N-Body Dynamical Modeling of Globular Clusters

Jun Makino
Department of Astronomy, U. Tokyo

Talk Overview

1. What I'm supposed to talk...
2. N-body technique and its limitations
3. Some recent results
4. Summary

What I'm supposed to talk...

The following is the questions listed in the mail I received from the organizer:

1. What are the current limitations in N-body dynamical modeling of globular clusters?
2. How do structure and initial conditions influence the binary spatial distribution and orbital period spectrum?
3. How do the results of n-body modeling compare with those of gas-dynamical modeling?

My talk: mostly on first question
Next talk: third question?

N-body simulation of star clusters

What do we do?

1. Set up an initial model for a cluster, with given radial profile, IMF, metallicity, binary parameters.
2. run the N-body simulation code, with good prescriptions for single and binary stellar evolution, tidal interaction, physical collision etc.
3. "Observe" the evolution of the model cluster

Sounds easy? It is more complex than it sounds...

Simulation code and Computer

What has been (and is still) the main limitation: Number of stars N which we can handle with reasonable machine time.

- Calculation cost of integration of single stars increase as $O(N^{3.3})$.
- Binaries (and triples, quadruples ...) become more and more difficult to handle as N becomes larger.

Overall calculation cost

- calculation cost per crossing time
  - force calculation cost per (average) timestep $O(N)$
    treecode still not available for high-accuracy calculations
  - Number of timesteps $O(N^{1/3})$
    should resolve nearest neighbours
- relaxation timescale $t_r \sim (N/\log N)t_{cr}$

Overall calculation cost: $O(N^{3.3})$

Past history

Calculations past core collapse

Year	N	Ref	Machine
1961?	40	von Hoerner	–
1974	500?	Aarseth (mass spectrum)	–
1985	3000	Inagaki (mass spectrum)	Facom M-380
1987	1000	Makino	Hitac S-810
1992?	10000	Spurzem and Aarseth	Cray YMP/C-90?
1996	32768	Makino	GRAPE-4
2003	65536	Baumgardt	GRAPE-6

Past history

Factor of 1000 increase in 40 years: Doubling time = 4 years.

Roughly consistent with evolution of computer speed (100 times per decade)

Still about 10 years away with "real" globular clusters (wait for GRAPE-10).
(Mass spectrum reduces calculation time by factor 10 or so).

GRAPE project

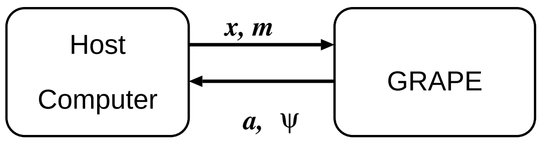
GOAL:
Design and build specialized hardware for simulation of dense stellar systems.

Rational:
You can do larger simulations (better resolution) for same amount of money.

	Year	Peak	Cost	Cost/TF
GRAPE-6	2002	64 TF	4M$	0.07
ASCI White	2001	12 TF	200M$	17
Earth Simulator	2002	40 TF	300M$	7.5
ASCI Q	2003	30 TF	200M$	6.7
IBM BG/L	2005?	400 TF?	50M$?	0.13?

Basic idea of GRAPE

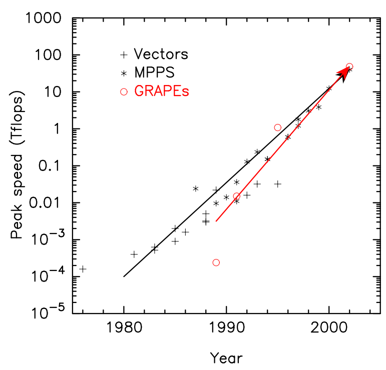
Special-purpose hardware for force calculation
General-purpose host for all other calculation



Advantages of GRAPE

- Special-purpose hardware
  - Hardwired logic → No software needed
  - Pipelined processor → High performance
- General-purpose host
  - Programmable in high-level languages
  - existing programs can be used with "small" modifications
  - can be used with Barnes-Hut tree/Aarseth scheme

Evolution of GRAPE systems



Peak (and actual) speed similar to largest supercomputers

Building cost about 1/100.

Binaries etc

Why to look at binaries?

- They do interesting things (like emitting X-rays, gravitational waves, radios, and much more)
- They do different things in clusters than in field
- Some interesting ones are MUCH MORE frequent in clusters (e.g. LMXRB)

However, they are very, very hard to deal with in N-body calculations.

