Stellar Dynamical formation scenario for IMBH and its “observational support”

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Talk Overview

1. Introduction
2. M82
    - Observation
    - Interpretation
3. M15
    - Observation
    - Modeling
    - Interpretation
4. G1
5. Summary

Introduction — Two types of BHs

Gap in the mass of “known” BHs

- Stellar mass BH $\sim 10M_\odot$
    - Type II SNe (?) NS-NS merger?
    - X-ray observations
- Supermassive BHs $> 10^6M_\odot$
    - Lies at the center of spirals/ellipticals
    - Central engine for QSO, AGN
    - Variety of observational “evidences”

Anything in between?

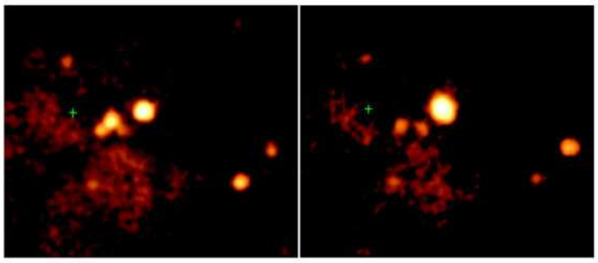
IMBH

“Finding” of Intermediate-mass blackholes

- $> 700M_\odot$ in M82?
  Matsumoto *et al.* ApJL 2001, 547, L25, Chandra
  Kaaret *et al.* MN 2001, 321, L29
- 4000 $M_\odot$ in M15?
  Gerssen *et al.* AJ 2002, 124, 3270, HST
- $2 \times 10^4M_\odot$ in G1?
  Gebhardt *et al.* ApJ 2002, 578, L41, HST

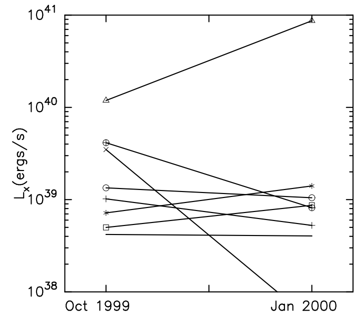
IMBH (candidate) in M82

Matsumoto *et al.* ApJL 547, L25



Multiple point sources with high variability.

Variability



The strongest source shows significant 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 (2)

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

still unpublished...

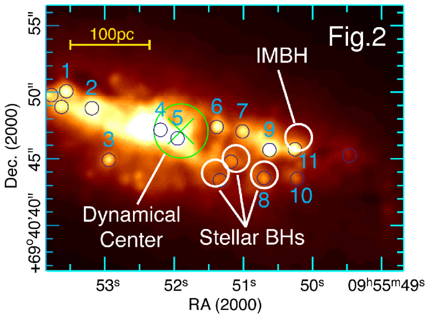


Fig.2
100pc
IMBH
1
2
3
4
5
6
7
8
9
10
11
Dynamical Center
Stellar BHs
Dec. (2000)
55"
50"
45"
+69°40'40"
53s
52s
51s
50s
09h55m49s
RA (2000)

IR Counterpart (3)

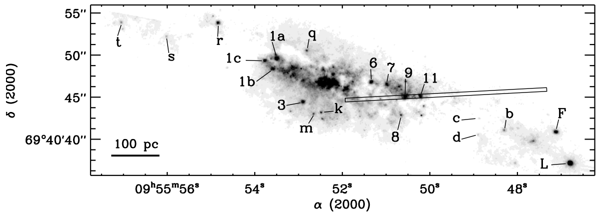
McCrady, HST NICMOS archival image...

`http://astron.berkeley.edu/~nate/pr010802.html`

IR Counterpart(3')

HST NICMOS/Keck NIRSPEC

McCrady et al. (astro-ph/0306373)


55"
50"
45"
69°40'40"
δ (2000)
100 pc
t
s
r
1a
q
1c
1b
3
m
k
6
7
9
11
8
c
d
b
F
L
09h55m56s
54s
52s
50s
48s
α (2000)

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 ~ 10Myrs.
- Low M/L

Mass segregation? Top-heavy IMF?

IMBHs in star clusters?

It seems clear that IMBHs coexist with young and compact clusters ($< 10 Myrs$), which experienced LOTS of SNe very recently ($\sim 1 Myrs$).

How were IMBHs formed?

