Black Hole binary (mergers)

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Talk Organization

1. What's the problem?
2. Overview of previous works
3. New calculation
4. Result
5. Discussion

What's the problem?

- Many (if not most) ellipticals *seem to* have central massive black holes.
- Central structure of these ellipticals is consistent with dynamical origin of BH (cusp too shallow for either adiabatic or thermal growth of the BH mass)

One "natural" interpretation: Merging of galaxies with massive central black holes.
Begelman, Blandford, Rees (1980),
Ebisuzaki, Makino and Okumura (1991)

What will happen to black holes?

1. They sink to the center through dynamical friction (or when merging completed they are in the center of the merger)
2. They form binary because dynamical friction further reduce their velocity.
3. Once formed, the binary keeps becoming harder through interaction with nearby stars.

How BHB hardens?

Formation mechanism is the same as that for massive binaries in star clusters. However, BHB (black hole binary) is different from usual massive binaries:

- large number of stars = long relaxation time
- large BH mass = small random motion of BHB

Hardening of BH might slow down once nearby stars are all depleted (loss cone formation)

Loss cone depletion

If loss cone is formed, the evolution timescale would become very long (essentially the relaxation timescale of the parent galaxy). Merging would not occur within the Hubble time.

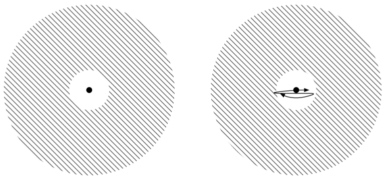
Questions:

- Whether or not M_{BH} can grow through repeated merging.
- Event rate for LISA.
- What happens if BHs do not merge.

Is loss cone really formed?

Theoretically nontrivial.

If loss cone is formed, there is nothing that prevents BHB from moving around.
↓
Doesn't BHB move to near the boundary of the "loss-cone" region?



Previous N-body works

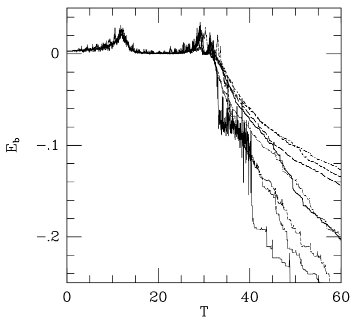
- Makino 1997
- Quinlan 1997
- Milosavljević & Merritt 2001
- Chatterjee, Hernquist & Loeb 2003

Results are, well, not quite consistent with each other or with the loss-cone argument.

Makino 1997

- Merging of two King model ($W_o = 7$)
- N 2K — 256K
- $M_{BH} = M_{Gal}/32$
- GRAPE-4 (NBODY1)
- soft potential for field particles, BH is treated as point mass
- No Gravitational wave (true for all calculations discussed in this talk)

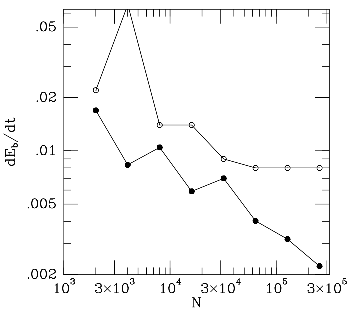
Binding energy



Larger N → slow evolution

How slow?

Hardening rate



Upper: E_b 1/160 – 1/80

Lower: E_b 1/10 – 1/5

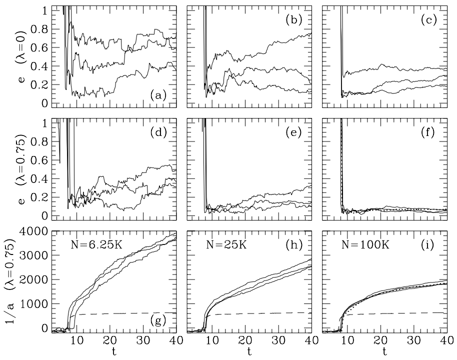
Late phase: Slope depends on N, but too weak (around $-1/3$)

Not consistent with thermal relaxation argument

Quinlan 1997

- Two BHs in a Plummer model
- N 6.25K — 200K
- $M_{BH} = M_{Gal}/100$
- SCF + direct
- SCF for field-field, direct for BH-BH & BH-field
- (J-dependent particle mass).

