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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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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 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.

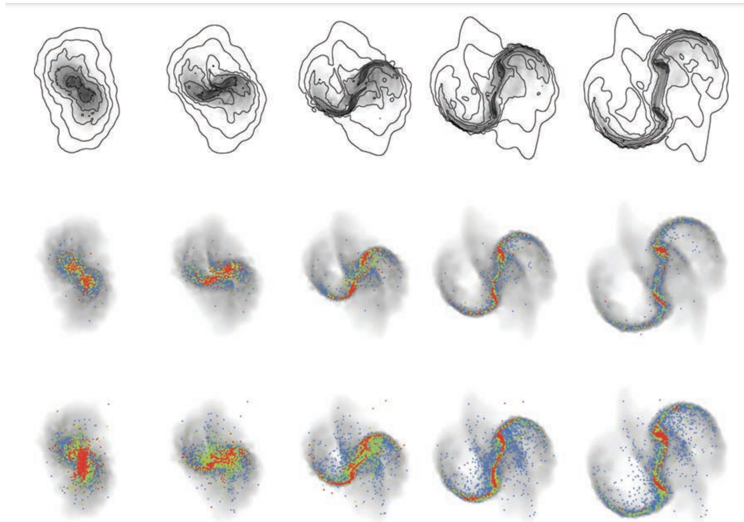


Figure 1: From Barnes (2004), detailing simulation of the Mice Galaxies (NGC 4676) and their dynamical evolution. This figure tracks star forming regions at different time units using a color coded tagging method. The top row involves contours of gas densities, the second and third rows detail star formation 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.

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. It could move towards the center of either galaxy through a tidal bridge, or outwards in a tidal tail. 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 through tidal tails that are formed when the galaxies perform a close flyby. This paper investigates the mass transfer of different galactic components, namely disk material, central bulge material, and dark matter halo material. Any and/or all three of these different materials may undergo mass transfer when the flyby happens, although the disk material is most prominently seen through the tidal tails and bridges formed during an encounter. In order to determine which material undergoes mass transfer, we will need to study the potential and kinetic energies of different regions as the galaxies undergo close encounters. If the kinetic energy of a particle exceeds the gravitational potential energy of the host galaxy, it will 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 to. 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. Additionally, mass transfer in the dark matter halos between the two galaxies can affect their Hernquist profiles, which provide an analytic distribution for the dark matter surrounding galaxies Hernquist (1990). This dark matter redistribution may greatly affect a galaxy's Hernquist profile, which in turn affects solutions for the potential energies and accelerations of galactic components.

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 gravitationally over time.

This type of simulation is called an N-body simulation, because it calculates the mutual gravitational forces between a large number (amount N) of particles 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 simulation 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 many potential energies and kinetic energies for many particles, so I can accurately assess mass transfer efficiently.

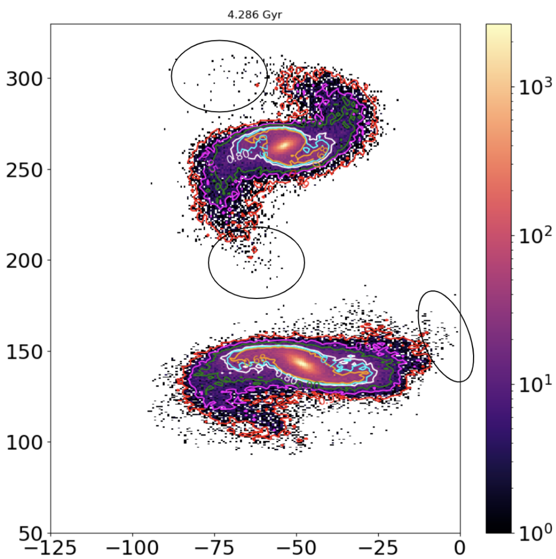


Figure 2: Snapshot of disk particles in MW (top) and M31 (bottom) galaxies through a 2D density contour histogram, recently completing a close encounter 4.286 Gyr from today, with circled regions of potential mass transfer in black ellipses. Instead of selecting every single particle to check if mass 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.

