Eccentricity Evolution of Super Massive Black Hole Binaries – Implications for GWs detection

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Abstract*— The evolution of SMBH binary is shaped by three distinct phases. Dynamic friction phase is followed by stellar encounter with binary's orbit and finally gravitational waves emission phase governs the coalescence. In the 2nd phase, further orbital decay may be constrained due to limited supply of stars at binary's orbit. This stalling leads to larger coalescence time. In this work, we study eccentricity evolution of merging binary having different mass ratio black holes. Using large scale direct N-body simulations on parallel GPU supported high performance computer cluster, we modeled major merger 1:1 where merging galaxies have M_{bh}/M_{bulge} ranging 0.001-0.6. Results show that for M_{BHSec}/M_{BHPrim} > 0.01, eccentricity shoots up rapidly during transition from phase 1 to 2. Coalescence time is very sensitive to SMBH binary eccentricity. The rise of eccentricity witnessed for M_{BHSec}/M_{BHPrim} > 0.01 will result in prompt coalescence of two SMBHs. Hence these binaries become the promising candidates of GWs to be sensed by future space borne GWs detectors like eLISA and PTA.

***Keywords* — Dynamic friction – Binary – Bulge – Eccentricity – Coalescence time**

I. Introduction

There are observational evidences that most large galaxies do host massive black holes (BHs) at their cores [1] [2] i.e a galaxy hold single galactic nuclei. Studies also show existence of dual BHs in single system [3] Recent observations have suggested entangled connection in the evolution of SMBHs and their host galaxies [4]. As there are observational evidences that most large galaxies do host massive black holes at their cores [1] i.e. a galaxy hold single galactic nuclei. Still cases have been observed where in a single system, binary exists [3]. In the course of two merging galaxies if both the systems offer SMBH [5], the two centers will sink towards center of potential and the merger shall form binary in the resulting galaxy [6]. Subsequent evolution of two BHs happens as described. (1) Dynamic friction contributes for the gradual falling of the separation between SMBHs from each galaxy and is triggered by medium of gas and stellar background until radius of influence is crossed and binary is formed. (2) After the binary is formed, gravitational sling shot effect comes into play in a manner that stars in orbits intersecting the binary's are ejected at velocities very much comparable to the binary itself. Therefore dropping the angular momentum and further increasing the binding energy of binary. This in turn decreases the binary's orbital time. (3) The decay continues such that black hole binaries manage to shrink to a distance apart where emission of gravitational waves (GWs) become dominant. The emission carries away residual angular momentum and energy followed by coalescence of SMBHs.

The last stage of merger is dominated by appreciable outburst of gravitational waves which ultimately is a strong candidate of vibrations in space to be sensed by future space-borne gravitational wave interferometer [7].

Although galaxy merger rate can be derived from models of structure formation in which galaxies merge hierarchically [8] yet it does not necessarily indicate the coalescing rate of binary. How efficiently a binary must manage its exchange of angular momentum with neighboring stellar and gaseous medium i.e. a transition from phase 2 to phase 3 is raised as Final Parsec Problem (FPP) [9] and is major stated constraint to coalescence of binary within Hubble time. During phase 2 due to slingshot mechanism stars are ejected from the binary's orbit to extract energy and angular momentum but in spherical galaxies once all the stars are ejected out of binary's orbit, the changes in binary separation take place on much longer time scale and a refill to loss cone is required in order to step forth in binary evolution (Yu 2002) which is the well-known Final Parsec Problem [9]. Earlier studies has established that the rapid transition from 2nd to 3rd phase is possible i.e. this stalling can be cured [10]. Major merger results essentially into non-spherical galaxies the triaxial galaxies in massive binaries are rich in centrophilic stellar orbits which is then provided to the SMBH binary at high rates to avoid stalling [11] [12] [13]. Further the axisymmetric galaxies also solve the FPP for hardening rate becomes much faster than spherical models [14].

Investigating the time the binary will take during 3rd phase to coalesce, it was found that T_{gr} is critically dependent on eccentricity (e) [15].Up till that stage before coalescence where semi major axis and eccentricity can be termed constant over few orbital revolutions, Peter and Mathews (1964) formulate T_{gr} as a direct function of eccentricity. The relation proves: Higher the value of eccentricity, shorter the coalescence time will be. This declares eccentricity i.e. just before GWs become dominant, to be a deciding factor of coalescence time [15].

In this work, we carry out direct *N*-body merger simulations of two equal mass galaxies containing different mass ratios of central SMBHs and analyzed the eccentricity evolution of binary resulted due to these mergers.