- May have been formed at the same time when the cluster formed.
- May have been formed after the cluster formed

Possibilities

- IMBH has formed directly (or through a massive star) from gas cloud
- IMBH has formed through merging of stellar BHs/NSs

Both unlikely...

Single supermassive star

- Nobody has seen it. The largest known star is $180 M_\odot$ or so.
- Dynamical instability?

Merger of compact object

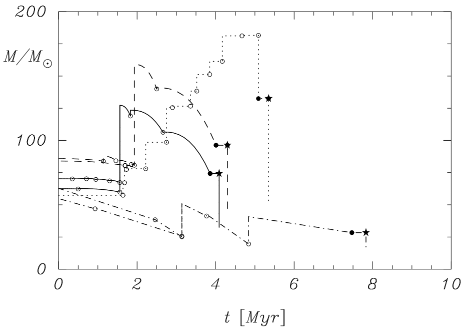
- Thermal evolution timescale too long.
- Binaries would be ejected by three-body slingshot.
- Remnants are less massive than MS stars. Will be ejected out of the core through thermal relaxation.

A possible scenario

1. A massive star forms through runaway merging of stars in the center of the cluster.
2. IMBH forms through collapse of massive star.
3. IMBH further grows by accreting other stars.

Simulation of young cluster

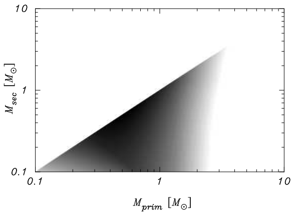
N-body simulation by Portegies Zwart et al. 1999 A&A 348,117



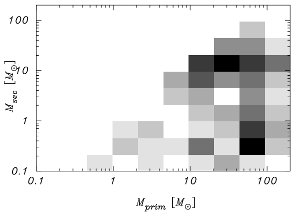
New results from simulation

- Mergings occur much more often than simple back-of-the-envelope estimate tells.
- Mergings occur primarily between most massive stars in the cluster.
- Mergings occur in the very center of the cluster.

How often is often?



Theory



Simulation result

Theoretical estimate: less than 1 collision
Numerical result: around 30 collisions

Why such a huge difference?

- Massive stars sink to the center through dynamical friction
- Massive stars form binaries by triple encounters
- Binary-single star interaction cross section is much larger than direct collision cross section
- Large fraction of resonant binary-single star interaction result in merging of two stars (Hut and Inagaki 1985)

Runaway merging

If the dynamical friction timescale of the most massive stars is short enough (less than their lifetime), runaway merging is inevitable.

The runaway star will end up as a fairly massive BH, like 100–200 $M_\odot$ or more.

Final outcome depends on main-sequence mass loss and evolution of supermassive stars itself...

BH growth after formation

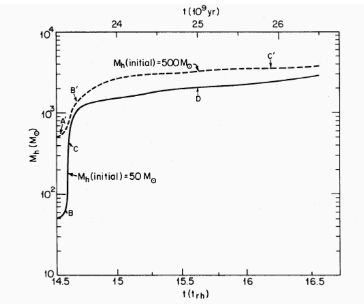


FIG. 8.—Growth of the central black hole is shown for the two cases with $e_a = 1$. M_h(initial) is the initial mass of the black hole inserted at $t = 14.5 t_{rh}$. Letters identify times highlighted in the next four figures. By $t = 16 t_{rh}$, both models have achieved black holes with mass $M_h \sim 3000\ M_\odot$, but subsequent growth is much slower.

Marchant and Shapiro 1980 ApJ 239, 685

Model cluster:
globular cluster
$N = 10^5$
1-D MC code

Underestimates the growth rate?
Eddington limit?

Why all globular clusters do not have IMBHs?

- Don't they? (M15/G1....)
- Difference in IMF?
- Difference in radius

MGG-11 has extremely short relaxation time ($\sim 100 Myr$).
Massive stars ($> 10 M_\odot$) can sink to the center before they go SNe.

Summary for IMBH theory

- Formation of IMBH through runaway merging and subsequent accretion of stars to the seed BH seems plausible.
  - Merging rate is high
  - accretion rate is also high
- This does not rule out other possibilities

At least, runaway merging *can* explain the existence of IMBH in the M82 compact cluster

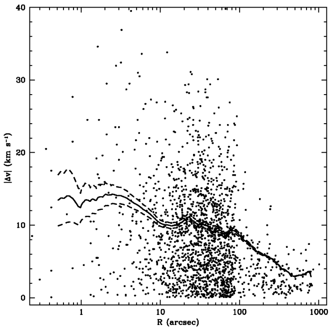
M15 — Claims

STScI Press release (Sept 18, 2002)

Van Der Marel led a team that uncovered a black hole in the center of the globular star cluster M15, 32,000 light-years away in the constellation Pegasus. His collaborator Joris Gerssen, also of the Space Telescope Science Institute, pinned down the black hole's mass at 4,000 times that of our Sun.

