Composite Bulges: The Coexistence of Classical Bulges and Pseudobulges

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Bulges in Disk Galaxies: The Traditional Picture
The Main (Stellar) Components of Disk Galaxies

- **Disk** — round & flat, exponential profile, young + old stars, gas, dust
  - Kinematically cool (stars in ordered, nearly circular motion)

- **Central Spheroid (“Bulge”)** — spheroidal or mildly triaxial, old stars with de Vaucouleurs $R^{1/4}$ (or Sérsic $R^{1/n}$) surface-brightness profile. Forms via early mergers.
  - Kinematically hot (some rotation, but dominated by random motions)
  - Bulge assumed to be visible as excess light in inner part of galaxy — “photometric bulge” — over & above disk light
But not all “bulges” look like small elliptical galaxies

M33: inner few hundred pc = spiral arms, star formation, flattened isophotes, rapid rotation — just like rest of disk!

(2MASS Large Galaxy Atlas K-band profile)
So some “bulges” may be “pseudobulges”...

- Kormendy (1982, 1993): some “bulges” are *disk-like* (e.g. Kormendy & Kennicutt 2004 and references therein):
  - Exponential or near-exponential SB profiles
  - Younger stellar populations (more like disk stars)
  - Spirals, rings, bars, and other disk phenomena
  - Highly flattened geometry (bulges supposed to be “spheroids”)
  - Disk-like stellar kinematics — rotation dominates over velocity dispersion
- **Different formation mechanism**: Supposed to form via some secular evolution process from the disk (e.g., bar-driven gas inflow + central star formation), instead of mergers?
WARNING:

A Simple “Classical bulge vs. Pseudobulge” Dichotomy Is Probably Not Be the Whole Picture!
Some Working Definitions

• **Photometric bulge:** Excess light in center of galaxy, above the outer exponential. (Standard assumption behind “bulge-disk” decompositions.)

• **Classical bulge:** *Spheroidal* (or weakly triaxial) and *kinematically hot* — like a low-luminosity elliptical galaxy, surrounded by a disk. (Probably from mergers, but I’ll ignore speculations about formation.)

• **(Disky) Pseudobulge:** When the photometric bulge region appears to be morphologically and kinematically *disklike*:
  - **Morphology:** geometrically thin like a disk or clearly dominated by disky structures (nuclear rings, spirals, bars, etc.)
  - **Stellar Kinematics:** dominance of rotation over velocity dispersion
  - (Things I’m agnostic about: dust and star formation, color, Sérsic index)
  - (Things I’m mostly ignoring: box/peanut structures in bars)
Let’s start with a simple case: Disk + classical bulge
NGC 1332: SA0 with Classical Bulge

Isophotes become rounder in center: consistent with rounder structure embedded in disk

Bulge-disk Decomposition (Sérsic + exponential functions):

$B/T = 0.43$

$R(b=d) = 12$ arcsec (1300 pc)

“Photometric bulge region”
Major-axis Stellar Kinematics: Kinematically Hot Bulge

Major-axis spectroscopy (Rusli+2011)

Ratio of in-plane velocity to dispersion:

Deproject observed $V_{\text{rot}}$ to in-plane value ($V_{dp}$), divide by velocity dispersion

= Local measure of relative importance of rotation vs. pressure support

$V_{dp} / \sigma < 1$ within photometric-bulge region \( \Rightarrow \) Bulge of NGC 1322 is kinematically hot
That was too easy—let’s get more complicated...
NGC 3945 and NGC 4371: S0 Galaxies with Multiple “Bulges”

NGC 3945 (SDSS)  

NGC 4371 (SDSS)
NGC 3945: Photometric Bulge is Flattened

“Bulge” isophotes very elliptical (similar to outer disk)

Partial nuclear ring + inner (nuclear) bar

Photometric bulge has same flattening as disk; disky substructure (nuclear bar + ring)

Pseudobulge?

Photometric bulge: r < 17 arcsec (1.6 kpc)
NGC 3945: Kinematics in Photometric Bulge

$V_{dp}/\sigma$ rises to $>2$ in photometric bulge region: kinematically cool, not a classical bulge!
But wait — there’s more!
NGC 3945: Inner Morphology

Rounder isophotes (ell = 0.2) inside disky/ring isophotes (ell = 0.35): $r < 1.5$ arcsec

Central photometric excess: B/D decomposition $\Rightarrow$ Sérsic component dominates for $r < 1$ arcsec

What are the kinematics of this inner region?
Kinematics of the Central Region

$V_{dp}/\sigma < 1$ in central bulge region: kinematically hot!
NGC 4371: Photometric Bulge is Flattened

R-band contours

“Bulge” isophotes very elliptical (similar to outer disk)

Nuclear ring with r = 10ʺ (750 pc)
Slightly blue, no dust
= mix of young & old stars

Photometric bulge has same flattening as disk; disky substructure (nuclear ring)

Pseudobulge?

