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Evolution of the MW/M31 Super Massive Black hole throughout the Merger Sequence (prior to final coalescence)*

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ABSTRACT

Black holes remain the central point of discussion in the world of Physics and Astronomy. One of the key aspects of the discussions are their role in affecting galaxy evolution. Earlier thought have little to no influence on the dynamics of galaxy evolution, the astronomical society changed their believes once the famous M-σ relationship came up. Now, it is believed that this relation indeed gives the estimation of the mass of the super massive black holes of the galaxy. In this paper, we would be testing the validity of the M-σ relationship by first calculating the velocity dispersion profiles of MW and M31 and then using them to estimate the black hole mass before and after the merger. Testing this relation is important because if this relation could serve as one of the very few methods we have right now to directly calculate the mass of black holes.Our hypothesis is that the mass of black hole of the remnant would be less than the sum of black hole masses before merger with mass excess being radiated away in gravitational radiation. Also, we tested the relation in different directions to see whether the choice of axis affects the calculation. We found out results completely opposite to our hypothesis, with the remnant black hole being more massive than the combined mass before merger. This is primarily due to the fact that are simulations don't have black hole or gas particles in them. However, we were indeed able to verify that velocity dispersion and the M-σ relationship are isotropic . So, based on our results, we claim that if the black hole particle data available, the M-σ relationship indeed can be used to model the black hole mass of the galaxies.

Keywords: Velocity Dispersion — Stellar Bulge — Galaxy Merger — Merger Remnant — Stellar Disk

1. INTRODUCTION

A galaxy is a gravitation ally bound set of stars whose properties cannot be explained by a combination of baryons (gas and stars) and Newton's laws of gravity (Willman & Strader 2012). The obvious question is how do they evolve. So, galaxy evolution is the study of how galaxies form, grow, and change over time. It seeks to understand the physical processes that drive the formation and evolution of galaxies, as well as the observed properties of galaxies at different cosmic epochs. In this paper we would be simulating the mass of Super Massive Black Hole(SMBH) of MW and M31 using the M-σ relationship for galaxies. In this relationship M stands for Mass of SMBH present at the center of the galaxy and σ represents the stellar velocity dispersion (Brown et al. 2009) of the galaxy bulge particles (concentrated at the center) . Velocity dispersion is a measure of the random motion of stars or gas within a galaxy. A stellar bulge is a structure that is found in the central region of some galaxies, including our own Milky Way. It is characterized by a high concentration of stars and a roughly spherical or ellipsoidal shape. The topic matters to our current understanding because, first of all this relation helps us to measure the mass of SMBH in distant galaxies which is otherwise not possible by direct observation. The presence of this relation also establishes the fact that black hole affects the properties of the galaxies. As earlier it was thought that as SMBH have a low gravitational potential compared to the host galaxy so, it shouldn't influence galaxy formation in any way. However, as this relation relates the

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black hole mass to the velocity dispersion of the galaxy, which is itself a intrinsic property of a galaxy, this lead the astronomical society to believe that SMBH directly influences galaxy formation. Our current understanding of the topic is that scientists have agreed that indeed M-σ gives a good estimate of SMBH mass as, the SMBH mass of several nearby galaxies have been computed and that agrees with the measurement by other methods (Suyama & Okano 2023). Moreover, the following equation governs the M-σ relation (Zubovas & King 2019) :

$$M = M_{sun} \times 10^8 \times A \left(\frac{\sigma}{200Kms^{-1}}\right)^{\alpha} \quad (1)$$

In equation 1 , many different models predict different values of A and σ . According to the recent studies the value for A is around 1.9 and value for alpha is around 5. Scientists are studying different models of how SMBH influences the evolution of the host galaxy.The most prevailing model is the active galactic wind feedback model. The outflows generated from the accretion disc of these SMBH can play a important role in the galaxy formation by affecting its star formation rate amongst many causes. The current open research questions in the field are those pertaining to the accuracy of this relation. Although quite a few SMBH measurements have been verified by this relation, but still we don't have enough sample space to conclude that this relation applies to all the galaxies in general. Moreover, not all galaxies have their SMBH at their center so, does the M- σ relation works on these galaxies? Moreover, M-σ doesn't do well on lower and high regimes. For example : M-σ predicts the SMBH mass for NGC 1277 (Trujillo et al. 2013) to be equal to $2.5 \times 10^5 M_{sun}$, however the actual mass is grater by a factor of 7. So, testing the M-σ relation on lower and high end of SMBH masses. Also, on a bigger picture the M-σ relation can help us answer the famous puzzle, that what came first : SMBH or the host galaxy?