Calculation cost scaling

Stable binaries are "hard"
$E < -1kT$ & $a < R/N$.
$1kT$ binary: $t_{orb} \sim t_{cr}/N$
$\rightarrow$ a single $1kT$ binary would be as expensive as the lest of the system.
A $100kT$ binary: 1,000 times more expensive.

We can do better

- very hard binaries can be regarded as point-mass particles
- Even modestly hard binaries feel perturbations from nearby stars only

Algorithms to handle binaries

Basic idea: Separate CM motion and internal orbital motion of the binary.

- Integrate CM motion with long timesteps
- Integrate the internal motion as a perturbed Kepler orbit. Calculate only the forces from nearby stars (perturbers)

In theory (Makino and Hut 1990), these treatment reduce the cost of binaries to $O(N)$, but with very large coefficient.

More numerical problems

Recipe for three-body interaction and triples

- Recognize triple system
- Move to local CM frame
- What to do then?

Something should be done for (almost) stable hierarchical triple
General stability criteria is not known (too many parameters)
On-the-fly stability judgment may be the only way.

Problem with binary physics

We want to handle binaries because they are affected by the interaction with other stars.

Pure gravitational interaction is sort of okay.
Non-gravitational interactions
  Tidal capture
  Collision/Merger
  Evolution of merger remnant

- Not too well understood
- Calculation code which combines all important "elementary processes" is still "the future" (the MODEST initiative)

MODEST

MOdelling DEnse STellar systems
or
MODifying Existing STellar codes?

First workshop: Jun 2002 (AMNH)
Second workshop: Dec 2002 (UvA)
Third workshop:Jul 2003 (Monash)
...

Current status

STARLAB/kira and NBODY4

Table-lookup for single star evolution
Fairly sophisticated binary evolution code
"Simple" treatment for tidal dissipation/merger...

Pretty advanced treatment for point-mass dynamics
Runs on GRAPE-4/6

So what can we do with present code and computer?

- Scaling studies
- Open clusters
- Young and Compact clusters
- "Realistic" GCs with "well-understood" scalings

Scaling Studies

Basic idea: If we do $N = 10^3, 10^4$ and 10^5, couldn't we extrapolate the result to understand $N = 10^6$.

Underlying assumption: In the first order, cluster evolution is driven by relaxation. (Fundamental assumption for FP/gaseous models)

Quite good for core collapse timescale.

Not very good for some others:

Evaporation timescale is not given by relaxation timescale
Coupling to binary evolution — no simple scaling.

Open Clusters

Good news: We can do real star-by-star calculations

Not-so-good news: Not too many interesting things happen

"Interesting" binaries are too hard

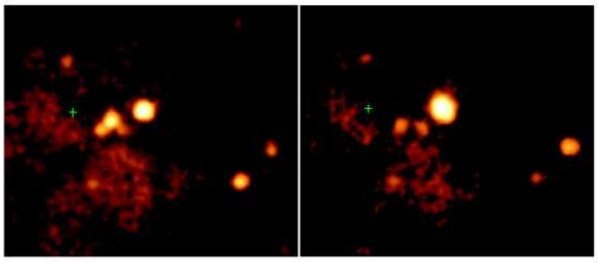
Young and compact clusters

- Arches, Quintuplet in the galactic center
- R136 in LMC
- Some of very young clusters in M82
- Age 1-10 Myrs
- $t_{cr} \sim 10^4$yrs
- $t_r \sim$10 Myrs

Doable with current hardware/software
Lots of interesting things happen
Example: Host cluster for M82 X-1

IMBH (candidate) in M82

Matsumoto *et al.* ApJL 547, L25



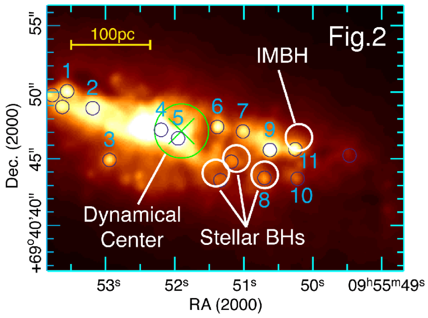
Multiple point sources with high variability.