Experimental set up is explained in section II that includes galaxy models in our study and numerical methods applied to carry out simulations. Results of merger simulation are presented in Section III. Section IV discusses the results from simulations and conclude the findings.

II. Models and Numerical Methods

We carry out direct *N*-body merger simulations of two equal mass galaxies containing different mass ratios of central SMBHs. For this study, we have modelled 1 primary galaxy and 5 secondary galaxies. Primary galaxy is chosen with high M_{bh}/M_{bulge} = 0.6 motivated by M_{bh}/M_{bulge} of NGC1277 [16]. M_{bh}/M_{bulge} of secondary galaxies set to be 0.001, 0.005, 0.006, 0.008 and 0.01 [17]. 5 simulations are run having major merger (1:1) but varying ratio of $\mathbf{M_{BHSec}/M_{BHPrim}}$.

To generate galaxy model, mass and density profiles presented by Dehnen & Tremaine are used. According to model, distribution is given as:

$$\boldsymbol{\rho(r)} = \frac{(3-\gamma)}{4\pi}\frac{a^{\gamma}M_{gal}}{r^{\gamma}\,(a^{\gamma}+r)^{4-\gamma}} \qquad (1)$$

$$\boldsymbol{M(r)} = \frac{r^{3-\gamma}}{(a^{3-\gamma}+r)^{3-\gamma}} \qquad (2)$$

Where $\boldsymbol{a}$ is semi major axis, $\boldsymbol{M_{gal}}$ is bulge mass of galaxy and $\boldsymbol{\gamma}$ is inerr density profile slope that can be varied from 0 to 3. Figure1 shows the variation of central density for values of $\boldsymbol{\gamma}$. Graph is brief examination of Dehnen model for values of $\boldsymbol{\gamma}$ 0, 0.5, 1, 1.5 and 1.75. The graph suggests higher central density for high $\boldsymbol{\gamma}$ value.

A massive particle is placed at the center of each modeled galaxy to represent SMBH. There has been established tight correlations between masses of SMBHs and bulge luminosity of their host galaxy [18] [5].

Magorrian (1998) described M_{bh}/M_{bulge} relationship which show a typical value of 0.5% with an upper limit be 3%. Converse to estimations by these correlations, recent studies have discovered implanted SMBHs significantly more massive. Reines (2011) claimed Henize 2-10 harbouring central BH with mass one million solar masses which is almost one 100 times more than what is expected. Massive BH in NGC 3115 carries 2.4% of M_{bulge} and is still higher than normal.

Results based on the mean value of Jean equation and entropy model, NGC 4486b is designated an outlier as 0.12 M_{BH}/M_{BULGE} is quite above the upper limit [18]. NGC1277 is another case where BH comprises 60 % of the mass of host galaxy which is oddly very large compared with mean value.

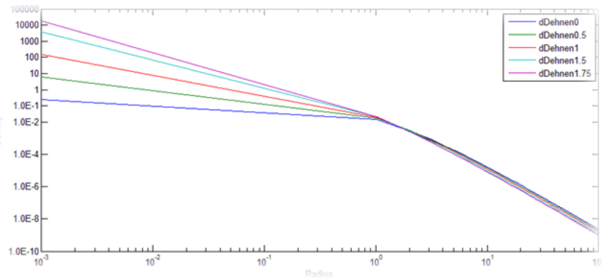

Figure 1. Dehnan density Profile for various values of $\boldsymbol{\gamma}$.

In model units we set G = a = 1. To calculate N particle forces and acceleration, we have used φ-GRAPE code based on Hermite scheme. Simulation sets are run on ACCRE GPU Cluster at Vanderbilt University.

III. Results

After each merger simulation, raw data was obtained and was transformed to orbital parameters using Kepler laws.

Figure 2 illustrates in parallel how the SMBH binary separation is reduced w.r.t time. Model units are used for separation on y-axis and time on x-axis. During first 100 years, BHs claimed positive and near zero orbital energy i.e. unbound and loosely bound orbits respectively. Binary had just formed near 100th year which is why X range contained like 100 to 600 for both the plots.