Figure (1) serves as the motivation for my project.

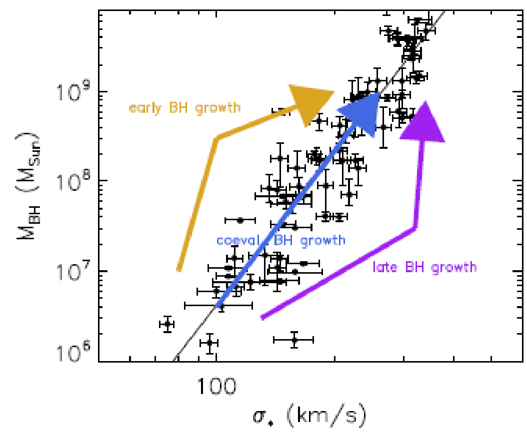

Figure 1. This figure (Gültekin et al. 2009) displays the evolution of black hole mass in accordance with the $M - \sigma$ relation. It explores the growth of black hole with respect to the galaxy bulge.

2. THIS PROJECT

The specific question I am going to answer are : I would explore the validity of M-σ relation . I would study the relation before and during the merger of MW and M31 and see whether the mass of the SMBH of the two galaxies change throughout the merger sequence. A galaxy merger is a process in which two or more galaxies come together and combine to form a new, larger galaxy. When two galaxies come close enough to each other, the gravitational forces between them cause them to become tidally distorted, with their shapes elongated and their gas and stars pulled out into tidal tails. Also, would the SMBH mass of the merger remnant would be the sum of the two black holes masses of individual galaxies just before merger or is it different than that? A merger remnant is the resulting galaxy that forms after two or more galaxies merge together. We would also study how to calculate the velocity dispersion, as velocity dispersion depends on the component of velocity that lies along the line of sight of the observer. So, we would calculate velocity dispersion in all 3 different directions (x,y,z) and put them into equation 1 and see whether we get same SMBH mass at each snapshot or not. Overall I would have two plots, one would be the time evolution of velocity dispersion and other would be the time evolution of the SMBH. The testing of M-σ relation is important as it would give us a method to directly measure the SMBH mass of the galaxies, which could reveal unknown facts about galaxies and enhance our understanding of galaxy evolution.

3. METHODOLOGY

In this section I would be detailing the procedure we followed to run our simulations and test our hypothesis. First of all, I would like to mention that I used the N body simulation methods as described in (van der Marel et al. 2012). An N-body simulation is a computer model that tracks the motion of individual particles, such as stars or dark matter particles, as they interact with each other under the influence of gravity. These simulations can be used to model the formation and evolution of galaxies, by starting with an initial distribution of particles and then following their motions over time. The simulation data taken from smoothed particle hydrodynamics code, GADGET-2 (Springel 2005) , had 3 particles types with type 1 being halo particles, type 2 being disk particles and type 3 being bulge particles. For our project we utilized the disk particles for center of mass calculations and the bulge particles for computing effective bulge radii and velocity dispersion profiles. A stellar disk is a component of a galaxy that consists of a thin, rotating distribution of stars that forms a flattened structure. The stars in the disk orbit around the galaxy's center of mass in roughly circular orbits that lie within the plane of the disk. The disk is usually dominated by young, relatively metal-rich stars, as well as gas and dust that are actively forming new stars.

We shall now describe an overview of our approach as described in fig 2.

We divided our calculations into two parts, before merger and after merger.

