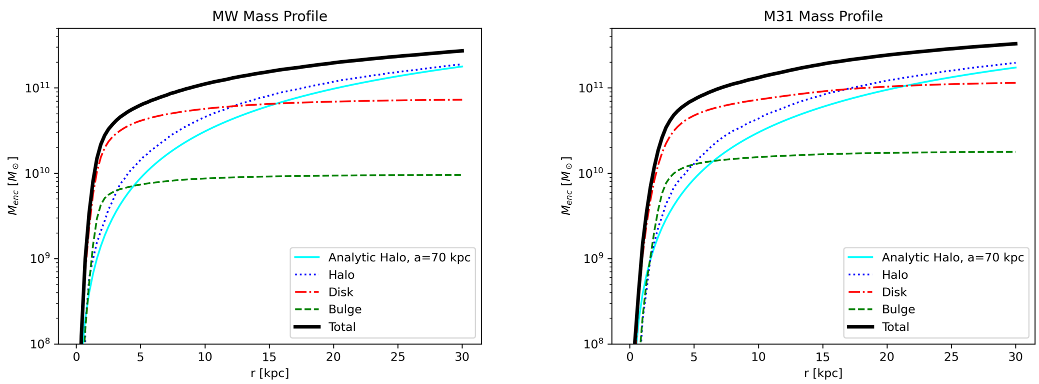


(a) (b)

Figure 4: Plot of MW's and M31's disk particles oriented face-on, with the Jacobi radius of each galaxy as a satellite. Any particles beyond this Jacobi radius are marked blue, and any particles inside are marked orange. As we can see, there are no MW or M31 disk particles beyond the Jacobi radius for each respective galaxy after the first fly by.

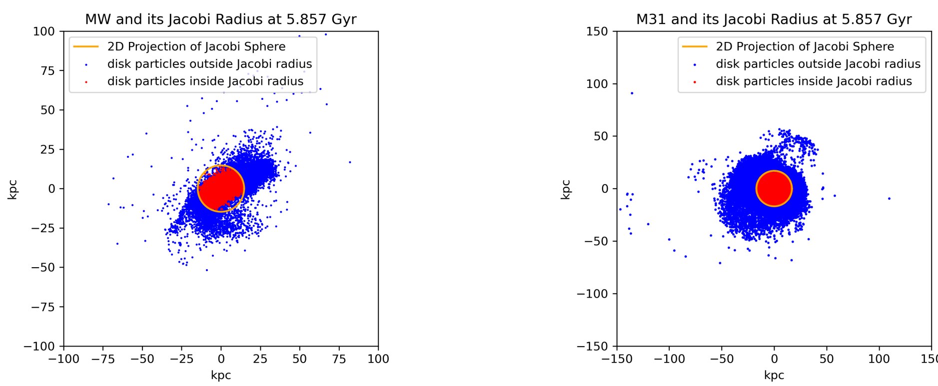
Since there are no particles outside of the Jacobi radius, we can say that there are likely no disk particles that undergo mass transfer during the first close encounter. We can apply the same analysis to the next close encounter, at 5.857 Gyr.

Calculating the New Jacobi radius at this time, we find that $R_{j,MW} = 14.73$ kpc, and $R_{j,M31} = 16.89$ kpc. Projecting this radius onto the disk of MW and M31 during this time provides us with



(a) (b)

Figure 5: Plot of MW's and M31's mass profiles with an analytic Hernquist profile to match the dark matter mass profile, at 5.857 Gyr. Interestingly the dark matter curve is smoother, and the fits are more precise. Here, $a_{MW} \approx 70$ kpc, and $a_{M31} \approx 70$ kpc.



(a) (b)

Figure 6: Plot of MW's and M31's disk particles oriented face-on, with the Jacobi radius of each galaxy as a satellite. Any particles beyond this Jacobi radius are marked blue, and any particles inside are marked orange. Now, the Jacobi radius has shrunken by quite a lot, and there may be more mass transfer possible.