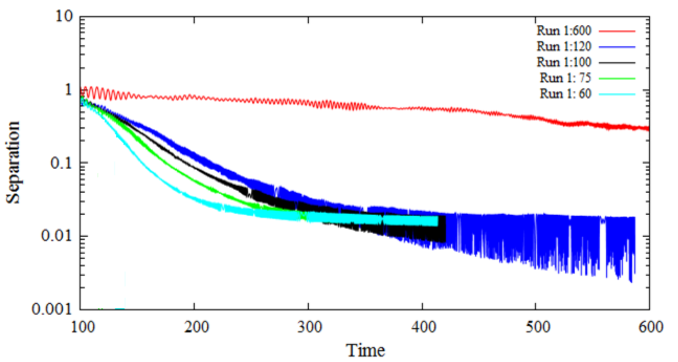

Figure2: Separation of SMBH binary w.r.t time.

Eccentricity is one of the six major keplerian elements which indeed is a decoding factor of coalescence time as discussed earlier. As binary progress in time, eccentricity will continuously be evolving - discriminating each of three merger phases. Graphical representation of evolution of eccentricity is compared in Figure 3 for 5 RUNS.

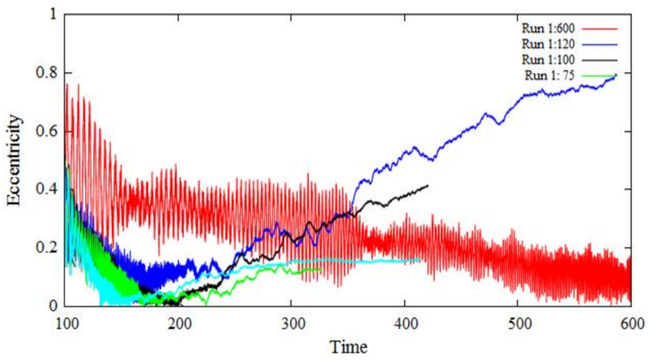

Figure3. Eccentricity evolution of SMBH binary w.r.t time.

IV. Discussion and Conclusion

In Figure 2 we plot separation between two BHs against time for 5 Runs. For comparison 5 Runs are placed in one plot. Figure 3 is eccentricity evolution of SMBH binary with time. From Red to Cyan the increasing ratio M_{Sec}:M_{Prim} represents the least comparable BH masses to the most comparable ones.

The early slow inspiral of each Run points towards 1st phase of merger when stellar density is quite low. The higher the M_{bh}/M_{bulge} value will be, with effective rapidness merger will cover the dynamic friction phase [19]. Keeping in view M_{bh}/M_{bulge} , Run2 has 5 times while Run5 has 10 times more massive Secondary SMBH than Run1. This is in accordance with rough estimation of time spent to shrink the separation down to a parsec e.g.~10Myrs and~6 Myrs which is roughly 5 and 10 times against Run1.

So we conclude the more comparable masses the binary will contain, the strongly the BHs will experience dynamic friction. In Figure 3, the upper boundary in each Run represent apoapsis and lower extreme of shaded part shows the periapsis of binary's orbit. The thicker the shaded part is, the more eccentric the orbit will be. This can also be verified for any time value in Figure 2 and 3. As dynamic friction circulates the binary's orbit, the rise of eccentricity is a hint of transferal from 1st to 2nd phase.

For Run1 the rise of eccentricity is slow i.e. e has reached to 0.6 in 30 Myrs hence binary is stalled at 2nd phase. For Run 2 binary has evolved quickly to e=0.6 as in about 10Myrs which is a third of a time than Run1.

Secondary SMBH in Run3 is 6 times more massive than Run1. The rate with which its eccentricity evolves is very much comparable to Run2 and is even high.

Run5 and Run4 exhibit exceptional evolution of eccentricity. Although in about 5Myrs binary's orbit circulates and managed to reach e=0, yet sluggishly it starts being elliptical again and gradually flattens to e~ 0.2 in next 5-7Myrs respectively. These Runs have settled their eccentricity to very low value which correspond to larger coalescence time.

Relating eccentricity values of all 5 RUNs to equation (1), we get to conclude that the galaxies which undergo major merger having M_{BHSec}:M_{BHPrim} greater than 1:100 will offer higher eccentricity values that correspond to shorter coalescence time. These mergers will ultimately become marked targets for future space borne GWs detectors.

All through we have used model units which are not restricted to some special galaxy case. Transformation can be applied to real galaxy data to directly estimate merger time. These findings have directed a fresh pathway to calculate event rate for eLISA and other antennas of GWs detection.

This work was initiated as final year student project having assigned timeframe. It can be further enhanced by adding features which could diversify the significance of research. So far the study has divide two regimes effected by $\mathbf{M_{BHSec}/M_{BHPrim}}$ of binary, yet closer ratios can be chosen for next simulations to further insight the regimes. Added, the work can also be extended using other density profiles investigated by Dehnen.

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