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Tidal Evolution of M33's Dark Matter Halo—Mass loss of Dark Matter and changes to internal dark matter profile

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1. INTRODUCTION

The spiral galaxy M33, which is located in the constellation Triangulum, is the third largest member of our Local Group of galaxies. Also, M33 and M31 are the closest massive galaxies to the Milky Way, and all of these galaxies(MW,M31,M33) are spiral galaxy. Thus, there are the large amounts of dark matter which were expected to dominate these galaxies, particularly in the outskirts of galaxies' disks, according to optical measurement of the rotation of spiral galaxies (Blok 2010). As indicated by the project entitled "orbital analysis an velocity measurements" which were presented in van der Marel 2012, M31 and the MW will merge at t = 5.86 Gyr (Marel et al. 2012). During the process of merging, the orbit of M31MW and the orbit of M31M33 will reduce with time, so these galaxies become closer to each other.Thus, the shorter orbits of M31MW and M31M33 will result in stronger gravitational interactions between the MW, M31 and M33. In other words, stronger gravitational interactions between galaxies will render the impact of tidal fields between galaxies stronger, which will consequently change the morphology and kinematics of the inner and outer structures of all galaxies. In addition, the bound mass of a smaller satellite galaxy (like M33) will decrease over time, due to the tidal field of a massive galaxy(Boylan-Kolchin et al. 2011). Given that, this project is to investigate the tidal evolution of M33's dark matter halo, emphasizing on two points: 1.mass loss of dark matter, 2.change of internal dark matter profile.

'Dark matter' has long been a much-contested topic in the area of astronomical sciences. The majority of mass in the universe is in the form of dark matter. According to the cold dark matter theory, I know that dark matter could only interact with baryons via gravity. As dark matter predominates the mass of galaxies, dark matter will control the gravitational filed of galaxies or the depth of potential well. If the total mass of dark matter decreases in the galaxy, the galaxy will not retain part of its baryons nor accrete more gas. In other words, the change of the total dark matter mass of the galaxy controls the evolution of the galaxy. Therefore, studying the mass loss of the dark matter halo will help us to understand the evolution of satellite galaxies (like M33) which are affected by strong tides.

After t = 10 Gyr, the MW and M31 will formed a merged remnant, and M33 will lose 23.5percent of its stars which, in other words, will be stripped off M33 (see the first graph on the right of figure1) (Marel et al. 2012). This result indicates that the mass of M33 will lose due to the tidal evolution of MW and M31 merger process. Elsewhere, in Boylan Kolchin et al(2012)'s research, astronomers could potentially detect the signal of dark matter annihilation, if the internal dark matter density becomes high enough(Boylan-Kolchin et al. 2011). If the internal dark matter density of a satellite decreases, the expected annihilation signal will be lower. So the change of internal dark matter density profile of a satellite galaxy(like M33) is very important to indicate whether astronomers can detect the signal of dark matter annihilation in order to do the future dark matter detection experiments. Then, the questions will be focusing on M33.

Boylan Kolchin et al.(2012) is indeed inspirational for this project. Is the central dark matter density profile of M33 sufficiently high enough to produce a dark matter annihilation signal? And will that density profile change in the future? Everything related to dark matter is still an intriguing question. However in this project, the mainly focus is to study that how does the tidal evolution of M33M31MW system impact the M33 dark matter halo through the mass loss of M33 dark Matter and changes to M33 internal dark matter profile based on the limited evidence I have.

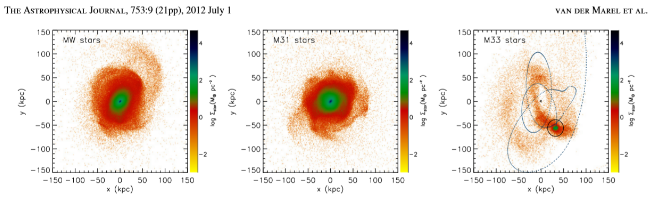

Figure 1. :illustrates the mass distribution of the MW, M31 and M33 in the final snapshot of the simulation, when the MW and M31 have coalesced. The final snapshot of the M33 simulation is on the very right. In the last simulation Snapshot of M33, 23.5 percent stars of M33 that will be stripped from M33. Much mass per particle is outside the Jacobi radius of M33 Marel et al. (2012).

