Dry minor mergers and size evolution of early-type galaxies In high density environments

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Abstract

- To study size evolution of early-type galaxies, we simulate dry major and minor mergers between early-type galaxies with N-body simulations.
- In minor merger simulations, we perform continuous mergers and synchronized mergers. Furthermore we assume compact, less massive galaxies and diffuse, less massive ones as satellite galaxies.
- We compare the remnant properties : size, density and velocity dispersion.
- We derive efficiencies of size growth and of velocity dispersion decrease of ETGs from a set of simulations.
- Our results indicate that minor mergers, in particular continuous ones are very efficient way to size evolution of ETGs.

Background

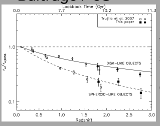
1. Importance of size of ETGs in the formation history

- Two major formation models of early-type galaxies(ETGs)
  - Monolithic collapse scenario
    - Intense starburst + passive evolution
    - agrees with SED of ETGs.
    - naturally explains old stellar population of ETGs.
  - Merger scenario
    - agrees with bottom up structure formation scenario in ΛCDM cosmology.
    - can produce photometric, kinematic properties of ETGs using N-body simulation
- One important clue is the size of high-z counterparts.
  - In pure monolithic formation, the size are unchanged.
  - If their size change with z, the evolution mechanism need to keep their old stellar population.

NGC 5128 (CFHT)

2. Evidence of size evolution of ETGs

Buitrago+ 08

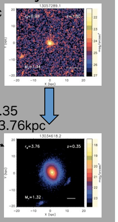


They compares the similar stellar mass ($\sim 1.3 \times 10^{11}$ M_{sun}) galaxies in various redshift.

Trujillo+ 07

z=1.8
R_e=0.98kpc

z=0.35
R_e=3.76kpc



High-z counterparts are in general very compact compared with local ETGs.

Local stellar mass-size relation by SDSS (Shen+2003)

$$R_e = 4.16\left(\frac{M_*}{10^{11} M_{sun}}\right)^{0.56} kpc$$

- These results indicate that for early-type galaxies, star formation history and mass assembly history are different.
- Size evolution is driven by dissipationless (no triggered star formation, no dissipation), dry mergers?

N-body simulations

Model galaxies

Two-component (stellar system + dark matter halo) Hernquist model

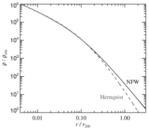
Hernquist profile: $$\rho(r) = \frac{M_* a}{2\pi r (r+a)^3}, \quad \Phi(r) = -\frac{GM_*}{r+a}$$

•Stellar system
We assume compact massive ETGs as the main galaxy.
Effective radius : 1kpc, stellar mass : 10^{11} M_{sun}

•Dark Matter(DM) halo
We associate the Hernquist profile with a corresponding NFW halo with the same dark matter mass within r_{vir} at z=2.

•The scale radius is

$$a = \frac{r_{vir}}{c}\sqrt{2\left[\ln(1+c) - c/1+c\right]}$$



Compact massive ETGs

Main galaxy: M1	Dark matter halo	Stellar bulge
mass	10^{12} M_{sun}	10^{11} M_{sun}
Scale radius	31.2 kpc	0.551 kpc
Virial radius	105 kpc	-
Effective radius	-	1 kpc

Compact less massive ETGs

satellite galaxy: S1	Dark matter halo	Stellar bulge
mass	10^{11} M_{sun}	10^{10} M_{sun}
Scale radius	12.0 kpc	0.256 kpc
Virial radius	48.8 kpc	-
Effective radius	-	0.464 kpc

diffuse less massive ETGs

satellite galaxy: S2	Dark matter halo	Stellar bulge
mass	10^{11} M_{sun}	10^{10} M_{sun}
Scale radius	13.3 kpc	0.631 kpc
Virial radius	120 kpc	-
Effective radius	-	1.15 kpc

Initial conditions

- Assumption of spherical and isotropic structure
- We reproduce particle position & velocity consistently from the density profile and the distribution function.
- We use analytical phase-space distribution function in Ciotti 1996 to make a two component Hernquist profile.