Now, we can check the energies of these disk particles. We want to apply the total energy calculation to the tagged particles in Figure 6. Doing so for MW, we find that the total mass of the particles outside the Jacobi radius is $1.056 \cdot 10^{10}$ $M_\odot$, and the total mass of particles with total energies greater than zero is $7.59 \cdot 10^{8}$ $M_\odot$. For reference, the total mass of the MW disk is $7.5 \cdot 10^{10}$ $M_\odot$.

To see how accurate the Jacobi radius is at predicting mass transfer, we can calculate how many particles within the Jacobi radius also have energies greater than zero. Doing so, we find that the total mass of particles within the Jacobi radius is $6.44 \cdot 10^{10}$ $M_\odot$, and the total mass of particles with energies greater than zero is $1.74 \cdot 10^{9}$ $M_\odot$. Unfortunately, there is more mass that is possible to be transferred inside the Jacobi radius than outside the Jacobi radius, but this is because there is simply more mass within the Jacobi radius than outside it. Fractionally, more of the mass existing outside of the Jacobi radius is transferred than mass inside the Jacobi radius. Overall, 3.7% of the total disk particle mass has a greater energy than zero relative to MW. We can do the same analysis with M31, and summarize the calculation results within a table. Now that we have our particles tagged for the sign of their total energies, we can advance to a further time and see where the particles end up. Because the Jacobi Radius calculation did not capture the majority of positive energy particles, we can just analyze the locations of our positive energy particles at later times. Specifically, we can see where the particles are located at 6.14 and 7.1 Gyr, which are times soon before and

Galaxy Name	M_{tot} (10^{10} $M_\odot$)	$M(< R_j)$	$M(> R_j)$	$M(< Rj)$, $E > 0$	$M(> R_j)$, $E > 0$	$\frac{M(E>0)}{M_{tot}}$
MW	7.5	6.44	1.056	0.1607	0.0713	0.0309
M31	12	9.645	2.355	0.293	0.0281	0.02676

Table 1: Table describing the amount of possible mass transfer between MW and M31 at 5.857 Gyr, based on our Jacobi radius and energy calculations. M_{tot} is the total amount of disk mass, $M(< R_j)$ is the amount of mass contained within the Jacobi radius, $M(> R_j)$ is the amount of mass contained outside of the Jacobi radius, $M(< Rj)$, $E > 0$ is the amount of mass within the Jacobi radius that has a total energy greater than zero (and hence can transfer away from the satellite galaxy), $M(> Rj)$, $E > 0$ is the amount of mass outside of the Jacobi radius that has a total energy greater than zero, and $\frac{M(E>0)}{M_{tot}}$ is the fractional amount of disk mass with a total energy greater than zero. All of these masses are in 10^{10} $M_\odot$.

soon after MW and M31 have merged together. This can give us a rough estimate to see how accurate this kind of energy calculation may be in predicting mass transfer and/or escape from the host galaxy to the neighboring galaxy. In order to visualize better the positive energy particles from both galaxies, we plot those particles together, and we do the same tactic for the negative energy particles. Because the galaxies are so close together now due to dynamical friction we can plot both of them on the same plot. Doing so at both 6.14 Gyr and 7.1 Gyr yields us