Implication of M82 IMBH (candidate)

- First candidate BH with mass >> 10, but (most likely) << 10^6
- Eddington mass $\sim 700 M_\odot$ = First IMBH (intermediate-mass BH).
- Off-center: Some 200 pcs away from the dynamical center of M82
- Center of the expanding shell of molecular gas (Matsushita *et al.* ApJ 2000, 545, L107)

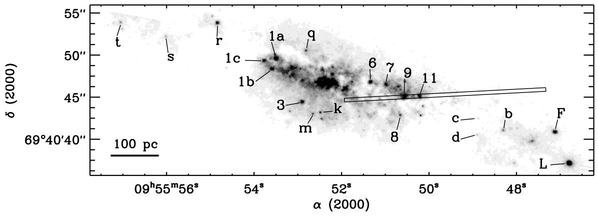
IR Counterpart (1)

SUBARU IRCS view of the center of M82 (K' band)
still unpublished...



IR Counterpart(2)

HST NICMOS/Keck NIRSPEC
McCrady et al. (astro-ph/0306373)



HST/Keck observation summary

Cluster #11 (MGG-11)

- $\sigma_r = 11.4 \pm 0.8$km/s
- half-light radius 1.2 ± 0.17pc
- kinetic mass $3.5 \pm 0.7 \times 10^5 M_\odot$
- Age $\sim$ 10Myrs.
- Low M/L

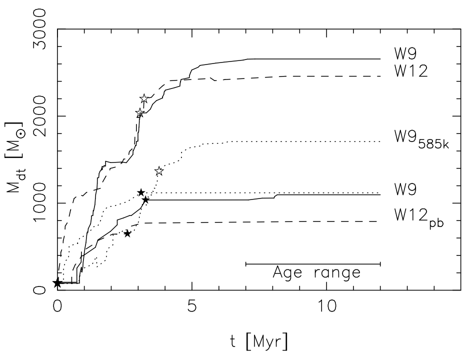
Mass segregation? Top-heavy IMF?

Simulation

Portegies Zwart et al., in preparation
Initial Condition

- King model with W_0 = 7-12
- Salpeter IMF (as suggested by McCrady et al)
- Star-by-star simulation for MGG-11 (MGG-9 is scaled)

Result

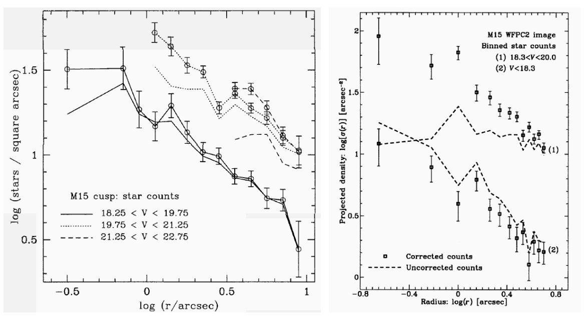


Runaway merging occurred for MGG-11, if $W_0 \geq 8$.
No runaway for MGG-9 with any W_0.

Scaled calculations for globular clusters

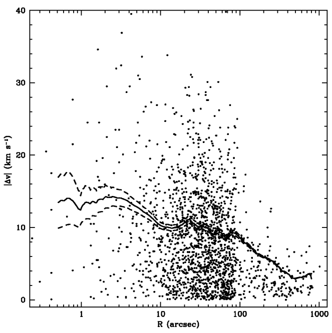
- M15
- G1
- Globular cluster with central BH

M15 Luminosity profile



Left: Sosin & King 1997, Right: Guhathakurta *et al.* 1996.

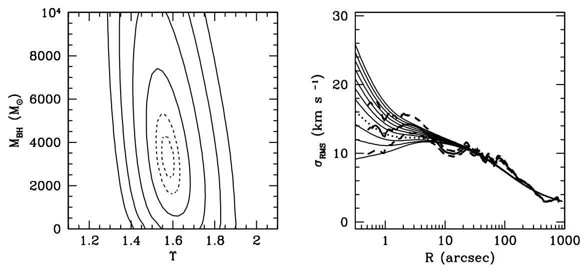
M15 Velocity dispersion



RMS velocity profile by Gerssen *et al.* (AJ 2002 124, 3270)

HST STIS, CFHT and other data combined.

Model



3000 $M_\odot$ black hole? (Gerssen et al 2002)

Why is a BH necessary?

Observed velocity dispersion is increasing inward for $r < 5''$.

Luminosity profile $\sim r^{-0.8}$, shallower than isothermal
↓
If M/L is constant, velocity dispersion should also decrease inward

Thus, there is some "missing mass" in the center, which they interpreted as central BH.

Questions:
Is M/L constant?
(Can we assume isotropic velocity dispersion?)