Result

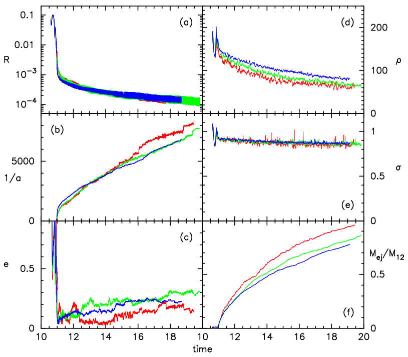


Hardening rate independent of N for $N > 100$K

Milosavljević & Merritt 2001

- Merger of initial galaxy model with $\rho \propto r^{-2}$ down to the central BH.
- N 8K — 32K
- $M_{BH} = M_{Gal}/32$
- Tree (Gadget)+direct
- Tree before BHB forms, direct after formation

Result



Independent of N

However, they argued that they could not see N dependence because N was too small (quite reasonable).

Chatterjee, Hernquist & Loeb 2003

- Same method as Quinlan 1997
- N up to 400K
- various M_{BH}

They claimed that hardening rate is independent of N for $N > 200K$.

I could not see that from their figures, though....

Summary of previous results

No agreement at all...

- No agreement between different people.
- No result consistent with the loss cone depletion argument.

So what was wrong?

- Too small N?
- Problem with numerical method?
- Initial condition?
- $\cdots$

New calculation

- Start from initial condition as simple as possible
- At the same time, select ICs so that theoretically loss cone can easily be formed
- use reliable (that is: simple) numerical method
- perform long, large-N calculations.

GRAPE-6

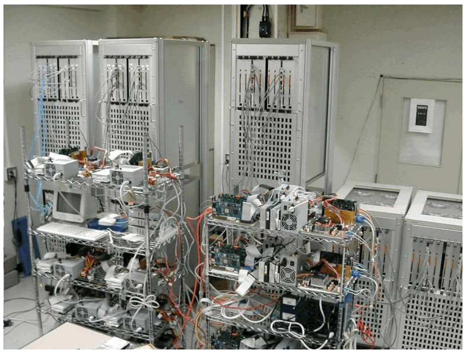
- Peak speed 64 Tflops
- Improved communication speed (2GB/s)
- Minor fixes for some "features" of GRAPE-4...

GRAPE-6 Overall structure

- 4 clusters
- 16 processor boards per cluster
- 8 processor modules per board
- 4 chips per modules
- 6 pipelines per chip
- 60 arithmetic units per pipeline

In total, 7.5×10^5 Arithmetic units operating at 90 MHz

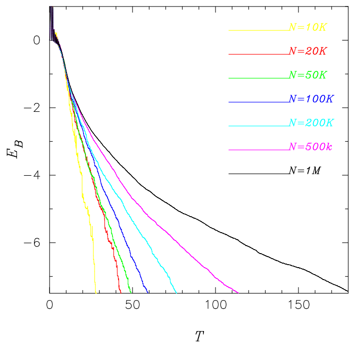
The 64-Tflops GRAPE-6 system



Calculation Details

- Two BHs in a King model ($W_o = 7$)
- N 2K — 1M
- $M_{BH} = M_{Gal}/100$
- Direct calculation on GRAPE-6
- Force from field: GRAPE-6, Force from BH: Host
- Soft potential for field-field. Others: point mass (very small softening)

Binding energy



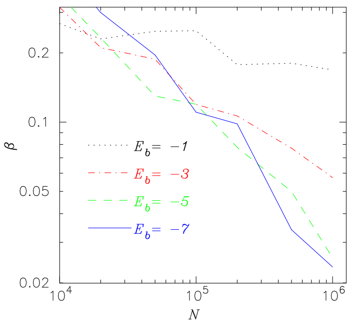
Heggie unit

E_b per unit mass

Slower hardening for higher N

How much slower?