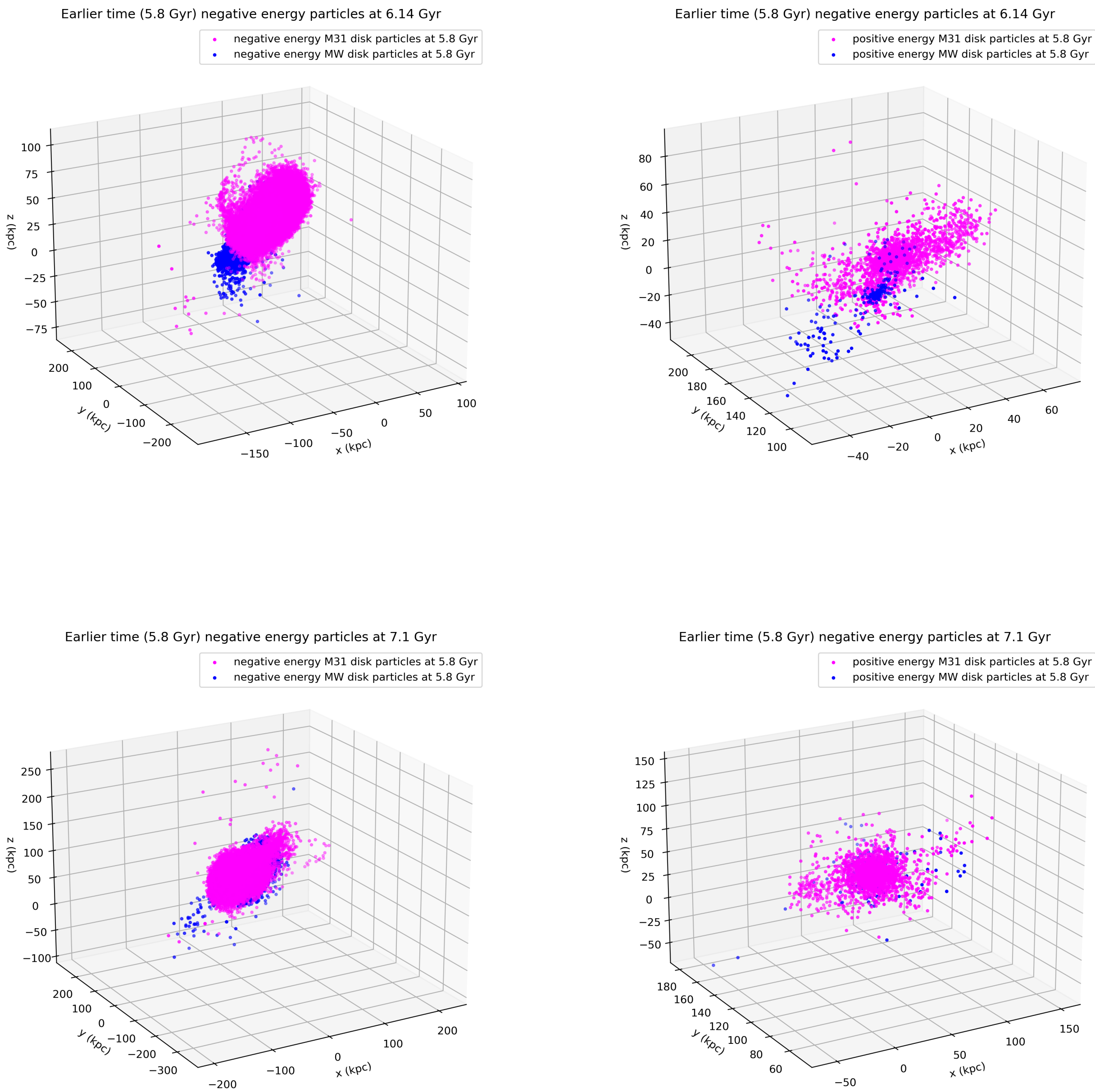


Figure 7: Plot showcasing the particle tracking at later times, to see how accurate the energy calculation is at predicting whether mass transfer or escape from a system is. The first row contains the current locations at 6.14 Gyr of positive and negative energy disk particles from both galaxies calculated at 5.8 Gyr. The second row contains these same particles, now at 7.1 Gyr. The first row demonstrates the last maximum separation distance between MW and M31 before they finally merge together. At 7.1 Gyr the two galaxies have completely merged together. These plots do show that negative energy particles are more tightly packed together than positive energy particles, which is expected.

This plot demonstrates that dynamical friction greatly impacts the energies of these particles, and even particles with earlier positive energies do not inevitably escape either system.