To get an idea of which particles are prone to mass transfer, I will first calculate if they 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. For a galaxy, the isothermal sphere model is valid up to ~ 50 kpc. In general,

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

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 (emperically 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. These particles can be tagged because the position of every particle is the same in every snapshot, so their index location can easily be recorded for future reference.

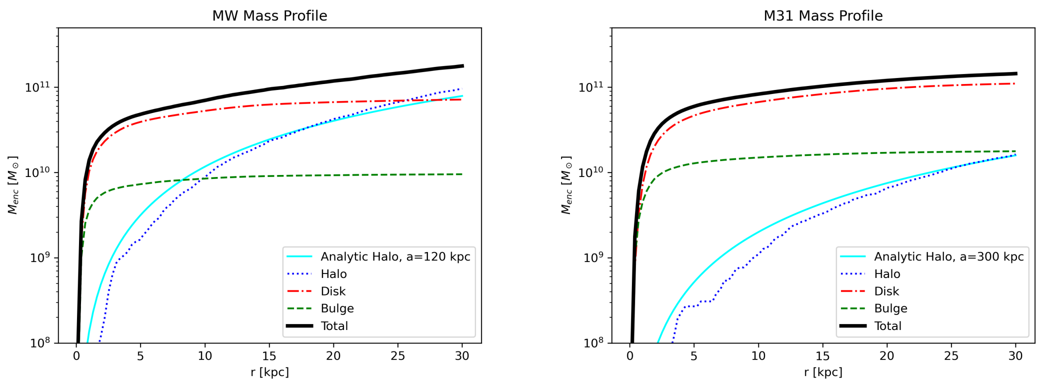
Plots will be essential to see where the mass transfer takes place. While the code will help determine which particles undergo mass transfer, plots will allow us to see where a particle undergoing mass transfer will eventually end up, whether it be in the spiral arm of the companion galaxy, the center 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 very important in Galaxy evolution. Additionally, performing the mass transfer analysis on the dark matter components of each galaxy will show how well Hernquist profiles hold up over time, which tells us how well our theoretical models reflect dynamically changing galaxies.

I believe that 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. I believe 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. Additionally 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.

However, there may be a very large amount of dark matter transfer between the two galaxies. Because the dark matter halos are very large compared to the disks and bulges, when the two galaxies perform a close flyby the dark matter halos of the two galaxies will mix together. This mixing will surely cause some dark matter particles to become bounded to the partner galaxy and vice versa. This interaction is not very easy to model with a Jacobi radius calculation because there is no longer a distinct satellite and host mass, since both are smeared together. This means we will likely just have to run the energy calculation described above for all dark matter particles, regardless of whether they are within the calculated Jacobi radius or not.

4. RESULTS

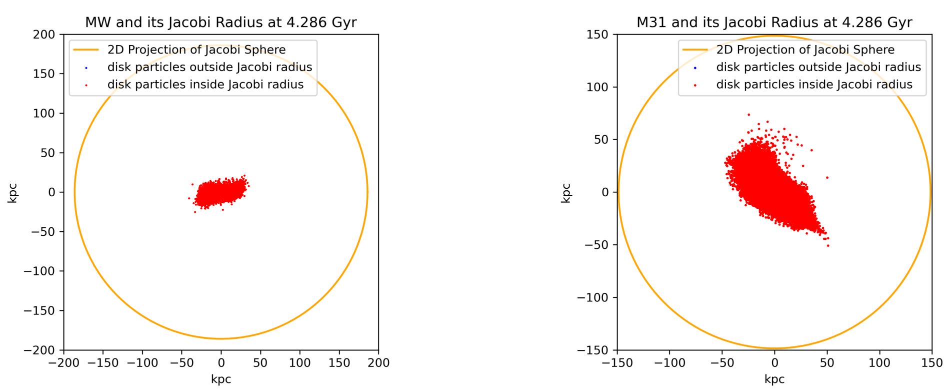
First, we need to see how well the analytic Hernquist mass profile holds up when the galaxies become deformed after a close encounter.