Previously, X-ray observations …… have identified ultra-bright X-ray sources that could also be interpreted as intermediate-mass black holes in star-forming galaxies. However, alternative interpretations for these X-ray sources continue to exist. By contrast, Hubble's measurements are based on the velocities of stars ……which yield a direct measurement of the black hole masses.

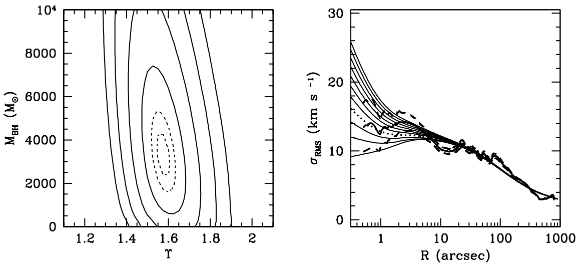
M15 — Observation



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

HST STIS, CFHT and other data combined.

Model

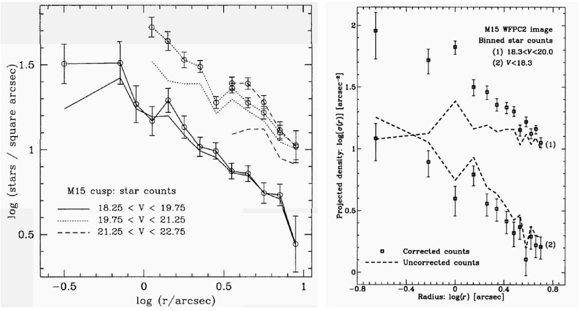


3000 $M_\odot$ black hole!

What Gerssen et al. did

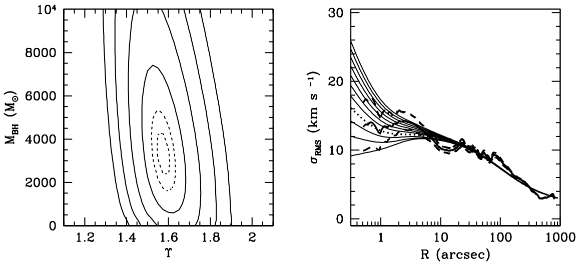
1. Calculate radial mass density profile from luminosity profile (a constant M/L γ and spherical symmetry assumed)
2. Calculate velocity dispersion profile from mass density profile.
3. Put BHs with various mass at the center and recalculate velocity dispersion profile.
4. Determine (γ, M_{BH}) which minimize χ^2, and you "found" BH.

Luminosity profile



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

Velocity dispersion with assumed central BH



3000 $M_\odot$ black hole!

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?)

Mass and Light

Globular clusters certainly do not have constant M/L

Age of GCs > thermal relaxation time
Heavy stars can sin to the center through relaxation (mass segregation)

When fully evolved, the central region will be dominated by most massive stars, with power-law density profile $\rho \sim r^{-2.23}$

Most massive stars: NS (1.4 $M_\odot$), WD
Observed stars : Red Giants(0.8 $M_\odot$)

How an evolved cluster would look like? — N-body simulation

N-body simulation

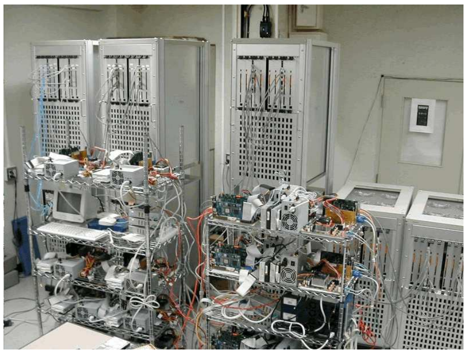
Baumgardt and Makino (MNRAS 2003, 340, 227)

- N=128k (mass at core collapse = $2 \times 10^4 M_\odot$ (~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.