Distribution function of each component:

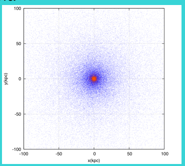
$$f_i(E) = \frac{1}{8\pi^2}\int_0^E \frac{d^2\rho_i}{d\Psi_{tot}} \frac{d\Psi_{tot}}{\sqrt{E-\Psi_{tot}}}$$

Due to the assumption of isotropic, $Q = E - \frac{L^2}{2r_a^2} = E$

$$\tilde{Q} = q\left(1 + \frac{\mu}{1+bq}\right), \quad 0 \le q \le 1$$

q : non dimensional potential of reference component

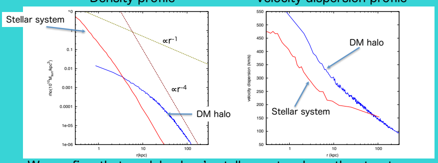
$$\therefore f(Q) = \frac{f_N}{\sqrt{8}\pi^2}\left(\frac{d\tilde{Q}}{dl}\right)^{-1} \times \frac{d}{dl}\left[\tilde{F}_i^{\pm}(l)\right], \quad l^2 \equiv 1 + bq$$



Initial state (~1Gyr after)

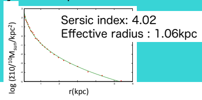
Density profile

Velocity dispersion profile



We confirm that model galaxy's stellar system keep the structure on the range, >=0.2kpc in ~3Gyr.

Surface density profile



simulation code & parameters

- ➢Simulation code : GADGET-2 (Springel 2005) – parallel tree, N-body simulation code
- ➢Number of particle, softening length

	DM particle	Star particle	Softening
Galaxy M1	10^5	10^4	0.05 kpc
Galaxy S1	10^4	10^3	0.05 kpc
Galaxy S2	10^4	10^3	0.05 kpc

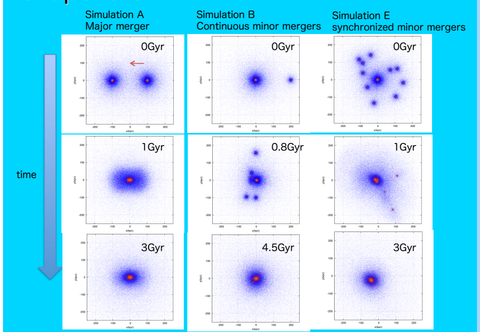
Dry major/minor merger simulation: Run A-E

	merger	Main galaxy	Satellite galaxy	
Simulation A	Major	M1	M1	
B	Continuous 10 minor	M1	S1	accretion every 0.2 Gyr
C	Continuous 10 minor	M1	S2	accretion every 0.2 Gyr
D	Synchronized 10 minor	M1	S1	accretion all together
E	Synchronized 10 minor	M1	S1	accretion all together

- ➢We assume that merger orbits are radial in all merger.
- ➢Relative velocity : ~200km/s (parabolic orbit)
- ➢Initial separation : 200kpc

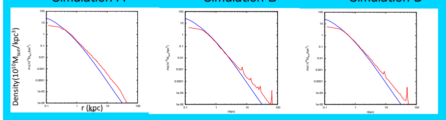
Results

Snapshots



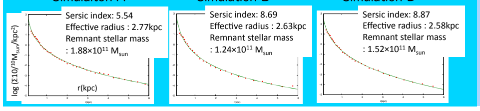
Density profile of remnant stellar system

Simulation A　　Simulation B　　Simulation D



Surface density profile : Sersic profile fitting

Simulaiton A　　Simulation B　　Simulation D



Simulaiton A: Sersic index: 5.54
Effective radius : 2.77kpc
Remnant stellar mass : 1.88×10^{11} M_{sun}

Simulation B: Sersic index: 8.69
Effective radius : 2.63kpc
Remnant stellar mass : 1.24×10^{11} M_{sun}

Simulation D: Sersic index: 8.87
Effective radius : 2.58kpc
Remnant stellar mass : 1.52×10^{11} M_{sun}

