Draft version May 7, 2020
Typeset using LaTeX default style in AASTeX63

Final Fate of Sun-like Stars: A Galactic View

Joseph Hickey

(Received May 6, 2020)

ABSTRACT

This paper analyzes the results of the simulation done by van der Marel et al. (2012a) focusing on bulk particle behavior before and after the merger. Mixing within a galaxy can change the observed characteristics after a merger which can lead to outliers in any attempt to categorize galaxies. We explore the migration of disk particles specifically in M31, the Andromeda Galaxy, and any patterns which may develop in the migration as the merger commences. Patterns of migration can give hints into what a galaxy may have looked like before a merger and give clues to the characteristics of the progenitor galaxies. We find that at the end of the simulation, disk stars have been greatly perturbed and become well mixed with a much more spherical distribution than in their progenitor. This finding shows a pattern of radius inversion which may help explain irregularities in the populations of stars within an elliptical galaxy.

Keywords: N-body Simulation, Major Merger, Proper Motion, Quenching, Gravitationally Bound

1. INTRODUCTION

In the MW-M31 merger, many stars will undergo large changes in their orbital characteristics and likely never return to the environment that birthed them. One approach to modeling this merger is to run an N-body simulation, a simulation in which galaxies are broken down into uniform "particles" with a mass determined by the spatial volume represented and the local density as calculated from a density profile of the galaxy. In the N-body results of van der Marel et al. (2012a), it is possible to tag galaxy particles in M31 which have characteristics similar to our local environment and follow them through the merger to discover what shared fate we may have. By following these particles, we can generate a statistical array of futures including ejection from the system, capture by a satellite, and changes in orbital radius and eccentricity.

The next major change to our local environment is the MW-M31 merger and so all characteristics of this major merger, a merger in which the participants are severely disrupted by the process because their masses are of the same order of magnitude, are relevant to our understanding of not only the future of our galaxy but of other galaxies that are currently going through or settling from a similar merger. The presence of such a large array of elliptical galaxies is best explained by the merging of galaxies like ours. And so, by studying the dynamics of such a system, it could be possible to recover useful stellar population statistics and a kinematic history in evolved systems rather than assuming a population formed solely in the modern host.

It is known that M31 has a proper motion, the motion as observed from an arbitrary fixed point having had all observer motion subtracted out, that will force an orbital path which intersects with that of the Milky Way (van der Marel et al. 2012b) and will eventually undergo several tidal interactions before settling into a new merger product. Because M31 is near enough that individual stars can be resolved, it is possible to model the galaxy with a reasonably accurate N-body model to extract specific rather than general information from a simulation. By simulating the future merger, likely characteristics of the merger product can be determined such as the mass profile, the rotation curve, and the stellar density. Other galaxies in the local group such as M32, the SMC, and the LMC are often left out of simulations of this merger as their masses individually are less than even M33 and their current trajectories send them away from the merger zone (Kallivayalil et al. 2006; van der Marel et al. 2012a).

It is not well understood how stellar populations evolve spatially as their host undergoes a merger, whether they are ejected or captured by the partner galaxy or pushed around within. Studying the fate of stars inhabiting the region close to the solar radius sheds light on how far into the host the effects of the merger are felt. Major mergers represent the best scenario for studying the migration of mass in a merging system. Further, the night sky as seen from Earth will change not only due to M31 growing larger on the sky, but also due to the Earth's changing location in the merger system. It is possible our solar system will be ejected and the night sky may eventually be a view of the aftermath of the provided figure.

