The Formation of Disk Galaxies: The Bulge Perspective

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OUTLINE

0. DISK GALAXIES: THE PARADIGM
0.5 (GALAXIES &) BULGES: REALITY CHECK

1. NEWS on DATA
2. NEWS on SIMULATIONS (WITH & WITHOUT GAS)
3. IMPLICATIONS
THEORETICAL “PARADIGM” FOR DISK-GALAXY FORMATION

1) Baryons & Dark Matter within virialised systems have identical initial angular momentum distributions (Fall & Efstathiou 80)

2) Baryons conserve the angular momentum when cooling (Mestel 63)

→ EXPONENTIAL BARYONIC DISKS

3) BULGES originate from mergers of halos → LIKE ELLIPTICALS

4) Disks “grow” around spheroids → Disk Galaxy Population
VISUALLY: SMOOTH “HUBBLE SEQUENCE” 
→ SMOOTH B/D sequence

“PHYSICALLY”: “SHARP” DICHTOMY

kauffmann et al 2003
OBSERVATIONS. 1. KINEMATICS

Disk-like, cold kinematics (from $V/\sigma$ measurements)

(Kormendy 93; Kormendy et al 01)
OBSERVATIONS. 2. STRUCTURE

BULGES AT FAINT-END (Sb and later types),
NOT “deVaucouleurs”, R^{1/4} STELLAR DENSITY PROFILES

→ (ALMOST) EXPONENTIAL
“SERSIC” PROFILES
with n~1-2

\[ \Sigma = \Sigma_0 \exp\left(-\left(\frac{R}{R_d}\right)^{1/n}\right) \]

(e.g., Andredakis & Sanders 94;
de Jong 95; Courteau at al 96;
Carollo et al 98; Graham 2001;
MacArthur et al 03)

( n=4: deVaucouleurs;
n=1: EXPONENTIAL
i.e., AS IN DISKS )
OBSERVATIONS. 2. STRUCTURE

SLOAN
~100000 late-type galaxies

Disks: as in Mo, Mao & White 98;
Bulges: instability criterion or
merger recipe

Four key ingredients:
- feedback \( \rightarrow \) gas mass fraction
- bulge/disk ratio (uniform or instab. crit.)
- ang. mom. transfer bulge \( \rightarrow \) disk
- size-mass relation of bulges

Best fit:
\( \rightarrow \) Bulges generated
by disk instability

Shen, Mo, White et al 2003

Late-type = \( c<2.86 \) and \( n<2.5 \)
OBSERVATIONS. 3. POPULATIONS at z=0

MASSIVE BULGES (S0-Sab):
Z > 0.5 Z_{solar}

Mean <AGE>: >8-10 Gyrs
\Delta Age \sim 2 Gyrs

SMALL BULGES (Sb-Sc):
If Z=0.4 Z_{solar}
\rightarrow MEAN <AGE> \sim 2-to-5 Gyrs
\rightarrow BROADER \Delta Age

MANY SMALL BULGES:
\rightarrow YOUNGER than MASSIVE SPHEROIDS?
\rightarrow SIMILAR AGES OF SURROUNDING DISKS?

(Carollo, Stiavelli et al 2001, 2002; Carollo 1999)
• **z~1 regime: “Normal Disk galaxies”**:  
  → Disk scale-lengths not much evolved since  
  *(Lilly et al. 1998; Ravindranath et al. 2004;  
  GEMS? HWR’s talk?)*  
  → Disks + BULGES : Already in place
OBSERVATIONS. 4. POPULATIONS at z > 0

BARS ABUNDANT UP TO z ~ 1

Sheth et al 2003

GEMS??????
Colors of Bulges at $z > 0.5$: Bluer than ellipticals at similar $z$

COSMIC VARIANCE? AGE/METALLICITY?
1. BULGES: OBSERVATIONS
NEARBY BULGES: STELLAR POPULATIONS

HST ACS FOLLOW UP (+ U, B, I)

Scarlata, Carollo, Stiavelli & Wyse 2004
to be submitted (soon)
NEARBY BULGES: STELLAR POPULATIONS

SIGNIFICANT % of Sb-Sc BULGES are on average “YOUNG” AND METAL-RICH stellar structures

*EXCLUDING CENTRAL DISTINCT NUCLEI

COLORS of “UNDERLYING” POPULATIONS OF SMALL BULGES*
(Scarlata, Carollo et al. 2004)

*PRELIMINARY!

MASSIVE BULGES

Es

*EXCLUDING CENTRAL DISTINCT NUCLEI
As a function of age/Z & mass, down to smallest bulges
BULGES AT INTERMEDIATE-z ?
BULGES AT INTERMEDIATE-z?