5. DISCUSSION

My original prediction of there being a relatively small amount of disk matter mass transfer on the scale of the galaxy mass was accurate, because on the first close encounter there was no mass transfer at all, and on the second close encounter each galaxy's disk had between $2-4\%$ of the total disk mass gaining enough energy to escape, which is itself only about 1% of the total galaxy's mass. However, this amount of mass with positive total energy is on the order of $10^9\ M_\odot$, which is very large on the scale of a star's mass, as my hypothesis predicted. Also, both of these galaxies lose about the same amount of mass, and if this transferred mass ends up in the disk of the other galaxy, the net mass transfer could be even smaller. This could still change the galaxy composition by quite a bit, but by this time there is only one more close encounter before the galaxies merge anyway, which significantly changes the galaxy anyway. This analysis has demonstrated that the amount of mass that gains enough energy to become positive (i.e. unbound to the system) is non-negligible. This mass can therefore change the distribution of matter within a galaxy, and cause effects such as quenching/stellar formation, and AGN feedback, which as indicated by Ji et al. (2014) can effect the structure of the internal components of the galaxy. Further analysis can pinpoint where these particles go before MW and M31 merge together. Good next steps to take are to repeat these Jacobi radii and energy calculations for dark matter and bulge particles to get a full picture of the mass transfer, and more closely track the positive energy particles in finer snap number increments. In fact, a movie of the evolution of these tagged particles would likely be very useful, because we can track them in real time in different spatial ranges.

Of course, this analysis made many assumptions about the potential energies of the particles. In order to reduce the computational time from calculating each contribution of gravitational potential from every particle, we assumed that the potentials were accurately described by the Hernquist potential, and Miamoto-Nagai potential. However, because these galaxies get deformed, these potentials may likely not be true at later times, such as when we did our calculation at 5.8 Gyr. Also, when these galaxies get close together the dark matter halos, which are much larger in scale than the disk or bulge, will completely mix together. This can significantly increase the amount of dark matter binding the disk or bulge particles to the galaxy, meaning that our represented total energies may not truly be positive because of the influence from the neighboring galaxy's dark matter. Lastly, dynamical friction also decreases the effective energy of any given particle in a galaxy, which we excluded from our energy calculation. This demonstrates that there are factors possibly reducing the energy of a given particle, and thus reducing the true amount of mass transfer, so our values in Table 1 are likely overestimates of the mass transfer, which can further be confirmed by Figure 7, showing that the disk particles don't actually escape the system very much.

6. CONCLUSION

Theoretical calculations show that MW and M31 will undergo several close encounters, and eventually merge together, allowing the opportunity for potential mass transfer between the two galaxies in the process. This potential mass transfer can influence the structure of each respective galaxy, and influence the rate of star formation and spiral-like structures of each galaxy, influencing each galaxy's respective evolution before their final merger. We have attempted to quantify this mass transfer by tracking disk particles inside and outside each galaxy's Jacobi radius at certain times, as well as calculating particles with total energies above zero and below zero, symbolizing free particles and bound particles respectively. This quantification is important to gain estimates for what fractions of the disk will transfer away from one galaxy, and the tracking is important to see where these particles will move to, allowing us to assess the accuracy of our energy predictions. We have found that no mass transfer occurs until ~ 5.8 Gyr, and despite $\sim 3\%$ of each galaxy's disk having positive energy, dynamical friction and extra dark matter mass hinder the ability of the particles to escape and transfer elsewhere.

This hindrance is particularly noticeable in Figure 7, because even at maximum separation after our energy calculation, the positive energy particles are not much further away from either galaxy than the negative energy particles, which indicates that there likely aren't many particles that escape either system. However, there is some mixing between the two galaxies, since the positive energy particles are smeared together. This mixing could be very relevant for features such as star formation and AGN feedback. Once the two galaxies have merged together there is an even smaller difference between positive and negative energy particles, because everything is smeared together. This is what we predicted earlier on, that mass transfer would become meaningless at late times, especially considering that few particles have been able to escape the disks. This is likely due to larger dark matter halos for the combined remnant, and large amounts of dynamical friction slowing all particles down.

A good continuation is to construct a movie that plays out these tagged particles over frames to get a better picture of the mass transfer. This movie can be taken over the centers of the two galaxies to see if there is transferred mass between the two that ends up the center of the other, which could influence AGN re-ignition and thus feedback. Additionally, incorporating dynamical friction into the energy calculation could place better constraints on particles undergoing mass transfer, as well as using more accurate dark matter masses once the galaxies get closer together, because those likely create deeper potential wells for the particles to break from. These closer analyses can better answer the question of when mass transfer happens, how much mass transfer happens, and where this transferred mass moves to.

7. ACKNOWLEDGEMENTS

This research made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2018, 2013)

This research made use of matplotlib, a Python library for publication quality graphics (Hunter 2007)

This research made use of NumPy (Harris et al. 2020)

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