Hardening rate

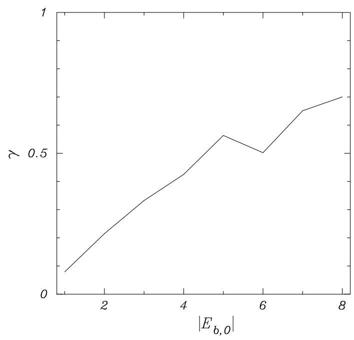


$\beta = |dE/dt|$

In early phase hardening rate does not depend on N.

In late phase it does.

Relation between hardening rate and binding energy



$\beta = CN^{-\gamma}$

γ is larger for larger E_b

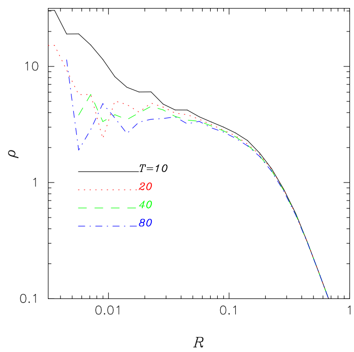
No sign of convergence...

Not inconsistent with asymptotic value being 1.

Summary of results

- Used similar initial model as Quinlan 1997
- Dependence of hardening rate observed as in Makino 1997
- Dependence becomes stronger as we go higher binding energy.
- Not inconsistent with loss cone depletion argument.

Loss cone ? — Density distribution

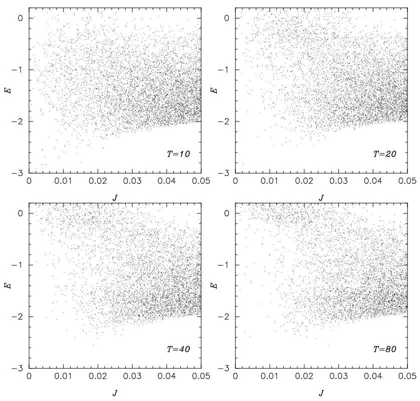


Density cusp disappears as binary evolves.

No density decrease inward

...

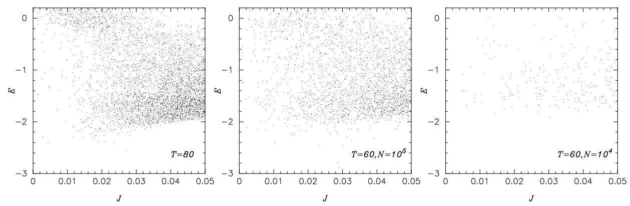
loss cone? — (E, J) space



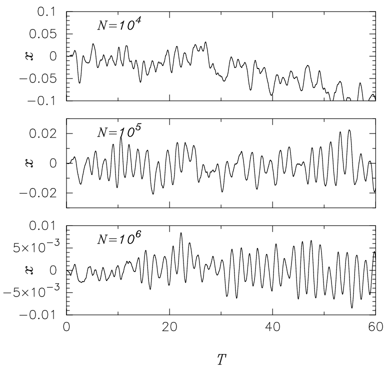
particles depleted from $J < 0.01$. (except for regions with small $E|$)

Loss cone is actually formed.

(E, J) space with different N



BH wandering



Summary

We followed the evolution of massive BHB in the center of galaxy with much larger N for much longer time than were used in previous works, with a reliable direct code on GRAPE-6.
Our main findings are:

- Numerical result is not inconsistent with simple loss-cone argument.
- Loss cone is actually visible in $(E - J)$ space.

In other words:

$\boxed{\text{Massive BHB would not merge in Hubble time through interaction with field stars and GW alone.}}$

What was wrong with previous works?

- Makino 1997
  - Small N, short simulation time
- Milosavljević & Merritt 2001
  - Too small N.
- SCF+BH
  - I do not quite understand...