→ ANALYSIS OF STELLAR POPULATIONS of DISK GALAXIES in GOODS/CDFS ACS

+ Ferreras, Lilly, Lisker, Mobasher

→ BULGES @ 0.5 < z < 1

Z’S: phot-z by Mobasher et al 2004 + ESO/FORS & VIRMOS DFs

$I_{AB} < 23.5 \quad <z> \sim 0.7$

SAMPLE SELECTION. 1. SED CLASSIFICATION
GOODS: MORPHOLOGICAL SELECTION

Asym > 0.3

$L_20 = 2\text{-nd order mom of brightest 20\% of galaxy flux}$
RGB color composite using B, V, I
I-z  V-I  B-V  COLOR PROFILES

pix-to-pix on drizzled images (0.03")
S/N_{pix}>0.5

Measured:
Average & variance

Compared with SSPs:

B&C 2003
- Standard Padova tracks
- IMF Salpeter 0.1-100M_{sun}
Age vs Z

RED = BULGE
BLUE = DISK

Plotted: 1-σ confidence levels

GREEN: $\chi^2$ MIN
“STATISTICAL” INTERPRETATION

NEEDS:

→ SIMULATIONS TO UNDERSTAND WHETHER/HOW BULGE COLORS ARE CONTAMINATED BY DISK LIGHT AS A FUNCTION OF z

→ UNDERSTAND SAMPLE SELECTION BIASES
  (e.g., different S/N in different passbands;
   C, M_{20} depend on passband, etc etc)

→ IN PROGRESS
DISTRIBUTION of $\Delta Age = Age_{\text{BULGE}} - Age_{\text{Disk}}$

**Preliminary**

AT $0.5 < z < 1$:

- MANY BULGES in INTERMEDIATE $\rightarrow$ LATE-TYPE DISKS HAVE AVERAGE AGES COMPARABLE TO AGES OF SURROUNDING DISKS
SUMMARY. 1. OBSERVATIONS

1. LOCAL Sb→LATER-TYPE BULGES:
   STRUCTURE, KINEMATICS
   and STELLAR POPULATIONS of DISKS

2. INTERMEDIATE-z “INTERMEDIATE-SIZE” BULGES:
   YOUNGER THAN Es
   and STELLAR POPULATIONS SIMILAR TO HOST DISKS

→ CONSISTENT WITH “LATE” BULGE FORMATION

→ Sb+ BULGES:
PRODUCTS OF INTERNAL DISK EVOLUTION?
2. BULGES: SIMULATIONS
**OUR SIMULATION SURVEY. 1**

(Debattista, Carollo, Mayer & Moore 2004 ApJL 604, 93
Debattista, Mayer, Carollo & Moore 2004, to be submitted soon)

1. Live Disk inside Dark Matter Halo FROZEN SPHERICAL POTENTIAL
   High resolution polar grid code
   (Sellwood & Valluri 1997; Debattista & Sellwood 1998)

• several x $10^6$ particles
PHOTOMETRIC/STRUCTURAL COMPARISON

Black Dots: Data from MacArthur et al 02

Projected simulations:
→ Different $i$
→ Different $PA_{BAR}$
(GLOBAL) KINEMATIC COMPARISON

In black:
Data JK et al 01

Projected simulations:
→ Different i
→ Different PA_{BAR}

→ (BUCKLED) BARS CAN MIMICK BOTH
JK’s PSEUDO-BULGES & “ISO-OBLATE-LIKE” KINEMATICS

(see John&Rob’s review,
OUR SIMULATION SURVEY. 2

(in collaboration with: L. Mayer, B. Moore & V. Debattista)

2. Live Disk inside LIVE, SPHERICAL Dark Matter Halo
   PKDGRAV  (Stadel 2001)

3. SPH+NBODY
   GASOLINE  (Wadsley, Stadel & Quinn 2004)
LIVE HALO: N-BODY

ADOPTED MODEL: \( \Lambda \)-CDM of MILKY WAY (e.g., Klypin et al 2002)

HALO: NFW with \( c=11 \) (cnf: cosmological simulations)
\rightarrow \text{adiabatic-contraction-recipe of Mo, Mao & White 98}

\[ V_{\text{virial-radius}} = 140 \text{ km/s (Peak: } \sim 200 \text{ km/s)} \]

Spin Parameter = 0.0465 (\sim \text{mean value in cosmological runs})

Disk/Halo Mass = 0.06 (\rightarrow \text{Scale-length: } \sim 3 \text{ kpc})