2. THIS PROJECT

In this paper, I will study the change of M33's dark matter halo profile and internal dark matter profile during the period of M31 and M33's orbit evolution. I will simulate the outer/internal dark matter mass profile and internal density disk/dark matter halo profile of M33 based on the simulation data of the merger of M31 and MW. The specific question of this project is to prove that M33 will lose dark matter mass due to the tidal influence from M31 and M33, and to show the change of mass loss rate of M33 as function of time. Next, proving whether the mass profiles of M33 will decay in the future is also a question that this project need to solve. The other question is to solve what happened to internal dark matter density profile of M33, whether it will change. Elsewhere, the dark matter density profile of M33 which I calculated is mean density profile, it is necessary to check the result through Hernquist mean density profile.

As detailed in the introduction, the dark matter will control the gravitational field or the depth of potential well of galaxies. Therefore, the change of M33 dark matter total mass matters whether M33 will lose its baryons or accrete less gas in the future. Also, it is important to know the change of M33 dark matter halo mass profile to predict the evolution of M33. In addition, if the internal dark matter density profile of M33 will be high enough to produce a dark matter annihilation signal, which matters whether human can do dark matter detection experiments of M33 in future.

3. METHODOLOGY

This project will simulate Jacobi Radius of M33 based on the tidal effect acting on M33 which is from M31 or the merger of MWM31. The Jacobi Radius simulation meant the maximum radius that a satellite galaxy(like M33) can extend due to the expected tidal radius. In order to do the simulation of Jacobi Radius, the mass of satellite galaxy(like M33) and host galaxy has to be calculated. Therefore, I will make a program to compute Jacobi Radius as function of time. Meanwhile, this project will also use the simulation of enclosed mass profile to simulate the M33 dark matter mass profile. The simulation meant the distribution of galaxy (like M33) mass as function of radius(in kpc), so it is necessary to make a program to plot M33 mass profiles of different periods in order to check the mass loss of M33. In addition, according to the M33 dark matter mass profile, the M33 dark matter mean density profile can be calculated. Thus, the project will use the simulation of Hernquist mean density profile based on Hernquist Profile.The Hernquist Profile considered the dynamical and tidal effect from the mergers of galaxies which are acting on the satellite galaxies, so it is more accuracy to check whether the M33 mean density profile is correct through Hernquist profile.

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

Figure 2. Jacobi radius based on tidal radius of host mass

In order to simulate M33 Jacobi Radius, the host galaxy mass and satellite galaxy mass has to be specifically defined (as shown on Figure 2). It is widely believed that only mass of M31 has to count into the host mass before the merger of M31 and MW, because M31 is the only massive galaxy closest to M33 which result in gravitational interaction. As mentioned in van der Marel 2012 that M31 and the MW will merge after t = 5.86 Gyr (Marel et al. 2012), so both the mass of MW and M31 will be counted into the host mass in order to calculating M33 Jacobi Radius after the merger of MW and M31(I select t = 6,5 Gyr). Then, making a plot of "Jacobi Radius vs Time" is to check whether the Jacobi Radius decrease, according to the 800 snapshots files of M33,M31 and MW orbit simulation which Prof. Gurtina,Besla provided.If the Jacobi radius is decreasing as function of time, examining how much mass is inside the Jacobi radius as function of time can demonstrate the mass loss rate and cumulative mass loss fraction as function of average time more obviously. In addition, in 800 snapshot files, the mass of M33 recorded as mass per particle for each recorded coordination, which is simulated from the position of M33 orbit. Thus, I can create the dark matter halo mass profiles which are based on different files. After that, the internal(the range is the Jacobi Radius of Snapshot 800) dark matter mean density profile of M33 can be plotted. In order to making Hernquist mean density profile to check the result, I will use a program to find the best scale radius for the Hernquist profile.

$$\rho(r) = \frac{Ma}{2\pi r}\frac{1}{(r+a)^3} \qquad M(r) = \frac{M_{halo}r^2}{(a+r)^2}$$

Figure 3. Hernquist Mass ProfileHernquist (1990).