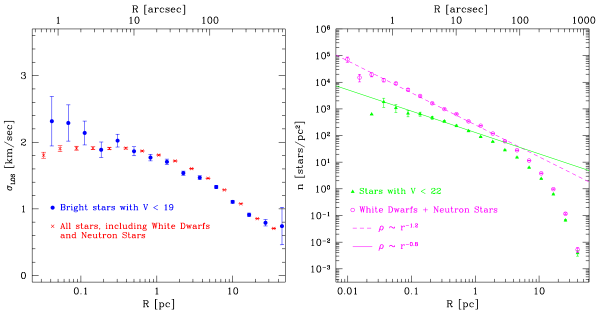
N-body simulation

Baumgardt and Makino (MNRAS 2003, 340, 227)

- N=128k (mass at core collapse = $2 \times 10^4 M_\odot$ ($\sim$1/40 of M15)
- Kroupa (2001) IMF (15 $M_\odot$ cutoff)
- Hurley *et al.* (2000) Stellar evolution
- NBODY4 on GRAPE-6
- $W_o = 7$ King model at 8.5kpc from GC
- reached core collapse at 12.6 Gyrs
- 40 days on a 4-Tflops GRAPE-6.

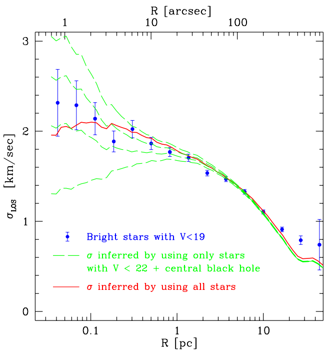
Results

Baumgardt et al., ApJ 2003, 582, L21.



Left: velocity dispersion; Right: Surface density.

We "found" BH...



Inversion of surface number density of bright stars gives too small central velocity dispersion without central BH.

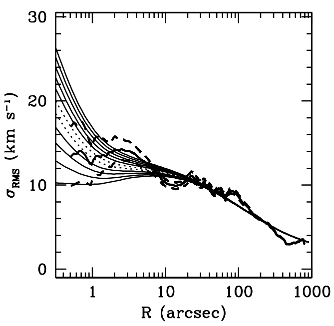
Black hole mass = $80 M_\odot$. If scaled to M15, $\sim 3 \times 10^3 M_\odot$ (Gerssen *et al.*: $\sim 3 \times 10^3 M_\odot$)

Why we "found" BH?

We "found" BH because we assumed constant M/L.

NS and massive white dwarfs dominate the center (mass segregation)
Their slope: -2.3
Slope of turnoff stars: -1.8
There is "dark mass" in the center.

"Realistic" M/L



M/L profile from multi-mass Fokker-Planck calculation by Dull *et al.* (1997)

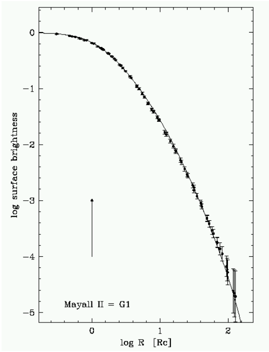
Large BH still necessary.

... There was plotting error in M/L profile of Dull et al paper... (Gerssen et al 2003)

M15 summary

- N-body simulation from "standard" initial condition can reproduce kinematic structure of the central region of M15 remarkably well.
- M15 looks like a cluster in deep core collapse, with NS and WD dominating the central cusp.
- Most likely, other GCs with central cusps are explained in similar ways.

G1 — Photometry

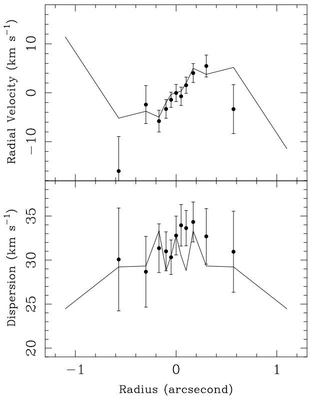


What is G1?

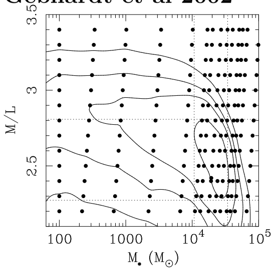
Meylan et al (2001)

- The most massive GC in Local Group
- resolved core
- Well fitted by a multi-mass King model
- Very long relaxation time ($> 40 Gyrs$)

G1 — Spectroscopy



Gebhardt et al 2002



What is G1?

Meylan et al (2001)

- The most massive GC in Local Group
- resolved core
- Well fitted by a multi-mass King model
- Very long relaxation time ($> 40 Gyrs$)

In other words,

- Looks relaxed though relaxation time is very long
- Has BH and resolved core?