GRAPE-6

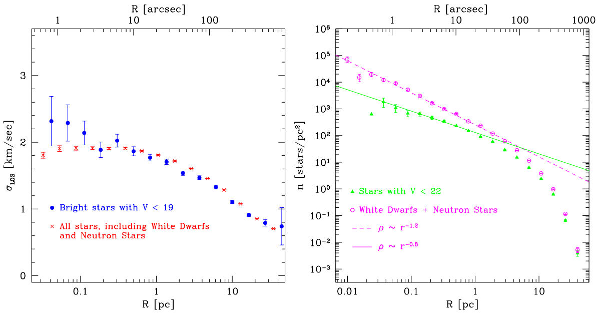
Special-purpose computer for N-body simulations.

63 Tflops peak — World's fastest computer.



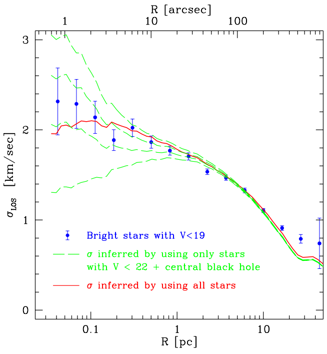
Results

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



Left: velocity dispersion; Right: Surface density.

And 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.*: $\sim 3 \times 10^3 M_\odot$)

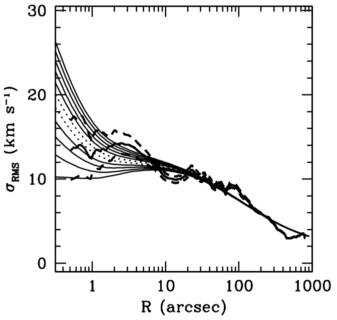
Why we “found” BH?

We “found” BH because we assumed constant M/L.

If we use the true M/L, of course we do not need BH.

But didn’t Gerssen *et al.* try realistic M/L as well?

“Realistic” M/L

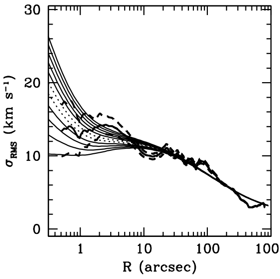


M/L profile from multi-mass Fokker-Planck calculation by Dull *et al.* (1997)

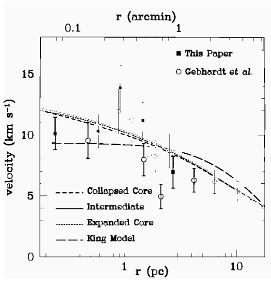
Very small change in the velocity profile. Large BH still necessary.

So why the difference?

Gerssen



Dull



Using same M/L, they got very different velocity profiles.

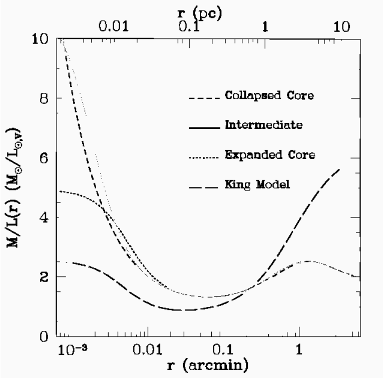
Addendum :

Gerssen et al. astro-ph/0210158 (Oct 8, 2002).

...

After the completion of our paper, the authors of the D97 paper discovered an unfortunate error in their Figures 9 and 12. The labeling along the abscissa of these figures is incorrect due to a coding error in supermongo plotting routines (H. Cohn and B. Murphy, private communication, 2002). The units along the top axis should have read ‘arcmin’ instead of ‘pc’, and the labeling in arcmin along the bottom axis is incorrect. The net result is that the radial scale of these figures in the D97 paper is too compressed by a factor 2.82.

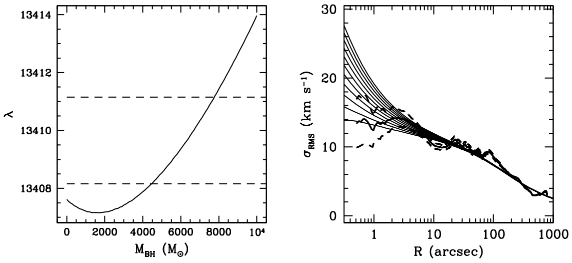
Dull M/L



should have read ‘arcmin’ instead of ‘pc’

New plot

New plot (astro-ph/0210158):

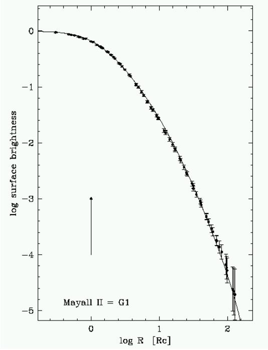


Black hole disappeared, or *“0.6 — σ detection”*.