Disk Height = 0.05 \times \text{Disk Scale-length}

Softening: 300pc

\[ 10^6 \rightarrow 10^7 \text{ DM particles} \]
$10^6$ DM particles + $2 \times 10^5$ stars; $10^5$ gas

(same softening)
THE GAS

IDEAL with $P = (\gamma - 1)\rho u$

$\gamma = \text{ratio of specific heats} = 5/3$
(gaseous disk represents atomic hydrogen component)

→ Solved internal energy equation which includes artificial viscosity term to model irreversible heating from shocks
→ Adopted standard Monaghan artificial viscosity and Balsara (1995) criterion to reduce unwanted shear viscosity

→ Adiabatic runs: Thermal energy can rise (compressional & shock heating) or drop (decompressions)
→ Radiative cooling: Energy can be released also through radiation; Standard complete cooling function with primordial H+He (sharp drop at $10^4$ K)
GASEOUS DISK

\[ T = 10000 \text{K} \quad \text{(consistent with observed gas velocity dispersions; Martin & Kennicutt 2001)} \]

\[ \text{Expo surface density profile with same scale-length of stellar disk} \]

\[ \text{Thickness determined by local hydrostatic equilibrium} \]

GLOBAL STABILITY: COMBINED STABILITY of gas+stars

For chosen \( T \) \[ Q_{\text{gas, min}} \leq Q_{\text{stars, min}} \] (Jog & Solomon 91)

\[ \text{IF THE DISK REMAINS COLD, GRAVITATIONAL INSTABILITIES WILL BE MORE VIGOROUS IN THE GASEOUS DISK AND AFFECT THE DEVELOPMENT OF NON-AXISYMMETRY EVEN IN THE STELLAR DISK} (\text{e.g., Rafikov 2001}) \]

\[ \text{STABILITY OF COMPONENTS NOT SIMPLY “ADDITIVE”} \]
STAR FORMATION à la Katz 1992

1) gas particles turn gradually into star particles
   → i.e., they remain “hybrid” for some time, and each gas particle can “make” more than one star particle as its mass decreases

2) To turn into stars gas particles must be:
   → in a collapsing region (convergent flow, i.e. DIVv < 0 around target particle in a volume containing 32 SPH neighbours)
   → Jeans unstable (because either \( t_{\text{dyn}} \) or \( t_{\text{cool}} \) < \( t_{\text{sound}} \), the timescale for pressure waves to propagate
   → above density threshold (=1 atom/cm\(^3\)) → \( \frac{d \ln \rho_g}{dt} = -\frac{c_s}{t_g} \)
   \[ t_g = \text{max between local } t_{\text{gasdyn}} \text{ & local } t_{\text{cooling}} \]
   → reproduces Kennicutt’s law

3) Efficiency parameter (set to give SFR of local spirals)

4) Stars form with Miller-Scale IMF
   (used for SNI&II rates → NOT today!)
% GAS MASS IN R<r AT DIFFERENT TIMES
50% Adiabatic vs cooling

Cooling 10% vs 50%

RADIAL PROFILE of J GAS AT DIFFERENT TIMES

10%: huge loss inside; note “inversion” at R/h~0.5

50% cooling: initial loss & final gain
RADIAL PROFILE of $J$ STARS AT DIFFERENT TIMES

NG vs cooling 10%

NG vs 10% SF

50% cooling vs adiabatic
TOTAL $J_{\text{final}}/J_{\text{initial}}$ for Stars, Gas & DM

<table>
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<tr>
<th></th>
<th>Stars</th>
<th>Gas</th>
<th>DM</th>
</tr>
</thead>
<tbody>
<tr>
<td>collisionless</td>
<td>0.89</td>
<td></td>
<td>1.004</td>
</tr>
<tr>
<td>Cooling 10%</td>
<td>0.99</td>
<td>0.83</td>
<td>1.001</td>
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<tr>
<td>Cooling 50%</td>
<td>1.055</td>
<td>0.77</td>
<td>1.001</td>
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<tr>
<td>Ad. 50%</td>
<td>0.98</td>
<td>0.89</td>
<td>1.006</td>
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<tr>
<td>SF (10%)</td>
<td>0.94</td>
<td>1.35</td>
<td>1.001</td>
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</table>

DM: LEAST “RESPONSIVE” (DOMINATES MASS)

HOWEVER: **3-WAY EXCHANGE**, ALL COMPONENTS INVOLVED
10% mass in gas (with RADIATIVE COOLING)

ROUNDER, SMALLER, FLATTER “BULGE”
50% mass in gas (with RADIATIVE COOLING)

