Formation and evolution of galactic structures: Nature versus nurture

Input from theory and simulations

E. Athanassoula
LAM/OAMP
Marseille
– Incomplete

– Reflect the opinion of the reviewer.

– Only few cases are clear-cut. \( P_{\text{nature}}/P_{\text{nurture}} \)

– \( P = P(z) \)

– Destruction of structures
<table>
<thead>
<tr>
<th>Disc Galaxies</th>
<th>Ellipticals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disc</td>
<td>Shells and ripples</td>
</tr>
<tr>
<td>Bulge</td>
<td>Dust lanes with peculiar kinematics</td>
</tr>
<tr>
<td>Bar</td>
<td></td>
</tr>
<tr>
<td>Spiral</td>
<td></td>
</tr>
<tr>
<td>Warps</td>
<td></td>
</tr>
<tr>
<td>Bridges and tails</td>
<td></td>
</tr>
<tr>
<td>Thick discs</td>
<td></td>
</tr>
<tr>
<td>Rings</td>
<td></td>
</tr>
</tbody>
</table>
Disc : Nature

Heller, Shlosman and Athanassoula 2007

Fall & Efstathiou 80; Gunn 82, Dekel et al 03, 06, 08; Keres 05, 2008; Brooks 08; Agertz 09
Disc: Nature
Disc: Nurture

\[ \text{Disc} + \text{Disc} = \text{Elliptical} \]

Toomre & Toomre 72; Barnes & Hernquist 92; Barnes 98; Naab & Burkhart 03; Naab, Khochfar, Bukhart 06 etc

but also

\[ \text{Disc} + \text{Disc} = \text{Disc} \]

Observational starting point: Hammer et al 05, 09

Simulations: Dominguez-Tenreira et al. 98; Barnes 02; Scannapieco, Tissera 03; Brook et al 04, 07; Springel & Hernquist 05; Robertson et al 06,08, Hopkins et 08; Governato et al 07, 08; Stewart et al 09
Equal mass progenitors

No bulge

Springel and Hernquist 2005
Springel and Hernquist 2005
1:2 mass ratio merger with 20% gas

Hopkins et al 2008
1:6 mass ratio merger with 15% gas

Hopkins et al 2008
1:1 mass ratio merger with 20% gas

Hopkins et al 2008
Bulge definitions

Definition 1

From morphology:
A smooth light distribution that swells out of the central part of a disc viewed edge-on

Definition 2

From photometric profiles:
The bulge is identified as the extra light in the central part of the disc, above the extrapolated exponential fitting the remaining (non-central) part.

Definition 3

From kinematics:
From the V/sigma plot
Bulges
Bulge definitions

Photometric definition

Kinematic definition

Binney 78, 05
Types of bulges (1)

Three different types of bulges - distinguished via their formation histories (Athanassoula 2005)

1) Classical Bulges
Formed by gravitational collapse, or hierarchical merging and corresponding dissipative processes. Occurs early on in the formation process and is sometimes externally driven.


2) Box/peanut bulges
They are parts of bars seen edge-on

3) Discy-bulges
Inflow of gas to the central regions and subsequent star formation
Formation from clumps in the proto-disc

Noguchi (1998, 1999)
Immeli et al (2004a,b)
Bournaud et al 2008, 2009
Classical bulge formation: companion infall

Pfenniger 91, Athanassoula 1999, Aguerri et al. 01, Fu et al. 03, Eliche-Moralet al. 06
Types of bulges (2)

Three different types of bulges - distinguished via their formation histories (Athanassoula 2005)

1) Classical Bulges

2) Box/peanut bulges
   They are parts of bars seen edge-on.

   N-body simulations: Combes & Sanders 81; Combes et al 90; Raha et al 91; Athanassoula & Misiriotis 02; Athanassoula 03, 05; O'Neil & Dubinski 03;

   Orbital structure: Pfenniger 84; Skokos, Patsis & Athanassoula 02a, b; Patsis, Skokos & Athanassoula 02, 03,; Martinez-Valpuesta et al 04, 06
Orbits (schematic)

Face-on

Edge-on

At an angle
N-body simulations

A bar seen:

Face-on

Edge-on and side-on

Edge-on and end-on
Types of bulges (3)

Three different types of bulges - distinguished via their formation histories (Athanassoula 2005)

1) Classical Bulges

2) Box/peanut bulges
   They are parts of bars seen edge-on

3) Discy-bulges
   Inflow of gas to the central regions and subsequent star formation.
   By bars and/or by interactions

Kormendy 1993; Kormendy & Kennicutt 2004

Regan & Teuben 2004
Discy bulges

Gas inflow: bars or interactions/mergings
Sersic index = 1
in general Sersic Index < 2

Face-on, it often has an oval shape or includes a bar (inner bar)

Athanassoula 2008
Summary (bulge types)

Three different types of bulges - distinguished via their formation histories (Athanassoula 2005)

1) Classical Bulges  
Both nature and nurture.