For the before merger calculations we treated MW and M31 as separate entities. So, the files created for both of them are the same. We first created a function to find the effective bulge radii. Basically, the M- σ relation uses only velocity dispersion of the bulge particles. So, we must create a method to compute velocity dispersion of the bulge particles in x,y,z directions. However, we cannot include all the bulge particles from the simulation data as their would be outliers that might disturb the results. So, we choose only those particles that is enclosed in the radii that contains half the total bulge mass. For this, we first computed the center of mass say MW with respect to disk particles and found out the radii that enclosed half the total bulge mass. Now, we stored the velocity data (x,y,z) for these particles in different arrays and computed the standard deviations of these arrays. This method would return the velocity dispersion in the x,y and z direction of each of the galaxies. Now, we feed this array into the the M- σ relation as given in equation (1) to get the black hole mass array in x,y and z direction for MW. Now, we loop this over snap id's starting from 0 all the way up-to snap id 445 (which roughly corresponds to 6.35 Gyr, which is the instant when MW and M31 merge as computed using the plot from class as shown in figure (3). This method (named "Sigma.py") would return a .txt data file consisting of velocity dispersion and black hole mass in x,y,z directions for MW for each instant of time. We repeat the same process for M31.

We shall now describe the after merger code. So, for after merger we again need to find the effective bulge radii as described above, however, now we cannot treat MW and M31 as separate entities. So, we first modified our center of mass code, so that it can now input two files and calculate the combined center of mass. Now, for effective radii calculation, we created read in bulge particles from both MW and M31 and concatenated them into a single array and then used the same method above to find the effective radii of the remnant bulge. From their we just followed the same technique to calculate velocity dispersion, then the black hole mass and then looping over now from snap id's 450 to 801.

Now, we take the three data files created one each for MW and M31 before merger and one file for remnant after merger and read those files in the "plotting directory".In the plotting program we concatenate all the 7 parameters (velocity dispersion in x,y and z ; black hole mass in x,y and z ; time from before the merger and after the merger). This method creates 4 plots, one each for MW and M31 that shows velocity dispersion in x,y,z directions and one each MW and M31 that shows SMBH mass in x,y,z direction both beginning till the end i.e before the merger to after the merger.

Our main hypothesis was that we can sum up the SMBH masses of MW and M31 before the merger and compare it to the SMBH mass after the merger and the later should be less than the sum, as the excess must have been lost in gravitational radiation.

4. RESULTS

In this section we like to present the results we got from the simulation.

Our first two plots as shown in figure (5) shows the velocity dispersion profiles from before merger up til after merger for MW and M31. We see a shift in the plot at 6.35 Gyr which as described above is the time of merger. We can see from the two plots that the velocity dispersion profile is indeed isotropic, as we obtained consistent results in the three directions. We also see that the velocity dispersion of the remnant is greater than that of individual galaxies prior to merger. This was expected as the remnant has many more bulge particles. The main result if the velocity dispersion plot is that velocity dispersion is indeed isotropic. We shall discuss the choice of our directions in the discussion section.

Our second plot is our main result, which is the SMBH mass of MW and M31 before and after merger as shown in figure (4). Although we have different plots for MW and M31 to differentiate the before merger dynamics as after merger the plots are the same as MW and M31 are no longer different entities but a combined galaxy merger remnant. The table (1) shows the black hole mass results in different directions . The first column