Photometric bulge = inner 25 arcsec [2.1 kpc]
Stellar Kinematics in Photometric Bulge

Major-axis spectroscopy (WHT-ISIS)

$V_{dp}/\sigma$ rises to $\sim 1.5$ in photometric bulge region. Again, kinematically cool, not a classical bulge!
(Yes, there’s more ... )
Central (rounder) structure inside pseudobulge!

Rounder isophotes (ell = 0.3) inside disky/ring isophotes (where ell = 0.4): \( r < 5 \) arcsec

Central photometric excess: B/D decomposition (+ nuc.ring), with Sérsic component dominating for \( r < 5 \) arcsec

Like a small classical bulge inside the pseudobulge…

What are the kinematics of the central 5 arcsec?

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Kinematics of the Central Region

Central region (r < 5 arcsec):
$V_{dp}/\sigma$ inner plateau, clearly < 1: kinematically hot!
Other Examples: NGC 1068, 2859, 3368, and 4699

NGC 1068

NGC 2859

NGC 3368

NGC 4699

Radius along major axis [arc sec]

\[ \frac{V_{dp}}{\sigma} \]

\[ \frac{V_{dp}}{\sigma} \]

\[ \frac{V_{dp}}{\sigma} \]

\[ \frac{V_{dp}}{\sigma} \]

Davies+2007 (SINFONI)

Shapiro+2003

Gerssen+2006

Erwin+2014 (WHT-ISIS)

de Lorenzo-Cáceres+2008 (SAURON)

Bower+1993

Fabricius+2012

SINFONI AO data

SINFONI AO data

SINFONI AO data

SINFONI AO data

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Dynamical Modeling

• For 3 of these composite-bulge galaxies (+ NGC 1332), we have SINFONI AO data

• Dynamical modeling to get SMBH masses
  • Nowak+2010, Rusli+2011, Erwin+2014 (in prep)

• Gives us stellar orbital structure as a byproduct

• What do our models tell us about the stellar kinematics in these structures?
Stellar Dynamics from Schwarzschild Modeling of SINFONI Data

Classical Bulge

- NGC 1332

Composite Bulges

- NGC 3368
- NGC 4371
- NGC 4699

Vertical (z) anis., Isotropic, Planar anis.

Classical bulges are isotropic; disky pseudobulges are anisotropic (as expected for flattened disk)

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Composite-Bulge Galaxies

• 9 clear cases (so far): NGC 1068, 1543, 1553, 2859, 3368, 3945, 4262, 4371, 4699

• Majority are S0; NGC 3368 = Sab, NGC 1068 & 4699 = Sb

• All but 1 are clearly barred

• Not an unbiased sample...

• ... but we can estimate a lower limit: at least 20% of barred S0 galaxies have composite bulges
“Disky Pseudobulges”

- Typically flattened, with exponential surf.-brightness profile
  - Scale lengths 130–1300 pc (median = 550 pc)
- Kinematically “cool” (V/sigma > 1)
  - But not kinematically cold like outer disk (where V/sigma >> 2)
  - Planar-biased anisotropy similar to large-scale disks
- Anywhere from 40–95% of photometric bulge luminosity (i.e., usually the dominant part of the photometric bulge)
  - 11–59% of total galaxy stellar mass (mean = 33%)
- Often — but not always — has disky substructure: nuclear bar and/or ring
“Classical Bulges”

- Typically oblate (not as flat as outer disk!)
  - Sérsic profiles: \( n \sim 0.9–2.2 \) (median = 1.5)
  - Effective radii \( \sim 25–430 \) pc (median \( \sim 120 \) pc)

- Kinematically “hot”
  - \( V/\sigma < 1 \)
  - (But some rotation is present)
  - Evidence for isotropic velocity dispersion

- B/T \( \sim 2–20\% \) (mean = 6\% of galaxy stellar mass)
Composite-Bulge Components in Mass-Radius Plane

$R_e [pc]$ vs. $M_* [M_\odot]$
Some of these embedded “classical bulges” are rather small ...
Are they really nuclear star clusters?

No.

- Even the smallest ($r_e \sim 30 \text{ pc}$) are an order of magnitude larger than typical NSCs ($r_e \sim 2-5 \text{ pc}$)

- Many have $r_e \sim$ several hundred pc

- Similar mean densities to NSCs, but 2–3 orders of magnitude more massive

- At least one of them has a prominent NSC inside
Composite Bulges Coexist with Boxy/Peanut-Shaped Bulges (Another type of “pseudobulge”)

NGC 3368: “Box+spurs” morphology (Erwin & Debattista 2013)

Blue = “spurs” (flat outer part of bar)

Green = “box” (projection of vertically thick inner part of bar = box/peanut bulge)

Red = Disky pseudobulge

(Classical bulge = round innermost isophotes)

Coexistence of classical bulges, pseudobulges, and boxy bulges (Athanassoula 2005)
Black Holes & Composite Bulges

• SINFONI observations for SMBH measurement

• 15 disk galaxies (S0 + spirals)
  • 6 with classical bulges
  • 3 definite composite-bulge galaxies
  • 6 spirals not as well determined
    • mix of pure pseudobulges and composite bulges?

