Two Phase Formation of Massive Galaxies

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Focus: High Resolution Cosmological Zoom Simulation of Massive Galaxies

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But first, what have we learned from 50 years of observations?

- Giant elliptical galaxies form early and grow in size and mass without much late star-formation.
- Major mergers are real but rare at late times (or else disk galaxies would have been destroyed).
- Dark matter does not dominate the inner parts of elliptical galaxies.
- Half of all metals are ejected from massive systems (*cf* winds and cluster metals).
Start: WMAP Spectrum of Cosmic Perturbations

- $\Omega_{\text{tot}} = 1, \ [1.010 \pm 0.016]$
- $\Omega_{\text{cdm}} = 0.22 \pm 0.02$
- $\Omega_{\text{baryon}} = 0.044 \pm 0.002$
- $\Omega_{\text{lambda}} = 0.73 \pm 0.03$
- $n = 0.962 \pm 0.015$
- $H_0 = 71.5 \pm 1.5 \text{km/s/Mpc}$
- $\sigma_8 = 0.80 \pm 0.01$
- $\tau_{\text{scat}} = 0.086 \pm 0.002$

(WMAP 2008)
fast forward to structure growth computed in dark matter component ->
Second Step: hydrodynamic “Zoom Method”.

- Select region of interest.
- Put down finer grid.
- Add hydrodynamic equations.
- Add atomic physics: adiabatic, + cooling, + heating, + non-equilibrium ionization.
- Radiative transfer: global average, + shielding of sinks, + distribution of sources.
- Heuristic treatment of star-formation.
- Repeat calculation using tidal forces from larger region and do details of smaller region.
What have we learned?

- The onset of massive galaxy formation is early and follows re-ionization at $z = 6$.

*High sigma peaks rapidly form stars from merging streams to initiate formation of cores of most galaxies. Disks and massive envelopes are formed later.*
## Overall Picture of Two-Phase Growth

<table>
<thead>
<tr>
<th>Phase</th>
<th>In situ star formation</th>
<th>Accretion of stars</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Epoch</strong></td>
<td>6 &gt; z &gt; 2</td>
<td>3 &gt; z &gt; 0</td>
</tr>
<tr>
<td><strong>Baryonic mass source</strong></td>
<td>Cold gas inflows</td>
<td>Minor and major mergers</td>
</tr>
<tr>
<td><strong>Size of region</strong></td>
<td>&lt; ~ 1 kpc</td>
<td>~ 10 kpc</td>
</tr>
<tr>
<td><strong>Stellar metallicity</strong></td>
<td>Super-solar</td>
<td>Sub-solar</td>
</tr>
<tr>
<td><strong>Energetics</strong></td>
<td><strong>Dissipational</strong></td>
<td><strong>Conservative</strong></td>
</tr>
</tbody>
</table>
What is the observational* evidence (M. Kriek; ‘09)

\[ z \sim 2.5 \]

*Chart color represents specific star formation rate: high rate = blue.
Convergence to low and to a flat rotation curve at high resolution:

**Fig. 1.**—Circular velocity curves for galaxy A at four different numerical resolutions: $40^3$, $50^3$, $100^3$, and $200^3$ SPH particles and collisionless dark matter particles, respectively. Note how the rotation curves become increasingly flat as the resolution increases.
In Situ Star Formation

Convergence to stellar system formed very early which quickly becomes “red and dead”.

Fig. 2.— Star formation rate (SFR) histories, computed from stellar ages, of galaxy A versus lookback time at four different numerical resolutions: $40^3$, $50^3$, $100^3$, and $200^3$ SPH particles and collisionless dark matter particles, respectively. There is a strong trend that the low redshift star formation rate is reduced in higher resolution simulations.
Questions

• 1) Convergence: how do results change with resolution improvement; and why was high resolution needed?
• 2) Why does gas temperature increase though cooling time is short and no feedback was included?
• 3) Why is there a dramatic evolution of size?
• 4) Why is galaxy “red and dead” early but continues to grow in luminosity?

**ANSWER: TWO PHASE GROWTH WITH LARGE GRAVITATIONAL HEATING IN THE SECOND PHASE.**
Gas, at all radii, becomes hotter with time despite fact that the “cooling time” < the Hubble time! Why?

Fig. 3.— Time evolution of the gas temperature profile from $z = 5$ to $z = 0$ (from bottom to top) for halo A ($200^3$ resolution). The average temperature of the gas is steadily increasing. At the end of its initial formation phase at $z \approx 2$ the galaxy is surrounded by a halo of hot gas heated to the virial temperature.
2) Physics - why does gas not cool?