Summary for M15

- The “finding” of IMBH in M15 was due to a simple mistake in modeling.
- In fact, an N-body simulation from a standard set of initial parameters reproduces the observed luminosity profile and velocity profile quite well, without any need for IMBH.

G1 — Photometry

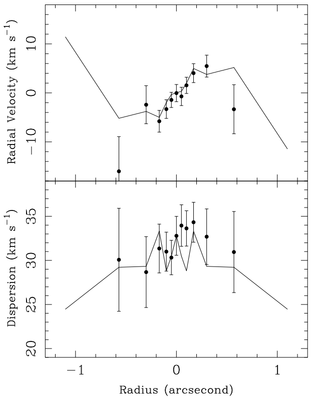


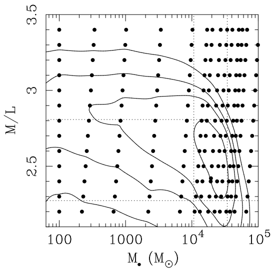
What is G1?

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





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In other words,

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

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There is something very strange....

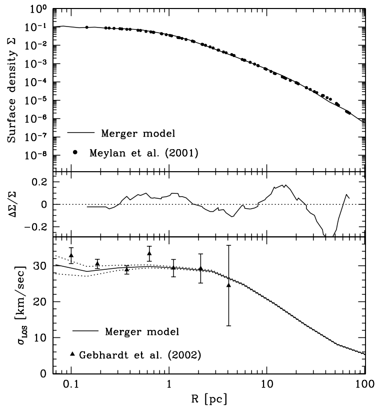
Evolutionary model of G1

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.

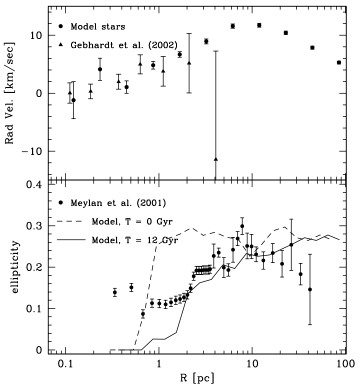
(No BH formed since runaway merging did not take place)

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

Why was BH needed for G1?

K. Gebhardt (private communication)

see also: http://www.space.com/scienceastronomy/blackhole_trick_030120.html

- velocity dispersion is consistent with No BH.
- Higher order moments suggest BH.

Radius(")	H3	dH3	H4	dH4
0.00	-0.009	0.020	-0.046	0.018
0.05	-0.035	0.019	-0.051	0.013
0.10	0.026	0.013	-0.052	0.007
0.17	-0.025	0.024	-0.039	0.019
0.30	-0.017	0.025	-0.046	0.019
0.57	0.003	0.034	-0.055	0.017
1.10	0.022	0.056	-0.034	0.063

H4 does not decrease outward — error in data reduction?

Summary for G1

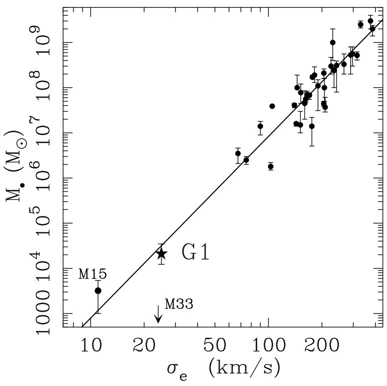
- The kinematical structure of G1 can be reproduced by a simple evolutionary model, without any need for BH.
- Rotation, ellipticity and luminosity profile are consistent with a merger origin.
- M/L does not increase inward.
- Observational "evidence" is likely to be due to some error in the data reduction to obtain the velocity distribution profile.

Are elliptical OK?

Many of “BHs” in Magorrian et al. (1998) : similar error bar as G1

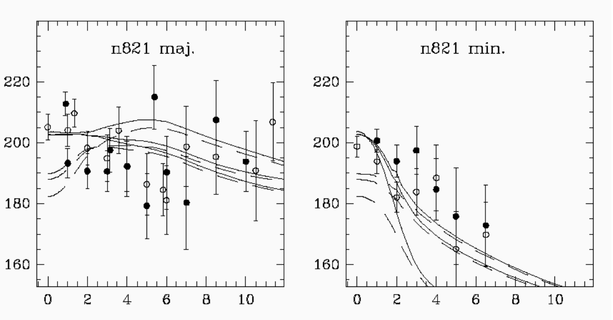
Same people analyzed the data using the same method.