First of all, according to Jacobi Radius equation, I have to define two equations in the code. The first one is to count mass per particle, which is in the range between center of mass position of M33 and M31, as host mass from M33 reading files (adding MW mass and reading MW files after t = 6.5 Gyr). The second one is to count mass per particle, which is in Jacobi radius of M33, as satellite mass. Next, I have to initialize the Jacobi radius, because I do not know M33's Jacobi radius. I will regard the first satellite mass as the initial Jacobi mass, and use the first host mass to get initial Jacobi radius. After that, I will bring the initial Jacobi radius, as the index, to Jacobi mass equation, when it is reading the second snapshot. And I can see how much mass per particle still in the initial Jacobi radius, and get new Jacobi mass. Through new Jacobi mass and second host mass, I will get new Jacobi radius. Since I get new Jacobi radius, I can bring it to the third snapshot and repeat above steps, but write a "if condition" for adding the mass of MW when "t ¿= 6,5 Gyr". Until the end of the "for loop", the program will text Jacobi Mass(1e10$M_\odot$,Time(Gyr), and Jacobi Radius(kpc) out to new data file.Then, those data can be used in plotting. Elsewhere, writing a new program is to read the mass data from the snapshot files which I will select the files when the Jacobi Radius is in local minima. After reading those data, the mass profiles of M33 in different local minima of Jacobi radius can be plotted. In addition, through dividing the spherical volume, the M33 mean density mass profile can be plotted from the M33 mass profiles. At the end, plotting the Hernquist mean density profiles with each mean density profiles separately after calculating the best fitted scale radius of each M33 mean density profiles. After plotting the Jacobi Radius vs time plot, if the mass of M33 will lose, the Jacobi Radius will decreased. In order to get detail of mass loss, examining how much mass is inside the Jacobi radius as function of time from "Jacobi Radius vs Time", can demonstrate the mass loss or mass loss rate as function of average time more specifically. The M33 dark matter halo mass profiles plots(when Jacobi Radius are at local minima), in which M33 is near its Perihelion of M33 and M31 orbit , can directly prove whether the mass of M33 dark matter halo lose through checking the mass distribution of these plots on the same radius(kpc). In addition, it can infer whether the dark matter annihilation will be observed in the future through checking the change of these mean density profile plots.

The first hypothesis of this project support that total mass of M33 will become smaller, and the amount of M33 dark matter will decrease as function of time. The second hypothesis of this project is that the decay of the dark matter distribution of M33 is tenable, because the gravitational balance of M33 itself has broken due to the stronger tidal effect of M31 or the merger of M31 and MW. Thus, part of M33 dark matter mass will strip out of M33. And the internal dark matter mass profile will decrease, because the Jacobi Radius decreased that shorted the internal range of M33.

4. RESULT

This figure(figure4) is 'Jacobi Radius vs time', I have also plot the M31 and M33 orbit on the plot. In order to see what happened in each step, I made the radius of M31 and M33 ten times smaller. As indicated by Figure 4, Jacobi radius is larger at aphelion of the orbit of M31 and M33, and smaller at perihelion of the orbit of M31 and M33. And the totally trend of "Jacobi Radius vs time" is tending to decrease as function of time. Therefore, the Jacobi Radius of M33 decreased, since the orbit of M31 and M33 decreasing as function of time.

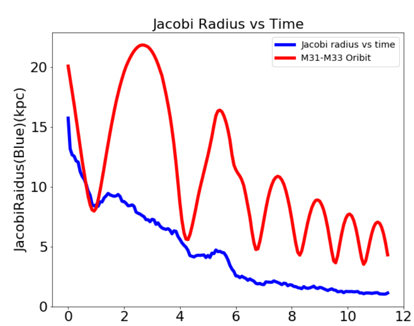

Figure 4. Jacobi radius vs Time, y axis is distance in kpc, x axis is time in Gyr. The blue line is Jacobi radius vs time, the red line is the diameter of M31 and M33 orbit vs time. the result I put ten times smaller M31 and M33 orbit is to show the relation between each time step more obviously.