2) Box/peanut bulges  
They are parts of bars seen edge-on  
Nature

3) Discy-bulges  
Inflow of gas to the central regions and subsequent star formation  
Both nature and nurture

But beware: More than one type of bulge can co-exist in the galaxy
Bars

Bar formation

Evolution driven by angular momentum exchange within the galaxy

Bars strength is proportional to the amount of angular momentum it lost

The angular momentum emitted by near-resonant material in the bar region is absorbed by near-resonant material in the outer disc and in the halo

Nature, although interactions may change the properties of the bar since the companion can participate in the angular momentum exchange
Time evolution
Face-on view
Spirals

Companion-driven spirals
Spirals

Swing amplified spirals

Both for grand design and flocculent spirals
Observations?  

Toomre 81
Spirals in barred galaxies

Romero-Gomez et al. 06, 07; Athanassoula et al. 09
Rings
Rings: Ring galaxies

Rings: Ring galaxies

Villa-Vargas & Athanassoula, unpubl.
Rings: Polar rings

Sparke 86; Arnaboldi & Sparke 94; Dubinski & Christodoulou 94; Bekki 97, 98; Tremain & Yu 00; Bournaud & Combes 03; Macio et al. 06
Warps

Disc only: only if outer disc truncation is unrealistically sharp (Hunter & Toomre 69)

Effect of the halo (flattened, misaligned) (Toomre 83; Dekel & Shlosman 83; Sparke & Casertano 88; Kuijken 91; Ideta et al 00; Nelson & Tremaine 95; Dubinski & Kuijken 95; Binney et al 98; Debattista & Sellwood 99)

– Cosmic infall (Ostriker & Binney 89; Binney 91; Quinn & Binney 92; Jiang & Binney 99; Lopez-Corredoira et al. 02; Shen & Sellwood 06; Jeon et al 09)

– Companions (Hernquist 91; Bailin & Steinmetz 03)
Warps

Hunter & Toomre 69; Toomre 83; Dekel & Shlosman 83; Mathur 84; Sparke 84; Christodoulou & Tohline 86; Sparke & Casertano 88; Ostriker & Binney 89; Binney 91; Hernquist 91; Kuijken 91; Christodoulou et al 93; Hoffner & Sparke 93, 94; Nelson & Tremaine 95; Masset & Tagger 97; Binney et al. 98; New et al. 98; Debattista & Sellwood 99; Brada & Milgrom 00; Ideta et al 00; Lopez-Corredoira et al. 02; Bailin & Steinmetz 03; Shen & Sellwood 06; Jeon et al 09
Shells and ripples

Nurture
Quinn 82, 84; Athanassoula & Bosma 85;
Huang & Stuart 85, 87;
Dupraz & Combes 86, 87;
Hernquist & Quinn 87, 88, 89;
Loewenstein et al 87;
Heisler & White 90;
Thomson & Wright 90, 91;
Weil & Hernquist 93;
Ehlerova et al. 97;
Merrifield & Kuijken 98

Nature
Fabian et al. 80; Williams & Christiansen 84
Disc Galaxies

Disc

Bulge (classical, boxy/peanut, discy)

Bar

Spiral

Warp

Bridges and tails

Thick discs

Rings (ringed galaxies, polar rings, rings in barred spirals)

Ellipticals

Shells and ripples

Dust lanes with peculiar kinematics
The end
Blast Wave Feedback

\[ n = 4 \times 10^6 \]

Governato et al
Orbits (cont.)

---

Athanassoula 2005
Box/peanut bulges are just parts of bars seen edge-on

Comparing simulations viewed edge-on with observations:

- Radial profiles (Athanassoula and Misiriotis 2004)
- Unsharp masking (Aronica, Athanassoula, Bureau, Bosma et al. 2003, Athanassoula 2004)
- Disk (Debattista, Carollo, Mayer and Moore 2004)

See Kormendy and Kennicutt 2004 for other references.
N-body simulations
Horizontal cuts

Athanassoula 2005 (also Athanassoula and Misiriotis 2002)

Lutticke, Dettmar and Pohlen, 2000
Formation of classical bulges: collapse and merging

Sommer-Larsen et al (2005)
Rings

Schwarz 81, 84, 85: Romero-Gomez et al. 06, 07; Athanassoula et al. 09
Rings

Schwarz 81, 84, 85; Romero-Gomez et al. 06, 07; Athanassoula et al. 09
Warps

Disc only : only if outer disc truncation is unrealistically sharp (Hunter & Toomre 69)

Rigid flattened, misaligned halo (Toomre 83; Dekel & Shlosman 83; Sparke & Casertano 88; Kuijken 91; Ideta et al 00)

Live halo: Dynamical friction will damp the warp (Nelson & Tremaine 95; Dubinski & Kuijken 95; Binney et al 98; Debattista & Sellwood 99)

Origin?

– Cosmic infall (Ostriker & Binney 89; Binney 91; Quinn & Binney 92; Jiang & Binney 99; Lopez-Corredoir et al. 02Shen & Sellwood 06; Jeon et al 09)

– Companions (Hernquist 91; Bailin & Steinmetz 03)