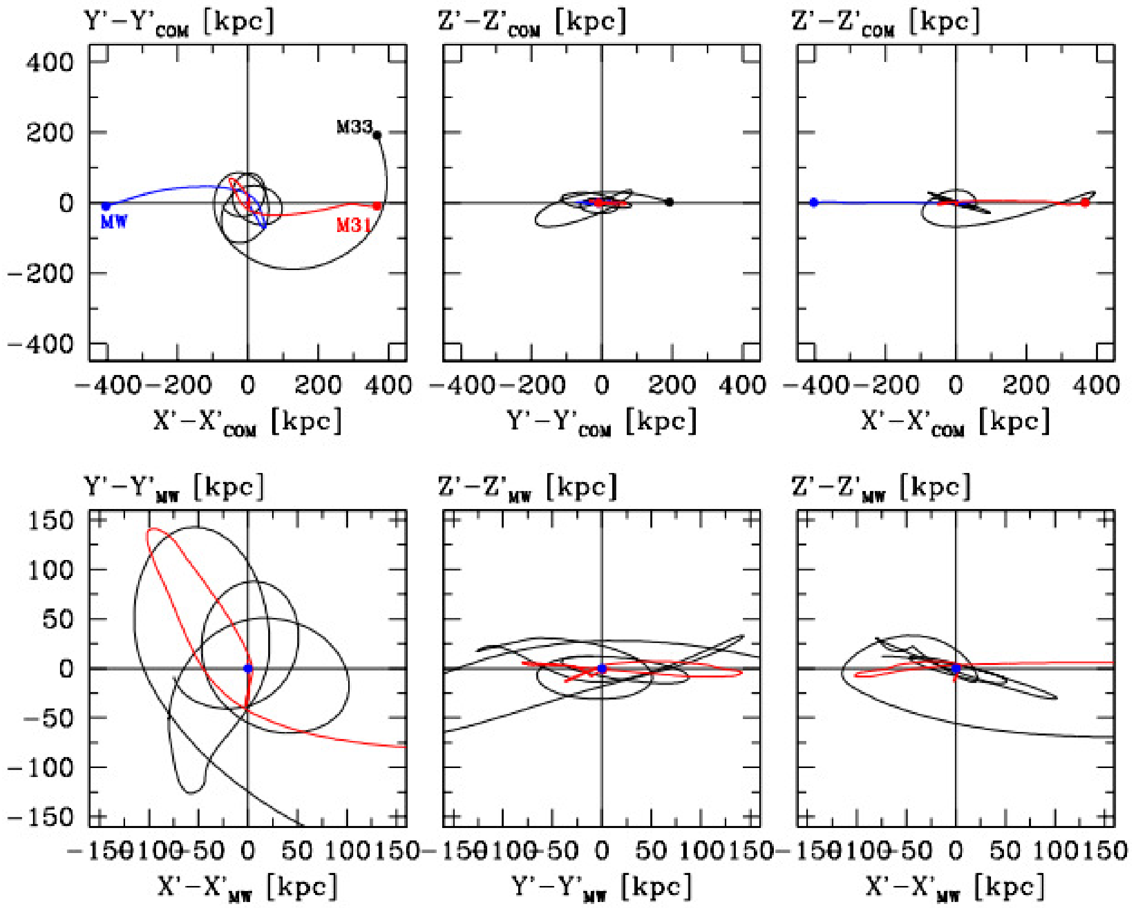

Figure 1. Orbital paths of the Milky Way-M31-M33 system. The top row shows a large area centered on the center of mass of the Local Group, the bottom row is more zoomed in and uses the Milky Way as it's fixed center. The bottom row is a good stand in for how the night sky may look post-merger with M33 slowly spiralling inwards. Figure courtesy of van der Marel et al. (2012a)

2. THIS PROJECT

In this paper, we study the spatial evolution of stars in the progenitor galaxies as they merge. By using uniformly formatted 6-dimensional simulation data, individual particles can be sorted based on their distance and velocity relative to the center of mass of the host galaxy. As the simulation moves forward, these same particles will migrate around the system being perturbed by the merging of galaxies.

Specifically, we seek to answer the question of the final fate of the sun by picking out particles that match the kinematics of the sun and determining their final position and velocity with respect to the merger product as well as whether they are bound to the central system or captured by the orbiting satellite galaxy, M33. Graphically determining the relationship between properties of these particles before and after the simulation will