• 3 already published (Nowak+2010, Rusli+2011); 3 still being modeled

• Erwin+2014, in prep
Formation of Disky Pseudobulges?

Discussions of pseudobulges often argue that they form from bar-driven “secular evolution” (e.g., Kormendy & Kennicutt 2004) Usually rather hand-waving

Is there any evidence for this from simulations?

Wozniak & Michel-Dansac 2009:

Isolated galaxy simulation (n-body + SPH gas, star formation)
Initial setup: stellar disk + 10% gas
Rigid DM halo

“Nuclear disk” amounting to 34% of galaxy stellar mass formed inside bar, radial extent ~ 500 pc

But: unclear how much this matches our disky pseudobulges Surface-brightness profile? Stellar kinematics?
Isolated Galaxy Simulation


Initial conditions: live DM halo (5M particles) w/ hot gas “corona” (5M SPH particles); no stars
Same as model HG1 of Gardner+2014

Evolved with n-body+SPH code GASOLINE
gas cooling, SF, stellar feedback as in Stinson+2006
feedback: Type I and II SNe; AGB winds
(no SMBH, so no AGN feedback)

Evolved for 10 Gyr ⇒ 6.5 × 10^{10} M\odot barred spiral

Massive “nuclear disk” with two(!) stellar rings forms inside bar
(~ 29% of total stellar mass at end of simulation)
Comparing Simulation with NGC 4371

Simulation has disk inside bar (similar to real galaxy!)

Note: disk is slightly *elliptical* (perpendicular to bar) — something to look for in real galaxies?

**Differences:**

1. Simulation’s disk is *much larger*

2. *Two* nuclear rings instead of one
Exponential Profile!

Radii of Nuclear Rings at 10 Gyr
Underlying exponential profile

Radius along major axis [kpc]

$\Sigma \left[ M_\odot/kpc^2 \right]$

10 Gyr
8 Gyr
6 Gyr
Stellar Kinematics

\[ \frac{V_{dp}}{\sigma} \] reaches values ~ 2 within “nuclear disk”/disky pseudobulge

But: peak \( \frac{V_{dp}}{\sigma} \) is at larger radii in simulation

No clear decrease in \( \frac{V_{dp}}{\sigma} \) at intermediate radii

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Some Agreement

Disky structure with exponential profile does form inside bar

Large $V_{dp}/\sigma$ value where this disk dominates

Nuclear ring(s) coexist with disk

Similar fraction of galaxy stellar mass

Some Disagreement

Observed disky pseudobulges:
- are significantly more compact
- have only 1 (or no) ring
- often(?) have nuclear bars

And, of course — no compact classical bulges in simulation
Summary

• At least some “bulges” are composite systems, consisting of:
  • Luminous disky component: disky pseudobulge
    • Usually exponential; disklike kinematics; ~ 30% of stellar mass
  • Embedded, lower-luminosity classical (kinematically hot) spheroid: classical bulge
    • Sérsic $n = 1–2$; ~ 6% of stellar mass; isotropic dispersions
  • Both classical-bulge and disky-pseudobulge components fall on same size-mass relation as ellipticals and (large) classical bulges

• N-body + SPH simulation of isolated disk galaxy forms disky pseudobulge inside bar, though it is too extended and has multiple rings instead of 1 or none
Where Next?

- We now have a much better idea of what kinds of structures are found in galaxy centers (and how to measure them!):
  - Nuclear star clusters
  - Classical bulges
  - Disky pseudobulges
  - Box/peanut bulges of bars (Erwin & Debattista 2013) …
- But how common are they, and how much of stellar mass is in each?
Idea for a Survey: Comprehensive Inventory of Central Stellar Structures in (Nearby) Disk Galaxies

• E.g., 30–50+ nearby S0–Sb(Sc?) at moderate inclinations (D < 25 Mpc, 30° < i < 70°)

• Imaging:
  • High-res. optical/near-IR (HST and/or AO)
  • Low-res. optical/near-IR (Spitzer archival; SDSS)

• Spectroscopy:
  • Stellar kinematics (High-res. for classical bulges; lower-res. for pseudobulges & disks)
  • Desirable: Stellar populations (Low-res. only?)

• Comparison with N-body (+ SF) models (V. Debattista)

• Dynamical modeling to determine orbital structure, anisotropy, etc.?