???



Typical elliptical “with BH”

NGC821 (From Magorrian et al 1998)



No sign for increase in velocity.

Summary (1)

- In very young and very compact clusters, massive stars sink to the center through dynamical friction and undergo runaway merging, which would result in a supermassive star and a seed BH.
- in the high-density central region, the seed BH can grow rapidly by accreting nearby stars.
- This scenario naturally explains the observation that IMBH in M82 coincide with a very compact and young cluster, MGG-11.

Summary (2)

- IMBH in M15 was due to modeling error.
- IMBH in G1 does not seem likely either.
- In other words, there is no evidence for any IMBH in GCs...

大質量ブラックホール連星の進化

1. 何が問題か？
2. これまでの自分及び人の仕事
3. 新しい計算
4. 結果
5. 考察

何が問題か

- 楕円銀河は大抵大質量ブラックホールを中心に持つらしい(Nukers を信じるなら)
- 楕円銀河の中心部の構造(輝度分布)は、「ブラックホールがある銀河同士の合体」と矛盾しない(銀河が合体してからブラックホールが成長したと考えると密度カスプが観測より深い必要がある)

つまり、大質量ブラックホールをもつ銀河同士が合体したと考えられる。
IMBH から MBH を作るにも合体が必要。
ブラックホール2つは合体できるか？

わかっている(つもりの)こと

- BH はできた銀河の中心に沈む(力学的摩擦のため)
- で、2つが連星系になる

この辺は球状星団で重い星が中心に沈んで連星を作るのと変わらない
違い:

- ブラックホールは非常に重い = ブラックホールのランダム運動は小さい
- 周りの星の数が非常に多い = 緩和時間が長い

このため、角運動量の小さい、ブラックホールと相互作用できる星が使いつくされる可能性がある (loss cone depletion) そうなると進化が遅くなる (Begelman, Blandford and Rees 1980)

Loss cone depletion

もしもこれが起きると(周りの星との相互作用と重力波だけでは)普通の大質量ブラックホール連星は宇宙年齢の間に合体しない。
合体するかどうか

- 合体を繰り返した時にブラックホールの質量が成長できるか
- LISA で観測できるか
- 合体しないとすれば何が起こるか

本当に depletion は起きるか？

理論的に自明というわけではない

Loss cone ができたらブラックホールの周りにはなにもない
↓
ランダム速度が小さくても、真空でなくなるところまで動いていかないか？

ちょっと別の話: 離心率が大きくなればなんとかならないか？

N体計算で調べる

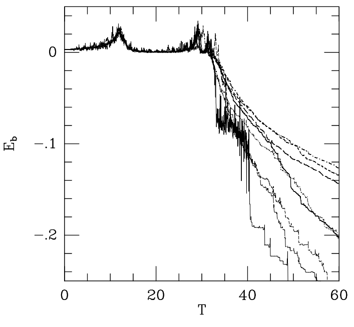
- Makino 1997
- Quinlan 1997
- Milosavljević & Merritt 2001
- Chatterjee, Hernquist & Loeb 2003

割合バラバラな結果、、、

Makino 1997

- King model ($W_o = 7$) 同士の合体
- 粒子数 2K — 256K
- $M_{BH} = M_{Gal}/32$
- GRAPE-4 での直接計算 (NBODY1)
- フィールド粒子同士は soft potential、BH が関係するものは $1/r$
- 重力波とかはなし