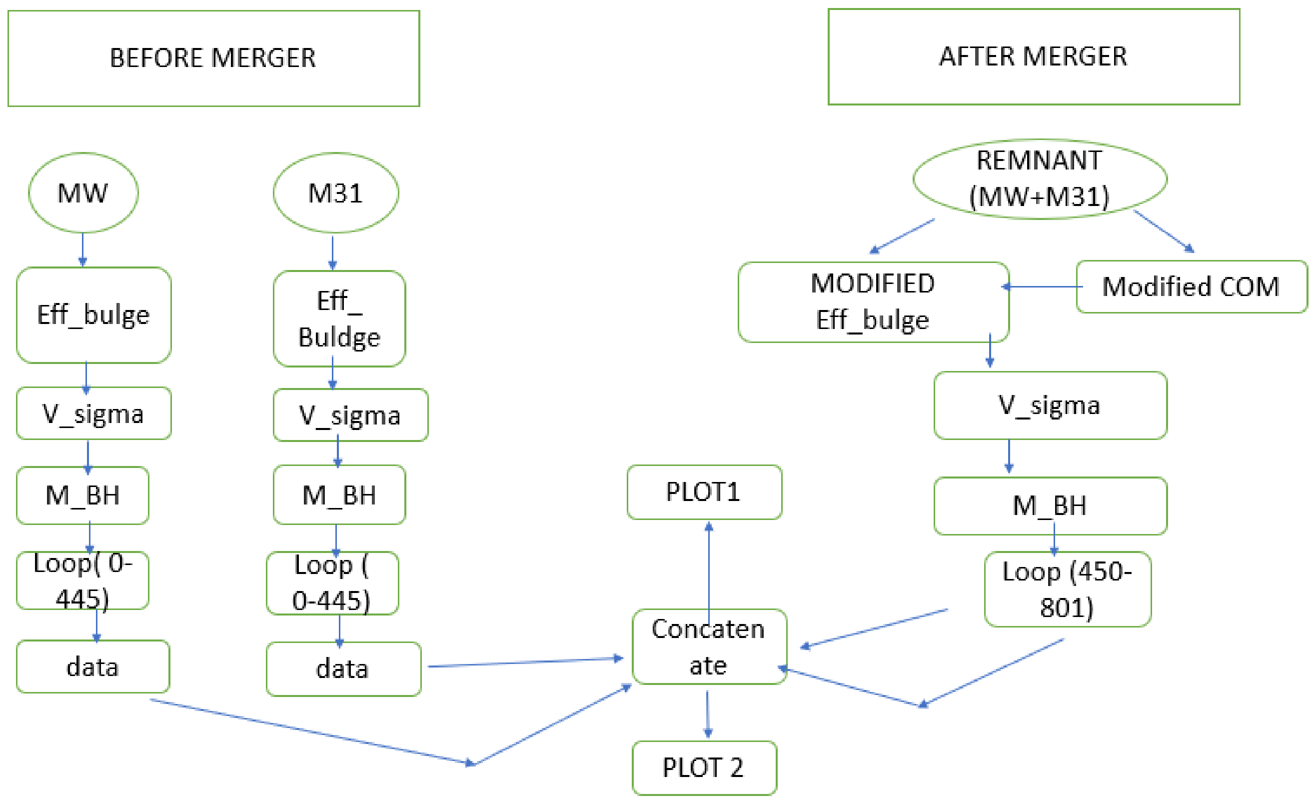

Figure 2. This figure displays procedure we followed to code the simulation.

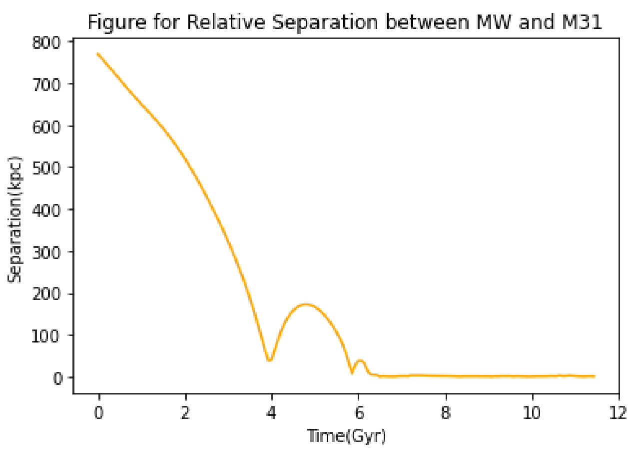

Figure 3. This figure displays the Separation between MW-M31

Direction	SMBH before ($\times 10^7 M_{\odot}$)	SMBH after ($\times 10^7 M_{\odot}$)
x	7.47	8.61
y	6.59	13.064
z	7.15	15.208

Table 1. The table shows the black masses just before merger and just after merger of MW and M31 system. Just before merger they are separate entity, so we summed up the masses whereas after merger they are single remnant

shows the sum of the black hole mass before merger and column two shows the black hole mass of the remnant just after merger.