(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.

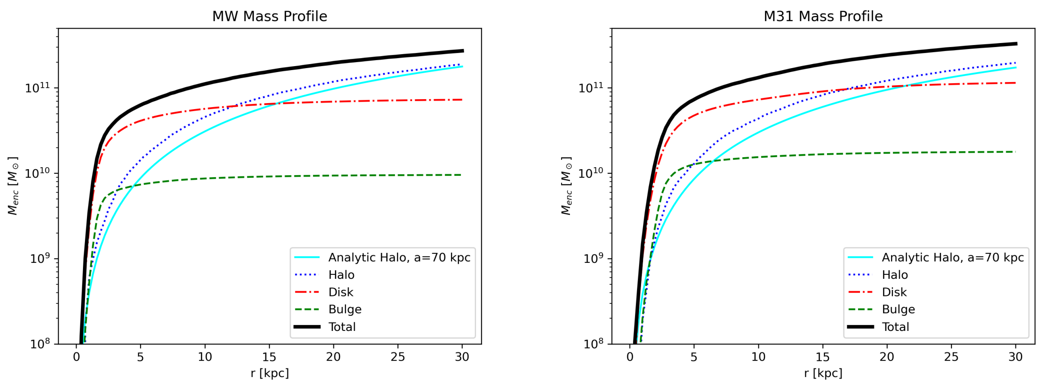
Because these fits are not too inaccurate, we can still use the Hernquist profile for this first close encounter. This allows us to come up our Jacobi radius for each galaxy by means of equation 1. Doing so, we get that $R_{j,MW} = 185.95$ kpc, and $R_{j,M31} = 148.55$ kpc. We can project these Jacobi radii onto plots of the galaxies to see if any particles lie outside of the Jacobi radius. Since there are no particles outside of the Jacobi radius, we can say that there are likely



(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.

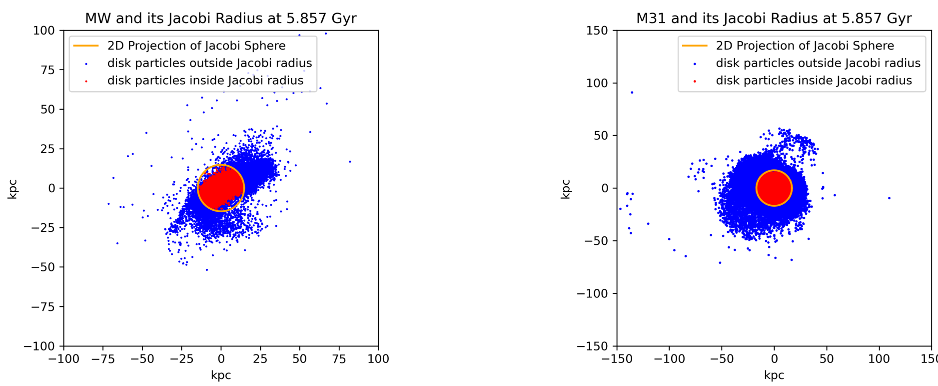
no disk particles that undergo mass transfer during the first close encounter. We can apply the same analysis to the next close encounter, at 5.857 Gyr.



(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.

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 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 blue 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.

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	0.174	0.0759	0.03698
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} $M_\odot$.

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.

Seeing as this amount of mass is non-negligible, it can change the distribution of matter within a galaxy, and cause effects such as quenching/stellar formation, and AGN feedback. 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. Also, with these tagged particles, we can track them to future times and see where they will end up in the future, whether it be in the partner galaxy, or outside of the system all-together.

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