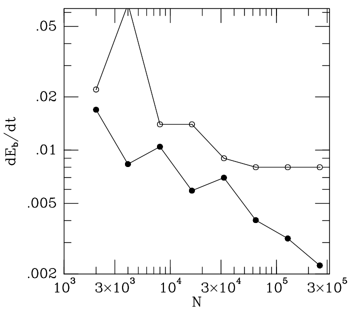
Binding energy



粒子数が大きいほうが進化が遅いのは確か

問題はどれくらい遅くなるか

エネルギーの変化率



上:　　エネルギーが 1/160 から 1/80 まで

下: エネルギーが 1/10 から 1/5 まで

最初のうちは粒子数によらない

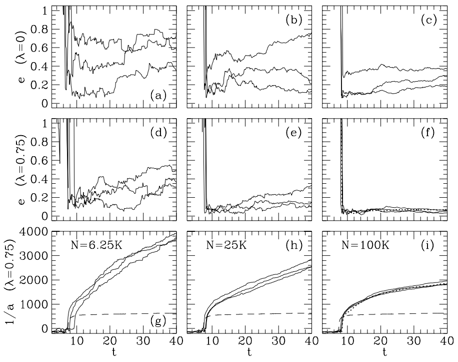
後になるとよる。傾き: $N^{-1/3}$ くらい

緩和時間の理屈に合わない

Quinlan 1997

- Plummer model 1 つでブラックホール2個置く
- 粒子数 6.25K — 200K
- $M_{BH} = M_{Gal}/100$
- SCF + direct
- フィールド粒子同士は SCF、BH が関係するものは 直接計算

結果

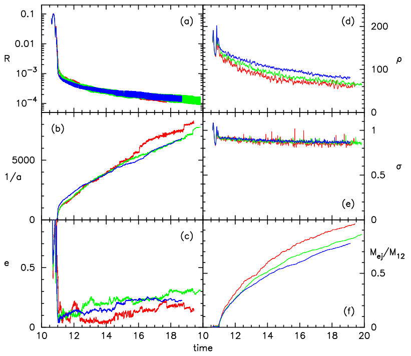


N > 100K では粒子数によらない!?

Milosavljević & Merritt 2001

- 中心まで $\rho \propto r^{-2}$ の銀河モデル作って合体させる
- 粒子数 8K — 32K
- $M_{BH} = M_{Gal}/32$
- Tree+direct
- ブラックホール連星ができる直前まで Tree、出来たら直接計算 (Sun Starfire 上の並列コード)

結果



粒子数によらない

但し、論文では「*N* が十分大きくなれば *N* によるはず」と主張 (実験的な根拠はない)

Chatterjee, Hernquist & Loeb 2003

- Quinlan 1997 と同じ方法
- 粒子数 400K まで
- M_{BH} はいろいろ

図を見ても分からないが、
$N > 200K$ で *N* に依存しなくなった
と論文には何故か書いてある

従来の結果のまとめ

なんだかよく分からない

- 人によって答が違う
- loss cone depletion の理論に合う結果は一つもない

何が悪かったか

んなことがわかってれば苦労はない

- 粒子数が足りない？
- 計算コードが怪しい？
- 初期条件の違い？

新しい計算

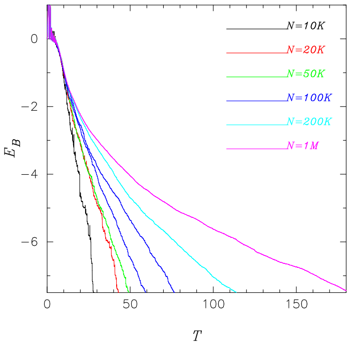
- なるべく単純な初期条件で
- なおかつできるだけ loss cone ができやすい条件で
- 信頼できる計算法で
- 大粒子、長時間計算をする

のが目標。

実際の計算

- King model ($W_o = 7$) 1 つでブラックホール2個置く
- 粒子数 2K — 1M
- $M_{BH} = M_{Gal}/100$
- 直接計算 on GRAPE-6
- フィールド粒子からの力は GRAPE-6、BH からの力ははホストで計算

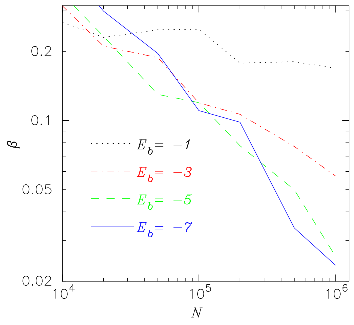
Binding energy



粒子数が大きいほうが進化が遅いのは確か

問題はどれくらい遅くなるか

エネルギーの変化率



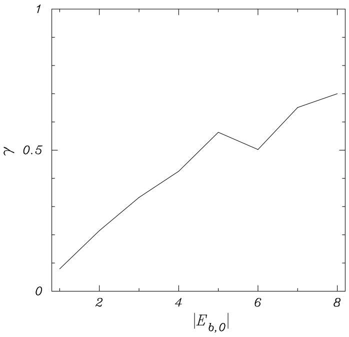
$$\beta = -\frac{dE_b}{dt}$$

最初のうちは粒子数によらない

後になるとよる。

エネルギーが大きくなるにつれて傾きが大きくなる???