So, although from the plots it looks like the SMBH is isotropic , the table (1) reveals the real picture. As the values in the table are of the order of ($\times 10^7 M_{\odot}$) we cannot say that all the three directions are nearly equal. However, we can say that x direction is different than y and z. So, basically, although y and z directions are the same , x is different. Nonetheless, neither of the results matches with our initial hypothesis which was that the SMBH mass of the remnant would be less than the combined SMBH mass of the two galaxies before merger.

5. DISCUSSION

Our results for black hole mass didn't agree with our initial hypothesis . Our initial hypothesis was that the black mass of the remnant just after the merger would be less than the sum of the black hole mass of the MW and M31 just before the merger . However, we can see from table (1) which has been made from the data presented in figure (5) that the black mass of remnant is rather bigger than the total mass before merger. The primary reason for this discrepancy is that our simula-

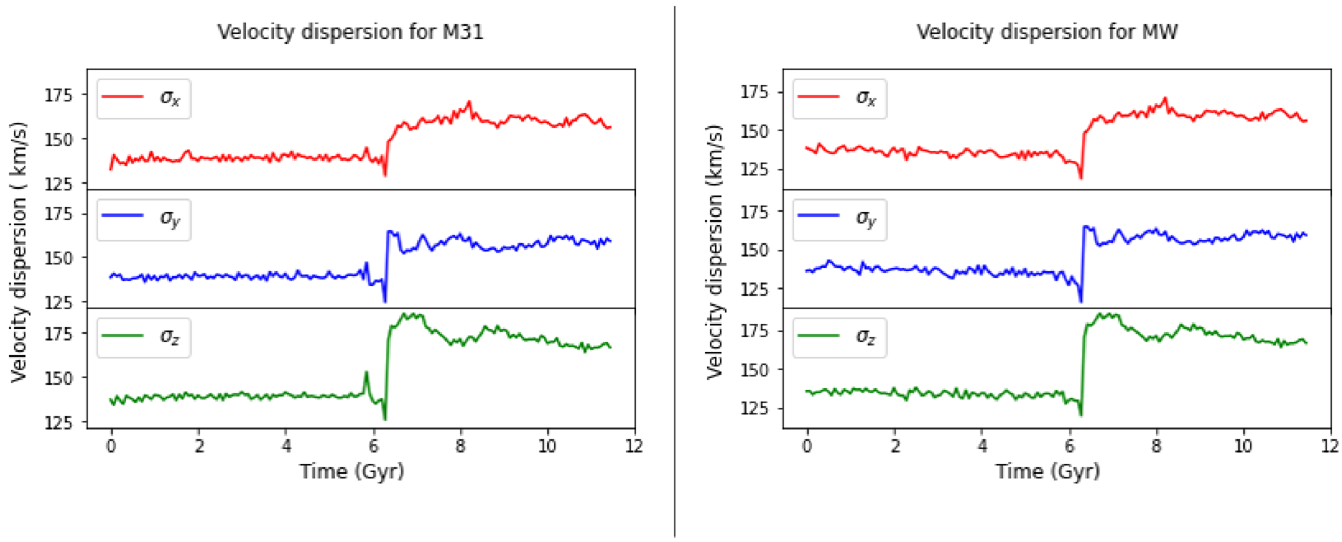

Figure 4. This figure displays the velocity dispersion profiles. On the left panel, we have velocity dispersion profiles of M31 and on right panel that of MW.