As indicated in Figure 5(M33 Average time vs Mass loss Rate), when the mass loss rate is below zero, M33 will lose part of its mass. And when the mass loss rate is greater than zero, M33 will add mass to itself. The overall trend of mass loss rate as function of average time is tending to be negative which M33 will lose mass as function of time. Otherwise, there are several value of mass loss rate which is positive

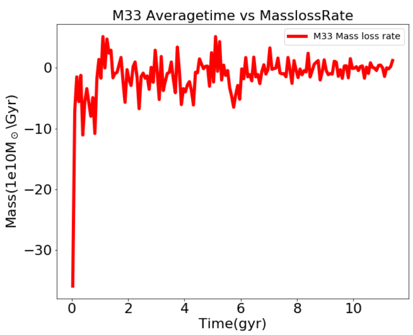

Figure 5. This graph is shown the relation between average time and Mass loss rate, y axis is mass loss rate in unit of 1e10M$_\odot$ per Gyr, x axis is time in Gyr.

In Figure 6, the "M33 Cumulative Mass Loss Fraction vs Time" graph directly demonstrated that the cumulative mass loss fraction of M33 will increase sharply around 0 to 6 Gyrs. And the cumulative mass loss fraction of M33 will stay around the peak ,which is 0.9, after the merger of M31 and MW(t = 6.5 Gyr). So as time goes by, M33 will lose its mass. The mass of M33 will lose for absolutely, it is necessary to check the M33 mass profiles to see more details of M33 dark matter halo.

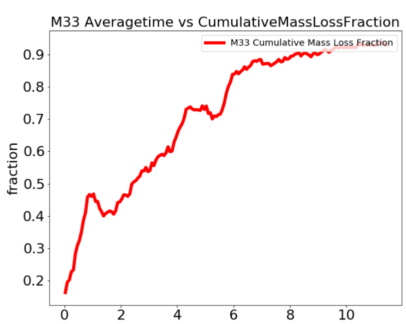

Figure 6. The graph is M33 Cumulative Mass Loss Fraction vs Time. The unit of y axis is dimensional less, because it is fraction between the change of Jacobi Mass and initial Jacobi Mass. The x axis is time in Gyr.

In Figure 7, the plots of M33 mass profiles,which I had taken from 1 initial snapshot file and 3 snapshot files which Jacobi Radius is at local minima,are M33 dark matter halo mass profile and M33 internal dark matter mass profile.The left plot, M33 dark matter halo mass profiles, shows that the trend of M33 dark matter mass profile is tending to decrease slightly as function of time. So, the M33 dark matter halo will lose its dark matter, and M33 dark matter mass profile will change.In addition, the range of M33 internal dark matter mass profiles is around 15 kpc based on the Jacobi Radius of the last snapshot file.The plot of M33 internal dark matter mass profiles, also keep the similarly trend as the plot of M33 dark matter halo mass profiles that M33 internal dark matter mass profile will decrease when the radius is greater than 4 kpc. For more details of M33 internal dark matter mass profile(r ¡ 4kpc), Hernquist mean density profiles will tell the answer.

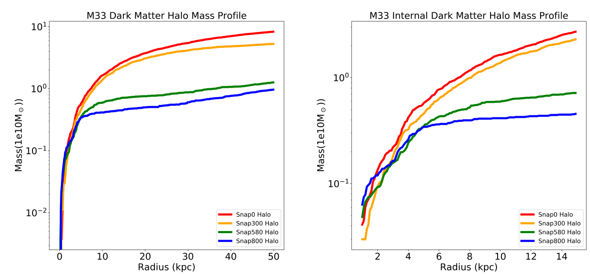

Figure 7. The graph is M33 dark matter halo mass profile. The unit of y axis is 1e10M$_\odot$, and x axis is radius in kpc. 1.red line is the M33 mass profile based on snapshot file 0, 2. orange line is the M33 mass profile based on snapshot file 300, 3. green line is the M33 mass profile based on snapshot file 580, and 4. blue line is the M33 mass profile based on snapshot file 800.

The comparison of Hernquist and M33 enclosed internal dark matter mean density is shown on Figure 8. As in dictated by the Hernquist mean density profiles on Figure 8, the distributions of M33 internal dark matter mean density profiles are tending to decrease from snapshot 0 to 800(0 to 10 Gyrs). And according to the relation between mass and mean density, the M33 internal dark matter mass profiles also will decrease when radius is smaller than 4 kpc. Elsewhere, the chance of the observation of dark matter annihilation in M33 center will decrease.