The fate of sun-like stars or any population of stars is an important result in galaxy evolution because, while gas is collisional and stars are not, their movements can still trace star formation. Since gas and dust are most abundant in the disk and toward the core of a galaxy, the behavior of particles near the solar radius of 8 kpc Malkin (2012) can shed light on how far into the interior of a galaxy gas clouds are disturbed and how they are distributed throughout the merger product.

```
mass in 1e10,  x, y, z, in kpc and vx, vy, vz in km/s
#type, m, x, y, z, vx, vy, vz
      1.00000   0.00384176     -28.0645      318.650     -662.661      36.7228     -157.391      23.5707
      1.00000   0.00384176     -493.565      684.068     -210.896      69.7691      30.1228      219.573
      1.00000   0.00384176     -471.257      630.925     -404.772      196.370     -91.7054     -7.68402
      1.00000   0.00384176     -517.846      815.795     -328.268      33.9139     -105.194      153.860
      1.00000   0.00384176     -367.662      551.696     -273.555     -71.0189     -136.484     -34.1668
      1.00000   0.00384176     -401.453      641.288     -265.216     -179.293     -10.1290     -169.608
      1.00000   0.00384176     -407.074      586.621     -323.056     -24.0792      142.837      202.571
      1.00000   0.00384176      537.686      596.228     -75.3892      46.5531     -121.482      11.4887
      1.00000   0.00384176      839.382      645.492     -1224.54      69.9949     -69.7555      52.9126
      1.00000   0.00384176     -361.794      620.384     -305.811     -61.6120     -61.5447     -142.379
      1.00000   0.00384176     -326.644      637.346     -273.262      185.309     -109.654      185.500
      1.00000   0.00384176     -505.736      764.495     -426.017      153.165     -175.261      165.832
      1.00000   0.00384176     -497.853      657.683     -1232.53      17.3922     -101.764      73.5306
      1.00000   0.00384176     -425.217      583.871     -240.592      85.4194     -258.551      177.729
      1.00000   0.00384176     -367.299      602.990     -290.318      173.340     -64.1790     -258.327
      1.00000   0.00384176     -358.683      616.805     -238.891      32.2302     -128.692      189.775
      1.00000   0.00384176     -386.954      605.076     -274.183     -26.9815      148.519      16.6632
      1.00000   0.00384176     -372.847      605.160     -289.054      26.7788     -315.265      75.2799
      1.00000   0.00384176     -521.995      791.238     -420.582      95.4747     -121.259     -86.5574
      1.00000   0.00384176      745.927     -1214.12      336.073      71.7715     -68.3937      50.4791
      1.00000   0.00384176     -364.598      635.844     -392.411      75.9425      167.956      48.0086
      1.00000   0.00384176     -374.746      565.649     -256.129     -44.9161      77.8865      118.685
      1.00000   0.00384176     -452.391      118.595     -171.833      92.4813     -21.3571      49.2873
```

Figure 2. Structure of the simulation data with each line representing a distinct particle. Left to right the columns represent the particle type, mass, position coordinates, and velocity coordinates. The ordering of these particles does not change between time steps.

3. METHODOLOGY

As previously stated, the simulations used in this paper and accompanying code come from van der Marel et al. (2012a) and represent the Milky Way-M31-M33 system as particles of constant mass distributed into a central bulge, rotating disk, and spheroidal dark matter halo for each galaxy with M33 having no central bulge worth differentiating from its disk. These simulations begin with an initial distribution of particles that mirror the observed properties of the simulated galaxies and return a new distribution at each time step with files available at multiple levels of spatial resolution as needed. The simulation operates on individual particles by calculating the acceleration caused by the host and nearby galaxies and applying the acceleration to the velocity and velocity to the position in a symplectic integration function.

To gather useful information from these simulation files, we take advantage of their uniformity of format. Each set of files is focused on a specific galaxy which reduces the file read times and calculation load. Additionally, particles are ordered in the files meaning; following the third particle in the initial file only requires pulling information from the third particle in every file. Since the data can be easily read into an array, the simplest way to follow a population of stars is to create a mask for the array which returns only that population and apply it to every other file of the host galaxy.