DOMINANT CAUSE OF TRANSFER OF ANGULAR MOMENTUM:
SPIRAL INSTABILITIES & CLUMPS @ EARLY TIMES (NOT BAR!)
→→→ very round structures
→ see models by Noguchi 2000
→→ DIFFERENT “REGIME” WHEN DISK
IS GASEOUS & HIGHLY TOOMRLY UNSTABLE

0.87Gyr
→ Can make “old” remnants!
50% mass in gas  (ADIABATIC CASE)

REMNANT MORE SIMILAR TO DISSIPATIONLESS CASE
CENTRAL STRUCTURE: SIMILAR THICKNESS OF MATCHED NO-SF RUN, BUT MORE ELONGATED!
“NEW” STARS:
AGE & SPATIAL DISTRIBUTION
GLOBAL COMPARISON. 1
GLOBAL COMPARISON. 2

Bar Amplitude

Vertical Thickness

$R_b/R_d$
GLOBAL COMPARISON

Gas: Qualitative trends as in Berentzen, Heller, Shlosman & Fricke 98

Improvements:

→ non-truncated, non-core
  "cosmologically-motivated" models
  with adiabatic contraction,
  link between $\text{spin}_{\text{halo}}$ & $h_{\text{disk}}$,
  30x DM particles
→ non-isoT EQ-S (i.e., we model heating in shocks, "complete" radiative cooling $>10^4 K$),
  10x gas particles
GLOBAL COMPARISON. 2

50% COOLING, 50% ADIABATIC & SF RUNS:

→ “NON-LINEARITY”, COMPLEXITY OF TRENDS,

→ STRONGLY DEPENDENT ON “PHYSICS” OF GAS & GAS HYDRODYNAMICS
KINEMATIC COMPARISON:
STELLAR V/s as a function of RADIUS (and TIME)
(GLOBAL) KINEMATIC COMPARISON

GAS:
- ROUNDER,
- COLDER
- (SMALLER)
  "BULGES"
(GLOBAL) KINEMATIC COMPARISON

BUT, STRONG DEPENDENCE ON:

→ \( f_{\text{gas}} \)
→ Cooling properties
→ Star Formation
→ Feedback ?

→→ DIFFERENT “REGIMES”
→→→ DISK INTERNAL EVOLUTION WITH \( z \): CAN BE VERY COMPLEX
SUMMARY. 2. SIMULATIONS

1. DISSIPATIONLESS DISK EVOLUTION (BAR BUCKLING)
   → BUCKLED BARS HAVE THE “OBSERVED” STRUCTURAL AND KINEMATIC PROPERTIES OF BULGES
   (FROM DYNAMICALLY-COLD TO -HOT, ISOTROPIC-OBLATE-ROTATOR-LIKE PROPERTIES)

2. DISSIPATIVE DISK EVOLUTION:
   A) CAN “ROUND, SHRINK & COOL” THE REMNANT (BUCKLED) BAR i.e., THE FINAL BULGE-LIKE STRUCTURE
   B) BUT: VERY COMPLEX PROCESS
      → VASTE RANGE OF “BULGE” PROPERTIES OBTAINABLE, INCLUDING THICKNESS, HOT DYNAMICS, “OLD AGES” ETC

→ DISSIPATIVE+DISSIPATIONLESS DISK (SECULAR=SLOW & NON) EVOLUTION CAN REPRODUCE THE ENTIRE PARAMETER SPACE of Sb & LATER-TYPE BULGES
CONCLUSION

1) Sb & LATER-TYPE BULGES: LIKELY NOT MERGER REMNANTS BUT PRODUCED BY INTERNAL EVOLUTION OF PARENT DISKS
IMPLICATIONS

2) IF Sb $\rightarrow$ Sc BULGES ARE THE RESULT OF DISK EVOLUTION

$\rightarrow$ TOTAL STELLAR MASS IN SPHEROIDS $\sim$ 50%

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<tr>
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<tr>
<td>H I typical mass ($10^9 M_\odot$)</td>
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<td>2.5</td>
<td>4.0</td>
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<td>1.8</td>
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<td>H$_2$/H I</td>
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(Fukugita et al. 98)

$\rightarrow$ FRACTION IN LATE-TYPE BULGES: NEGLIGIBLE
IMPLICATIONS

2) IF Sb$\rightarrow$Sc BULGES ARE THE RESULT OF DISK EVOLUTION

$\rightarrow$ ~30-40% of GALAXIES MUST BE BORN AS “PURE DISKS” (NO INNER “MERGER REMNANT” COMPONENT)

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(Fukugita et al. 98)

$\rightarrow$ IMPORTANT CONSTRAINT TO GALAXY FORMATION IN CDM!