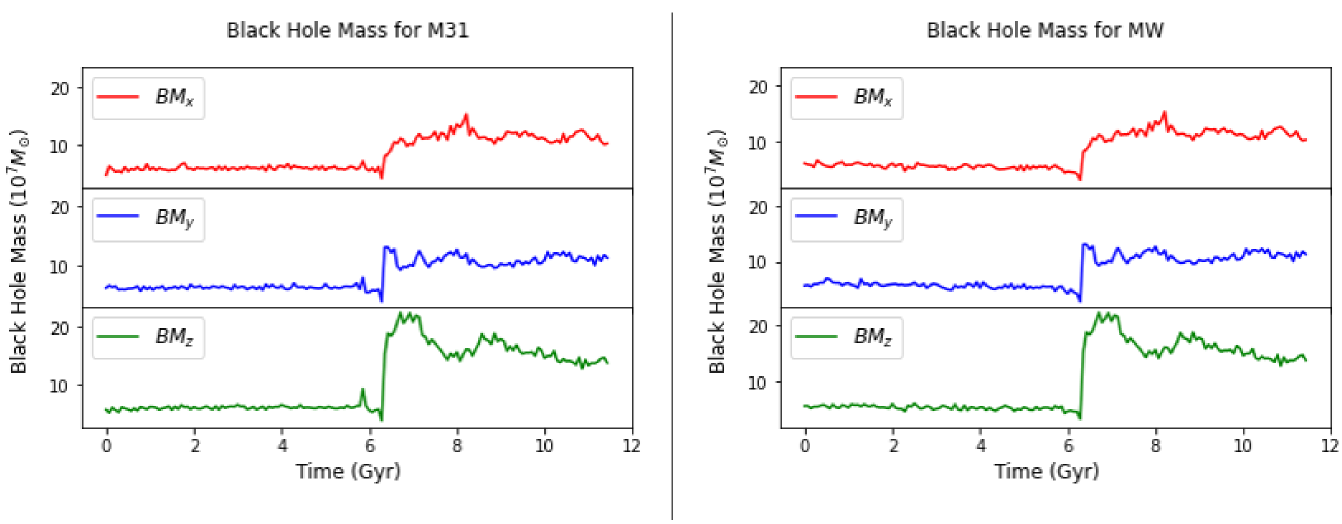

Figure 5. This figure displays the black hole mass before and after merger. On the left panel, we have Black hole mass profiles of M31 and on right panel that of MW.

tion data doesn't have black hole particles in it. Also they don't have gas particles. So, our calculations don't reflect the actual, but rather depict a handy wavy picture of the black hole merger. However, the order of black hole masses that we calculated is same as typical mass of black hole mass, this means that our overall aim of testing the M-σ relationship has been successful. So, we can safely say that indeed M-σ relationship could serve a s a potential method for mass estimation of super massive black hole of the galaxy.

Also, it could be used to study the behaviour of gravitational waves . Moreover, the hot field right now is black hole thermodynamics. It has been shown that black holes evaporate (Bardeen 1981) and they lose their mass in form of radiation, so although information cannot escape black hole it seems like energy can escape black hole. This challenges the long standing belief, that absolutely "nothing" can escape black holes. Overall, the M-σ relationship is a key element in galaxy evolution as, SMBH are a key element of galaxy so, studying their behaviour would indirectly help us to study the fate of the galaxy.

The major uncertainty in my analysis is the choice of my axis. We know that throughout the merger sequence galaxies rotate so their disks also rotate hence our initial coordinate system would also rotate. Hence, assuming the x axis to be pointing in the same direction throughout the merger sequence could potentially cause slight issues. However, I believe that as their is some sort of symmetry in the merger dynamics, the choice of axis doesn't matter.

6. CONCLUSION

In this project we simulated the Super massive black hole mass of MW and M31 before and after merger. We also looked at the velocity dispersion profiles of the two galaxies. This was done in an effort to verify the M-σ relationship. The study of the M-σ relationship is important as for a long time scientists didn't think that SMBH can effect galaxy evolution, however with the M-σ relationship being proven right, scientists eventually agreed that SMBH play a key role in galaxy evolution. However, this relation has not yet been tested to high precision, the preliminary results are promising. In this paper we tried to apply this relation to MW and M31 merger sequence. Our initial hypothesis was that the mass of SMBH would decrease after the merger, however we were not able to achieve desired results due to absence of black hole particle data in the simulation files. Nonetheless, the order of magnitude of the black hole masses achieved is near to the typical SMBH masses. Hence, the M-σ relationship could serve as a potential method for direct calculation of black hole mass given we know the velocity dispersion profiles of the galaxies, for which we have existing successful methods. The future work on this topic would be to include the black hole as well as gas particles in the data files and use them to test the M-σ relationship relation. We would also want to analyze this system from face on and edge on perspectives. Moreover, there are still corrections being made to the M-σ relationship parameters A and α . So, correct simulations may allow the precise measurements of these parameters.

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3 . Astropy (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018 doi: 10.3847/1538-3881/aabc4f)

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