5. DISCUSSION

As indicated in the result of this paper, the part of M33 mass will lose in the future, due to the tidal effect which is from the Local Group (M31MWM33 sys-

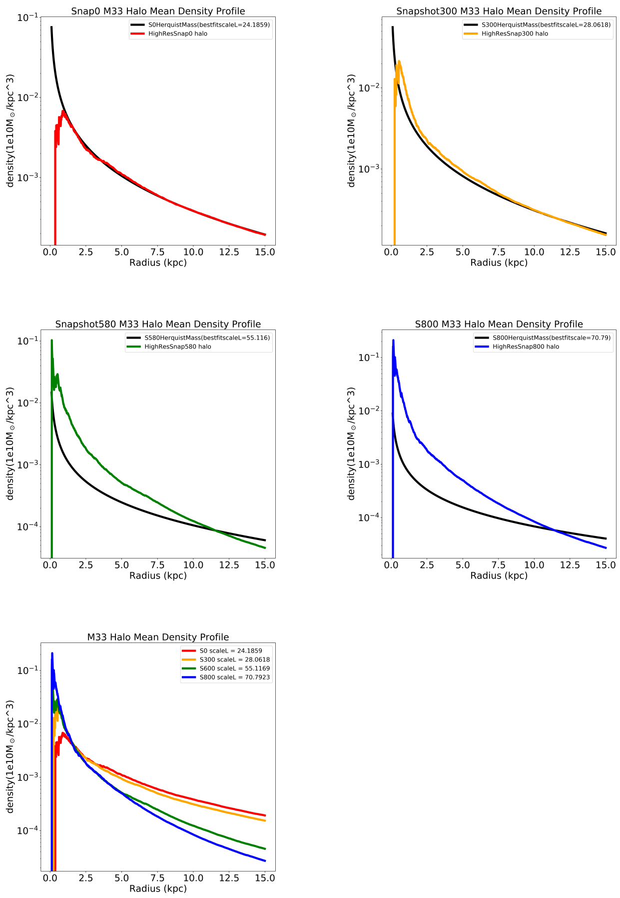

Figure 8. The graph is the comparison of M33 internal dark matter mean density profiles and Hernquist mean density profile. The unit of y axis is 1e10solar mass per cubed kpc. And x axis is radius in kpc. 1.red line is the the M33 internal dark matter mean density profile of snapshot file 0, 2. orange line is the M33 internal dark matter mean density profile on snapshot file 300, 3. green line is the M33 internal dark matter mean density profile of snapshot file 580, and 4. blue line is the M33 internal dark matter mean density profile of snapshot file 800. And all the black lines are the Hernquist mean density profile with best fitted scale length:1. 24.1859, 2. 28.0618, 3. 55.1169 and 4. 70.79

tem) acting on M33. The dark matter halo mass profile of M33 will change due to the orbit change of M31 and M33. As indicated by Figure 4, Jacobi radius of M31M33 orbit aphelion is larger than when M33 is at its perihelion. Therefore, the mass loss rate is higher when M33 is close to M31 or the merger of M31 and MW; and the mass loss rate is lower when M33 is far from M31 or the merger. In addition, the mass loss rate which is positive caused by the dark matter is passing through M33. The overall trend of M33 mass loss rate and dark matter halo profiles indicated that the gravitational well and depth of M33 will decrease in the future, especially after the merger of M31 and MW. It is not surprising to believed that M33 will accrete less gas and hold less baryons. M33 will lose in this "gravitational vs self balanced " battle to M31 and MW, most of M33's dark matter will strip out of. Otherwise, it is hard to detect dark matter annihilation in M33. As indicated by the M33 Hernquist mean density profiles on Figure 8, the dark matter mean density of M33 will keep decreasing in the future. As Boylan-Kolchin(2011) pointed that if the dark matter density of a galactic center is too low, astronomers could not observe any dark matter annihilation(Boylan-Kolchin et al. 2011). Therefore, there is no such a scientific value for searching on M33 in the future.

REFERENCES

Blok, W. J. G. D. 2010, Advances in Astronomy, 2010, 1–14, doi: 10.1155/2010/789293

Boylan-Kolchin, M., Bullock, J. S., & Kaplinghat, M. 2011, Monthly Notices of the Royal Astronomical Society: Letters, 415, doi: 10.1111/j.1745-3933.2011.01074.x

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

Marel, R. P. V. D., Besla, G., Cox, T. J., Sohn, S. T., & Anderson, J. 2012, ApJ, 753, 9, doi: 10.1088/0004-637x/753/1/9