Evolution of SMBH-SMBH and SMBH-IMBH Binaries: Effect of Large Mass Ratio

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Main points

If we consider stellar dynamics only (no gas),

- SMBH-SMBH binary would not merge
- SMBH-IMBH binary (or MBH binary with large mass ratio) do merge
Talk structure

1. SMBH-SMBH binary
   ● Summary recent results

2. SMBH-IMBH binary
   ● Why we consider SMBH-IMBH binary
   ● Simulation result

3. Summary
SMBH-SMBH binary

Many more talks on this subject...

- Formed by merger of two galaxies with SMBHs
- “Last parsec problem”
Last parsec problem

- (If there is not much gas) BHB evolves (hardens) through interaction with nearby stars.
- As it hardens, it becomes more compact and number of stars that can interact with BHB becomes smaller.
- At some point, BHB would kick out all stars it can interact (loss-cone depletion), and stars will be only slowly supplied through two-body relaxation.
- Orbital evolution becomes very slow.

This problem has been known for many years (e.g., Begelman, Blandford and Rees 1980).
\textit{N}-body simulations on loss-cone depletion

Theoretical prediction: growth timescale $\sim$ relaxation time $\sim N$ (number of particles)

- Before 2003 — Total Confusion
- After 2003 — Begin to converge (but...)
Before 2003

- JM 1997
- Quinlan 1997
- Milosavljević & Merritt 2001 (also 2003)
- Chatterjee, Hernquist & Loeb 2003

Results are not quite consistent with each other or with the loss-cone argument.
Not consistent with thermal relaxation argument
Quinlan 1997

$N$ up to 200K (One of the curves in "N=100K" panel is for $N=200K$)

Hardening rate independent of $N$ for $N > 100K$
Milosavljević & Merritt 2001

$N$ up to 32k

Hardening rate independent of $N$

Argued that they could not see $N$ dependence because $N$ was too small (quite reasonable).
The state of the art in 2003

No agreement at all...

- $N \leq 256K$
- No agreement between different people.
- No result consistent with the loss cone depletion argument.

“numerical N-body experiments are not well suited to probe these mechanisms over long times due to spurious relaxation.”

(Milosavljić and Merritt 2003)
GRAPE-6

- Special-purpose computer for Gravitational $N$-body problem
- Completed in 2002
- 32Gflops, 10W/chip
- Largest configuration 64 Tflops (2048 chips)
- Many copies have been built and used at more than 30 institutes
- Made direct simulations with $\geq 10^6$ particles practical
Some of the largest GRAPE-6 setups:

- Tokyo (64TF)
- Rochester (4TF)
- Heidelberg (4TF)
- Tsukuba (8+30TF)
GRAPE-DR — Next generation

5-year grant FY2004-2008, 2-Petaflops peak
First sample chip and board arrived May 2006
Currently being tested (no serious error found yet)
New simulations

- JM and Funato 2004
- Berczik, Merritt, and Spurzem 2005
Hardening rate $\beta$ depends on $N$. 

If we write $\beta \propto N^{-\gamma}$, $\gamma$ approaching to 1 for late phase

Not inconsistent with asymptotic value being 1.
$N$ up to 0.4M
Simulation significantly longer than JM and F 2004.

$N$ dependence
$\sim N^{0.8} \ (M_{bh} = 0.02)$
$\sim N^{0.33??}$
$(M_{bh} = 0.005)$
Summary of BHB $N$-body simulations

- $N$ much larger than old simulations
- Duration also longer
- Growth rate shows clear dependence on $N$
- Results not converged yet...
- “Last parsec problem” is there.
SMBH-IMBH binary

- IMBHs might exist in some young and compact clusters (Matsumoto et al. 2001, Kaaret et al. 2001)
- They might exist near Galactic center (IRS13E, Maillard et al. 2004)

Much controversy on both topics...
Evolution of SMBH-IMBH binary

SMBH potential dominates over background.

- Scaled-down version of SMBH binary?
- Any effect of large mass ratio?
Simulation


- Bahcall-Wolf cusp around SMBH
- SMBH $3 \times 10^6 M_{\odot}$
- IMBH $3 \times 10^3 M_{\odot}$
- 1 length unit $\sim 1$pc, 1 time unit $\sim 4600$ year
- Lowest star mass $\sim 3 M_{\odot}$
- IMBH placed at 0.1pc (runs A) or 0.01pc (runs B)
IMBH orbital evolution (runs A)

Slows down at late phase.

Not much dependence on $N$

(A1-A4 are for different $N$)
IMBH orbital evolution (runs B)

IMBH placed at 0.01pc
Field star mass smaller than that in runs A

Loss-cone depletion effect clearly visible
Eccentricity grows quickly after separation. Evolution stalled. Different from SMBH-SMBH binary.
Gravitational Wave timescale

Can become very short
($<< 10^6 \text{yrs}$)
Why does eccentricity grow?

Simple explanation:

There are practically no stars within the IMBH orbit.

↓

If the IMBH interacts with other stars, the interaction most likely occurs at the apocenter of IMBH orbit.

↓

Therefore the IMBH loses angular momentum more efficiently.
Change of $L$ in one orbit

Averaged over multiple orbits

$M$: mean(?)

anomaly, 180: apocenter

Spikes due to two stars strongly bound to SMBH

IMBH loses $L$ around and after apocenter
Why SMBH binaries do not become eccentric?

- In order to interact with IMBH, field stars need to come close to IMBH.
- For SMBH-SMBH binary, anywhere with distance order of BH separation is OK.

\[ t_{interaction} \begin{cases} \ll t_{orbit} & \text{(IMBH)} \\ \sim t_{orbit} & \text{(SMBH)} \end{cases} \]

Mass ratio makes difference
Summary

- SMBH binaries would not merge if there is not much gas
- SMBH-IMBH binaries do merge, even if there is no gas
- Main difference: eccentricity of SMBH-IMBH binary increases, while that of SMBH-SMBH binary does not
Some comments

- $N$-body simulation results are in many cases over-interpreted.
- Larger and more reliable simulations do help resolving fundamental issues.
N-body simulation

Portegies Zwart et al 2005

- 64K stars, Salpeter IMF (lower cutoff: $0.2M_\odot$)
- 2pc from GC, circular orbit
- Roche-lobe filling King model ($W_c = 9$)
Result
Result

- Cluster at 2pc, mass $10^4 M_\odot$: DF timescale≈a few Myrs
- Cluster at 5-10 pc must be more massive
Orbital evolution of cluster with DF

Fujii et al. 2006: Satellite galaxy $N$-body simulation

In full-nbody simulation, satellite falls faster.
Why?

- Satellite gives angular momentum to escaped stars
- Escaped stars, while remaining close to the satellite, enhance the dynamical friction
Circular orbit?

We do not know how young clusters are formed

Not much reason to assume a circular orbit

If initially in eccentric orbit, DF timescale can be much shorter