The process of creating the mask is done using a Python class file which is viewable in the associated Github repository. By taking in some initial information about the host galaxy and what population to isolate, the class checks the galaxy for particles within 10 percent of the specified radius which are composed of stellar components bound to the host galaxy. A bound particle has a total velocity below the escape velocity of the system defined by $v_{esc}^2 = 2U$ where U is the total gravitational potential of the particle. The gravitational potential is defined by two equations linked to the structure of the host. The Miyamoto-Nagai Potential (Miyamoto & Nagai 1975) describes a disk structure while the Hernquist Potential (Hernquist 1990) works to describe spherical structures. The variables a and b are scale parameters used to match the behavior of the structure.

$$\frac{-GM}{[R^2 + (a + (z^2 + b^2)^{\frac{1}{2}})^2]^{\frac{1}{2}}}$$

$$\frac{-GM}{(r^2 + a^2)^{\frac{1}{2}}}$$

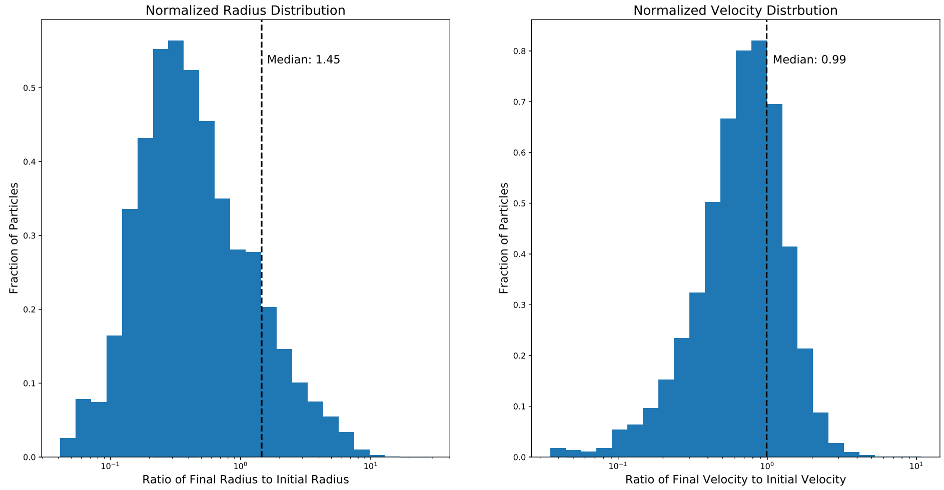

Figure 3. Final distribution of particles with respect to their initial positions and velocities. Normalized and displayed on a logarithmic scale

To best impart the results of this paper, 2-D histograms are generated at the initial and final times with the particles of interest highlighted. The initial and final histograms are provided in this paper as well as a normalized histogram representing the final environments of the particles. These figures show both the final spatial distribution of the population as well as the physical characteristics such as the percentage of ejected or captured particles. This distribution is especially important in understanding how far the tidal influence of one galaxy will reach inside of another.

We believe a large fraction of sun-like stars will remain bound to the merger product while a smaller fraction will be captured or herded by M33 and a negligible amount will be ejected from the system. Because sun-like stars are in the middle of a galaxy's disk, I believe the merger will change their orbital kinematics such that they are greatly perturbed but not ejected. M33 is a small galaxy but its gravitational cross-section is large enough to greatly influence particles that draw too near and can lead to highly perturbed and ejected particles being dragged along in its wake as if being herded. Particles with enough velocity to escape and also on trajectories which put them out of M33's reach can be ejected entirely from the system but fulfilling both of these requirements is less likely than failing either. These final states can be roughly determined by taking a ratio of initial and final kinematic properties.

4. RESULTS

The histograms shown in 3 give a statistical representation of where particles end in compared to their initial kinematics with the histogram on the left showing a ratio of radii and the right a ratio of total velocities. For any given initial radius, the median of the velocity distribution remains close to one whereas the median of the radius distribution is inversely proportional to the initial radius with a scale of approximately 12 kpc. The ratio of radii shows an average migration outward for the particular subset of particles this paper focuses on.

The inclusion of 4 and 5 is meant only to aid the reader in visualizing the migration of particles and any non-symmetric structure that could be concluded from them may not be representative of a true physical system but rather only of the selection criteria and simulation data. However, the final distribution of particles as a decreasing function of radius remains an interesting result which appears for every sub-population. The increased central density of the galaxy is the global result of an inward migration of particles with initial positions beyond the 12 kpc scale.