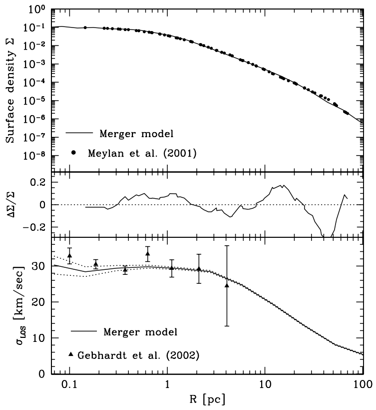
Evolutionary model of G1

Baumgardt et al. (ApJL 2003, 589, 25)

- Start from a binary globular cluster (to add rotation)
- Search for the initial model which gives good r_c and r_e (King, $\psi_0 = 6.5$)
- Compare velocity profile etc. with observation.

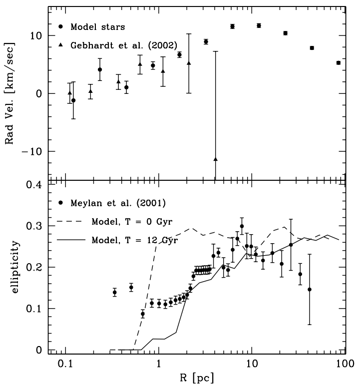
(No BH formed since runaway merging did not take place)

Result (1)



- Excellent fit for luminosity profile
- Good fit for velocity dispersion (observational error bar is large)

Result (2)



- Rotation velocity fits very well.
- Even ellipticity is good.

Summary for G1 model calculation

A pretty standard model cluster with

- large core before collapse
- r^{-4}-like halo formed by merging
- no BH

reproduces *all* available observational data.

Mass: $M_C = (8 \pm 1) \times 10^6\ M_\odot$.
roughly half of the multi-mass King fitting
No mass segregation in halo (different from multi-mass King model)

Summary for G1

- The kinematical structure of G1 can be reproduced by a simple evolutionary model, without any need for BH.
- Rotation, ellipticity and luminosity profile are consistent with a merger origin.
- M/L does not increase inward.

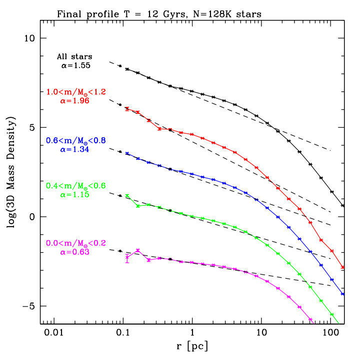
Globular cluster with central black hole.

Study of Young and Compact clusters suggests that it's not too hard to form IMBH.

How a globular cluster with massive central black hole look like? (Can theory guide observation?)

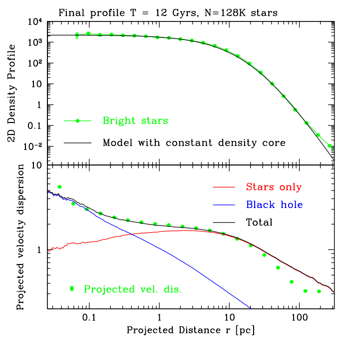
Simulation from initial model with central BH ($W_0 = 10$ King model)
Baumgardt et al, in preparation

3D density profile



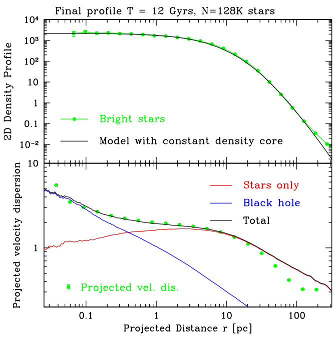
- Slope shallower for less massive stars
- Most massive: ~ -2 (not $-7/4$!)

Projection



- "Flat core"
- Subtle increase in the central velocity dispersion within the core.

Projection



- "Flat core"
- Subtle increase in the central velocity dispersion with the core.

IMBHs may hide in normal "King" clusters.

Summary

- N-body simulations have now become powerful enough to give quantitative predictions for three-dimensional structure of globular clusters (rotation and velocity anisotropy included)
- detailed direct simulation of coupling between binary evolution and cluster evolution is still a future goal, but not too far away.
- It seems likely that IMBHs are formed in Young and compact clusters through runaway merging.
- If a globular cluster harbor such an IMBH, it would look like an ordinary King cluster. Not something like a PCC cluster.