傾きと結合エネルギー



エネルギーが大きくなるにつれて傾きはどんどん大きくなる。

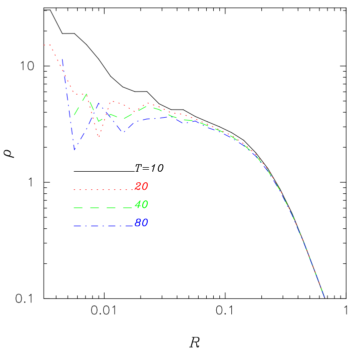
計算できた範囲では収束していない。

まあ、どうなるかといえば 1 にいかないとは言えないのではないか?

結果のまとめ

- Quinlan 1997 とほぼ同じ設定で計算した
- Makino 1997 と同じく、粒子数が大きくなるほど進化が遅くなる傾向は確認された
- 粒子数への依存性は、ブラックホール連星の結合エネルギーが大きくなるにつれて大きくなる
- Loss cone depletion と「矛盾はしてない」

loss cone はみえるか？ — 密度分布

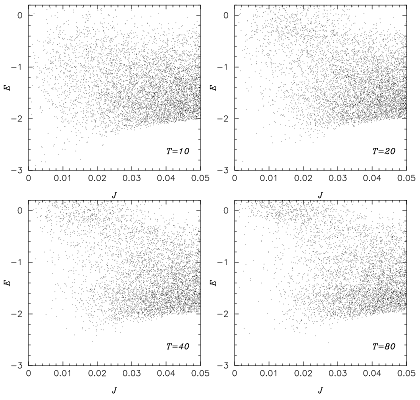


最初あった密度カスプが消えてはいる。

ブラックホールの近くで密度がさがってはいない

はて？

loss cone はみえるか？ — (E, J) 空間



$J < 0.01$ のところから粒子がなくなっている

J が小さくてエネルギー 0 に近いところには粒子がたまる

明らかに loss cone はできている。

従来の計算の問題は何だったか？

- Makino 1997
  - シミュレーション時間が短かかった
- Milosavljević & Merritt 2001
  - 粒子数もシミュレーション時間も足りなかった
- SCF+BH の計算
  - よく分からない、、、

まとめ

銀河中心での大質量ブラックホール連星の、周りの星との重力相互作用による軌道進化を、従来の計算より信頼できる計算コードで、大粒子で長時間積分した。
その結果

- まともな計算コードで
- 十分大きな粒子まで、十分長時間

計算すれば loss cone depletion は起きるということがわかった。
つまり:

大質量ブラックホール連星は星との相互作用だけでは重力波が効くところまで軌道が縮まない。

モデルの作り方 — Jeans equation

球状星団の星の分布関数は力学平衡、つまり無衝突ボルツマン方程式

$$\frac{\partial f}{\partial t} + \mathrm{v}\cdot\nabla f - \nabla\Phi\cdot\frac{\partial f}{\partial \mathrm{v}} = 0, \qquad (1)$$

の定常解になっている。で、これに対して星団が球対称で、平均の流れがない(どこで積分しても平均速度は 0)と仮定すると

$$\frac{d(\nu\overline{v_r^2})}{dr} + \frac{\nu}{r}\left[2\overline{v_r^2} - \left(\overline{v_\theta^2} + \overline{v_\phi^2}\right)\right] = -\nu\frac{d\Phi}{dr} \qquad (2)$$

但し、$\nu = \int f d^3\mathrm{v}$ (空間密度)

Jeans equation (等方)

速度分布が等方的とすれば、結局

$$\frac{1}{\nu}\frac{d(\nu\overline{v_r^2})}{dr} = -\frac{d\Phi}{dr} \qquad (3)$$

すなわち

$$M(r) = -\frac{r\overline{v_r^2}}{G}\left(\frac{d\ln\nu}{d\ln r} + \frac{d\ln\overline{v_r^2}}{d\ln r}\right) \qquad (4)$$

これは、ポテンシャルを作るものの質量密度と、そのなかで動いているものの密度、速度の間の関係を与える。

観測の解釈

いいかえると、Jeans 方程式を使うと

- (見えないものも含めた)質量分布
- (見えるものの)密度分布
- (見えるものの)速度分布

のうち2つがわかればもうひとつがわかる。