5. DISCUSSION

As the particles displaying sun-like kinematics move through the simulation, the bulk behavior of these particles is a diaspora with the vast majority having a large change in radius. The particles become spread across the origin galaxy with the majority moving away from the core. This behavior agrees with the hypothesis that stars at or around 8 kpc, while deeply bound, can possibly escape through a major merger. For escapes to begin occurring in the sample,

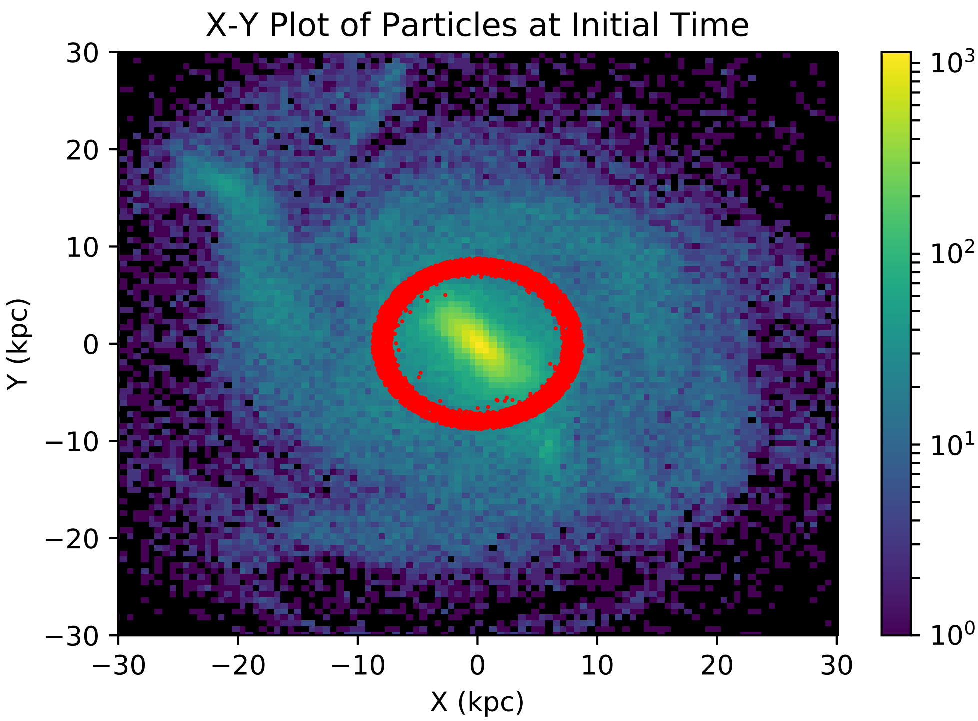

Figure 4. Initial positions of particles matching solar kinematics(i.e. at the solar distance and well bound to the galaxy)