Analysis

Effective radius, Sersic index

Sersic profile $$I_m(R) = I_e \exp\left\{-b_m\left[\left(\frac{R}{R_e}\right)^{1/m} - 1\right]\right\}$$

- ➢Fitting remnant bulge's projected profile to a Sersic profile on the range [0.2,~10] kpc.
- ➢Calculating the properties for 3 angles, and averaging

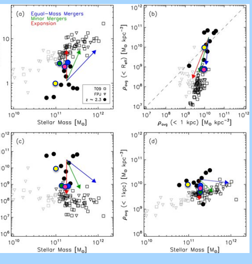
Surface density weighted velocity dispersion

$$\sigma_e^2 \equiv \frac{\int_{2\varepsilon}^{R_e} \sigma_{los}^2(R) I(R) R dR}{\int_{2\varepsilon}^{R_e} I(R) R dR}$$

Comparison of the results with observations (Bezanson+ 2009)

Observation
- ➢Black: high-z ETGs
- ➢White: local ETGs

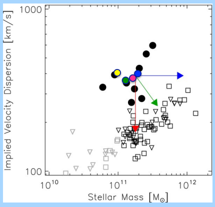
Simulation results
- ➢Yellow: Initial
- ➢Blue: simulation A
- ➢Green: simulation B
- ➢Pink: simulation D



Logarithmic slopes

$$R_e \propto M_*^{\alpha}, \quad \sigma \propto M_*^{\beta}$$

	α	β
Simulation A	1.51	-0.05
B	4.18	-0.84
C	3.70	-0.61
D	2.10	-0.21
E	2.57	-0.12



Summary of results

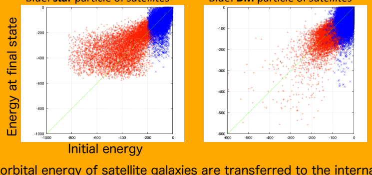
$$I_m(R) = I_e \exp\left\{-b_m\left[\left(\frac{R}{R_e}\right)^{1/m} - 1\right]\right\} \qquad \sigma_e^2 \equiv \frac{\int_{2\varepsilon}^{R_e} \sigma_{los}^2(R) I(R) R dR}{\int_{2\varepsilon}^{R_e} I(R) R dR}$$

	Stellar mass (M_{sun})	R_vir (kpc)	$r_{*,half}$ (kpc)	R_e (kpc)	ρ(<1kpc) (10^{10} M_{sun} kpc^{-3})	ρ(<R_e) (10^{10} M_{sun} kpc^{-3})	σ_e (km/s)
Initial	1.0×10^{11}	105kpc	1.42	1.07	0.993	0.856	237
A	1.88×10^{11}	388kpc	3.76	2.77	0.903	0.0934	229
B	1.24×10^{11}	396kpc	3.61	2.63	0.710	0.0990	198
C	1.28×10^{11}	495kpc	3.60	2.67	0.791	0.119	204
D	1.52×10^{11}	365kpc	3.42	2.58	0.825	0.0921	217
E	1.59×10^{11}	420kpc	4.84	3.52	0.918	0.0398	224

Change of energies of DM, star particles

•Red: **star** particle of *main* galaxy
•Blue: **star** particle of *satellites*

•Red: **DM** particle of *main* galaxy
•Blue: **DM** particle of *satellites*



- ➢The orbital energy of satellite galaxies are transferred to the internal energy of main galaxy.
- ➢Star particles of main galaxy gain internal energy by minor mergers.

Summary

1. We derive efficiencies of size growth and of velocity dispersion decrease of ETGs by dry major/minor mergers.
2. Minor mergers cause more efficient size growth and velocity dispersion decrease than major mergers.
3. In particular, continuous minor mergers cause more efficient size growth and velocity dispersion decrease than synchronized minor mergers.
4. We show that continuous minor mergers that are cosmologically expected are important process to explain observed size evolution of ETGs.

Future work

1. In future work, we will study the size evolution through realistic simulation using cosmological simulation in high density environment.