- Gas is steadily being heated by in-falling new gas ( -PdV and Tds).
- “Dynamical Friction” due to in-falling stellar lumps is very important for evolution of the stellar and DM components.
- Of course “feedback” from central black holes and from supernovae also exists and must be complementary to effects listed above (and this is now being added to the codes – thesis projects).
Dark Matter Evolution - density declines in second phase
Binding Energy ~ $10^{60}$ erg from both in-situ and accreted stars:
- In-situ energy is radiated,
- Accreted energy heats gas and pushes out DM
$(B-E)/s \approx 10^{42.5}$ erg/s from both in-situ and accreted stars:

- In-situ energy is radiated,
- Accreted energy heats gas and pushes out DM.
Astronomy

- Two phase growth. First, in-situ star-formation from in-falling cold gas, and then accretion of stellar lumps.
- DM initially increases in density (adiabatic contraction) and then decreases (dynamical friction).
- Metal rich component in center from in-situ star-formation and metal poor component in outskirts due to stellar in-fall of old and small systems.
- Stellar system grows in size with time and central velocity dispersion actually declines with time.
Size evolution - substantial growth (observed and computed); what is the cause?
First attempt at showing data from a set of $100^3$ simulations (L.Oser, Naab...)

Where & when are stellar particles made?
Assembly of galaxies:
Stellar material from minor mergers is made at early times and added at late times.
More Massive Systems are Older

**Fig. 12.** Mean age of the stars inside $r_{10}$ as function of galaxy mass. High mass galaxies consist of older stars than the low mass galaxies, recovering the phenomenon usually referred to as 'archaeological downsizing' ($t_{\text{mean}} \propto \log M_{\ast}^{1.6}$).
Fit to observations is good
Galaxy Size vs Mass

The graph shows the relationship between galaxy size, measured as $R_{1/2}$ in kpc $h^{-1}$, and galaxy mass, measured as $\log M_\ast [M_\odot h^{-1}]$, for accreted, total, and insitu galaxies.
What have we learned? Old news.

• For massive systems the 1977 work of Binney, Silk and Rees & Ostriker appears to be correct:

Cooling time of gas becomes longer than the dynamical time and star formation ceases. Systems live in hot bubbles and then grow by accretion of smaller stellar systems.
3) Why is there a dramatic evolution of size?
4) Why is galaxy “red and dead” early but continues to grow in luminosity?

• Evolution of size is apparent, not real. Both components keep roughly constant in size, but mean size grows as accreted material dominates.

• During the second phase, the luminosity and stellar mass may double but very few stars are formed.
Simplest Physical Modeling - via Virial Theorem

• Make initial, stellar system dissipatively from cold gas with gr radius $R_i$, Mass $M_i$, velocity dispersion $<V_i^2>$ & energy $E_i$:
  
  \[- E_i = -0.5 \frac{G M_i^2}{R_i} = -0.5 M_i <V_i^2>\]

• Add stellar systems conserving energy with total Mass $M_A = \eta M_i$, velocity dispersion $<V_A^2> = \epsilon <V_i^2>$ & energy $E_A$:
  
  \[- E_A = -0.5 M_i <V_i^2> \eta \epsilon\]
To make combined stellar system with grav radius $R_F$, Mass $M_F = M_I(1 + \eta)$, velocity dispersion $< V_F^2 >$ & energy $E_F$:
- $E_F = -0.5 \, G \, M_F^2 / R_F = -0.5 \, M_I < V_F^2 > (1 + \eta)$

Then, equating total initial and final states
- $E_F = E_I + E_A$, gives for the ratios of the in-situ to the ultimate state as follows:

- $<(V_F^2)/ (V_I^2)> = [ (1 + \eta \varepsilon) / (1 + \eta) ]$
- $(R_F / R_I) = [ (1 + \eta)^2 / (1 + \varepsilon \eta) ]$
- $(\Sigma_F / \Sigma_I) = [ (1 + \eta \varepsilon)^2 / (1 + \eta)^3 ]$
“major mergers”

\[ \varepsilon = 1 \]

formulae reduce to the classic result,

**BUT**

If minor then

\[ \varepsilon \ll 1, \]

velocity dispersion declines, the surface density declining dramatically, as in the numerical simulations.
Conclusions: High Mass Systems

• High resolution SPH simulations without feedback produce normal, massive but small elliptical galaxies at early epochs from in-situ stars made from cold gas.
• Accreted smaller systems add, over long times, a lower metallicity stellar envelope of debris (obvious test exists).
• The physical basis for the cutoff of star-formation is gravitational energy release of in-falling matter acting through \(-PdV\) and \(+Tds\) energy input to the gas.
• This simple two phase process explains the decline in velocity dispersion and surface brightness at later times.
• Feedback from SN and AGN are real phenomena - but secondary and mainly important for clearing out gas at late times and reducing stellar mass as compared to the simulations.
Primary cause of mass growth

- Early times and low mass galaxies:  
  - *Gas inflows.*

- Late times and high mass galaxies:  
  - *Accretion of satellites.*
To Be Done

• Do many more cases at high resolution; and repeat with different (eg AMR w R. Joung) codes. √

• Check two population GC predictions (w C. Conroy). √

• Look at X-ray properties. ☐

• Improve gas cooling and radiative transfer. ☐

• Repeat with SNI&II and AGN feedback. ☐

• Add recycled gas. ☐

(and make more mpgs!)