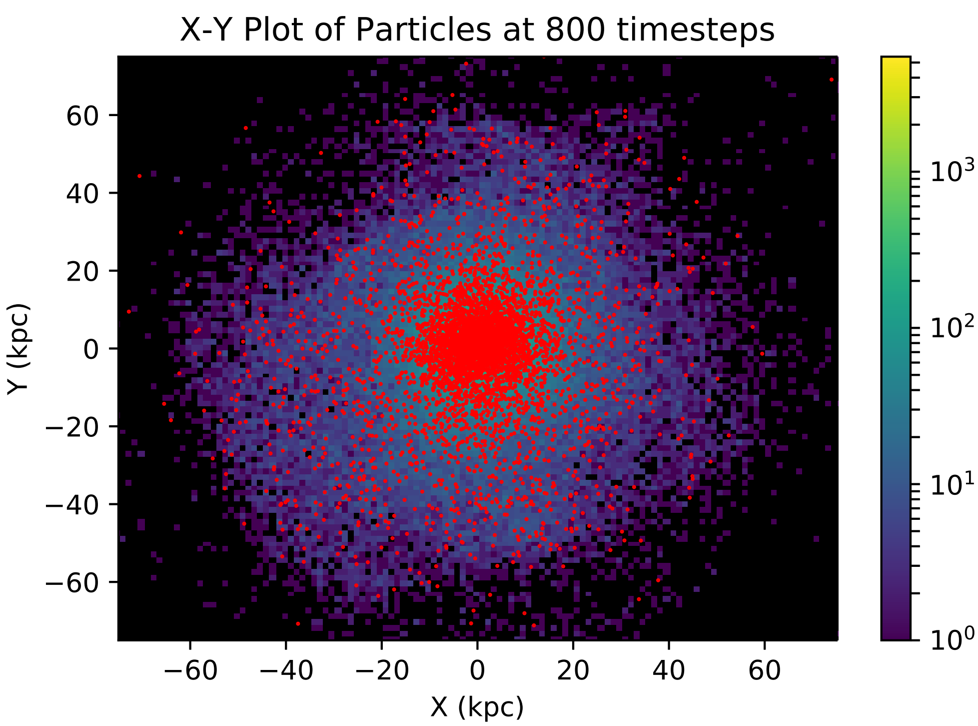

Figure 5. Final positions of particles matching solar kinematics, red markers set to have a displayed alpha value of 0.25 so as not to obscure underlying galactic structure

a 50 percent increase in halo radius is necessary. This outward migration of stars closer to the core of a galaxy and dense star forming regions may provide a mechanism for quenching, the rapid processing of gas and dust into stars leading to a gas-poor elliptical galaxy, after a merger. However, the results do not support the existence of a shepherd role for M33 in the time frame of the simulation with the population being observed. The redistribution of particles in a spherical central density profile lend credence to the theory of how many elliptical galaxies are formed and the median radius inversion supports thought experiments that do not globally assume stars in elliptical galaxies formed in regions similar to the ones they currently inhabit.

6. CONCLUSIONS

The results of an N-body simulation give insight into how the internals of the system responds to a turbulent event. Examining the results with a focus on individual kinematics provides a primordial model for the creation of some elliptical galaxies through merger events. The characteristics of these ellipticals may not reflect the truth of their structure if they are derived from a well-mixed population of stars far removed from their home environments. The spatial migration of stellar mass can give rise to false and inaccurate models that rely upon observations of the galaxy and not the history of the galaxy.

For any given initial radius, the median of the velocity ratio distribution remains close to one whereas the median of the radius ratio distribution is inversely proportional to the initial radius with a scale of approximately 12 kpc. The ratio of radii shows an average migration outward for the particular subset of particles this paper focuses on which agrees with the initial hypothesis of possible ejection and capture by the other galaxies.

Observations of galaxies that have evidence of recently undergoing a major tidal interaction are a good start to follow up on these findings. Applying the code to a higher resolution dataset may also provide further insight into the redistribution of particles. Comparisons with a hydrodynamical simulation may also be warranted as the collisional gas will form stars in dense regions which may appear due to the migration of gas clouds.

7. ACKNOWLEDGEMENTS

The author would like to thank Chirag Rathi, Jimmy Lilly, & Dr. Gurtina Besla for their help in troubleshooting code and offering much-needed support during the writing of this paper. The simulation data used was made available by Dr. Besla and the code that was written relies greatly upon the Python packages Astropy, Matplotlib, Numpy, and IPython which are created by the Astropy Collaboration, John D. Hunter, van der Walt et al., and Fernando Perez & Brian Granger respectively.

REFERENCES

Hernquist, L. 1990, ApJ, 356, 359, doi: 10.1086/168845

Kallivayalil, N., van der Marel, R. P., Alcock, C., et al. 2006, ApJ, 638, 772, doi: 10.1086/498972

Malkin, Z. 2012, arXiv e-prints, arXiv:1202.6128. https://arxiv.org/abs/1202.6128

Miyamoto, M., & Nagai, R. 1975, PASJ, 27, 533

van der Marel, R. P., Besla, G., Cox, T. J., Sohn, S. T., & Anderson, J. 2012a, ApJ, 753, 9, doi: 10.1088/0004-637X/753/1/9

van der Marel, R. P., Fardal, M., Besla, G., et al. 2012b, ApJ, 753, 8, doi: 10.1088/0004-637X/753/1/8