Central Gas Concentrations in SB Galaxies

20 nearby, low-inclination, unperturbed galaxies w/ C0 emission

Sakamoto et al. 1999
Central Mass Concentrations

Sample of well resolved, nearby barred galaxies with and without starbursts. High central gas densities, $0.3-2.0 \times 10^9 M_\odot$. Define type I: gas still inflowing; type II: gas in inner region; starbursts have $3-11 M_\odot/yr$ vs $0.1-2 M_\odot/yr$ for non-starbursts

Jogee et al. 2005
Central Mass Concentrations

Type I Non Starburst
- Early Stages of Bar-Driven Inflow
- Large fraction of circumnuclear gas is along bar, has large non-circular kinematics, and low SF efficiency.

Spontaneous or Tidally Induced Bar
with a gas supply inside its corotation

Type II Non Starburst
- Later stages of bar-driven inflow
- Most of circumnuclear molecular gas is concentrated in inner kpc, inside OILR of bar, and has predominantly circular motions.
- Significant fraction of gas below critical density for SF

Circumnuclear Starburst
- Large fraction of circumnuclear molecular gas is inside OILR of bar, has super-critical densities and intense SFR
- Compact stellar component (pseudo-bulges) with disk-like structure and high ratio of rotational to random motions built inside OILR
- Vertical ILRs of bar scatter stars → peanut-shaped bulges

- In presence of high density contrast, nuclear bars/disks decouple
- Possible gas fueling at r<< 100 pc
- Bar dissolution --> boxy bulges + dynamically hot disk??

Jogee et al. 2005
In a sample of 43 Seyfert galaxies, all have circumnuclear dust structures and almost all have nuclear spirals.

Pogge & Martini 2002
Bar-Induced Spirals

In new, very high resolution simulations, bar-induced spiral shocks may propagate to small radii depending on the state of the nuclear gas. Else it accumulates into a ring.

In simple double-barred models, the nuclear bar does not inhibit the propagation of the spirals to small radii.
Bar-Induced Spirals

Maciejewski 2004
**Gas Inflow in the Inner kpc: NGC 4303**

Double-barred galaxy

40” and 4” bar lengths

Velocity field in inner 8” consistent with a circularly rotating disk, inconsistent with Shlosman’s gaseous nuclear bars

*Schinnerer et al. 2002*
IC 342

The nearest face-on Scd with significant nuclear star formation; Weakly barred

Bar in CO 1.5 x 0.3 kpc (Lo et al. 1984); gas motions highly non-circular (Ishizuki et al. 1990) all the way down to 10 pc (Schinnerer et al. 2003); nucleus starbursting (Böker 1997) with luminosity-weighted age of 60 Myr (Böker 1999); inflow rates 0.003-0.14 M\(^{\text{\textsc{\textbullet}}}/\text{yr}; shocks detected in SiO (Usero et al. 2006)
Böker et al. (1997) found bar $a_B$ 55 pc with ILR at 35 pc corresponding to a ring-like structure of molecular gas. Ring is star forming.

Meier & Turner (2005) map 8 molecules in mm. $\text{CH}_3\text{OH}$ and HNCO trace bar-induced shocks.
Nuclear Ring SF Morphology

A) “Popcorn”  

B) “Pearls on a string”  

NGC 613

VLT SINFONI spectra

600 pc

Böker et al. 2007
Small Bar in SABcd NGC 6946?

$M_{H_2}(27\text{pc}) \sim 1.6 \times 10^7 \, M$

ring-like at 10 pc
How to Funnel Gas to Nuclei?
Disks in Nuclear Clusters

Best fitting 2 population model of NGC 4244 nucleus: 5% disk mass ~100 Myr

Seth et al. 2006
Bars-Within-Bars

Erwin & Sparke (2002) find nuclear bars in ~25% of early-types
### Nuclear Clusters in Bars

**TABLE 3**

<table>
<thead>
<tr>
<th>Class</th>
<th>With NC</th>
<th>Without NC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RC3</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unbarred (A)</td>
<td>76% (16)</td>
<td>24% (5)</td>
</tr>
<tr>
<td>Mixed (AB)</td>
<td>88% (23)</td>
<td>12% (3)</td>
</tr>
<tr>
<td>Barred (B)</td>
<td>67% (20)</td>
<td>33% (10)</td>
</tr>
<tr>
<td>Total</td>
<td>77% (59)</td>
<td>23% (18)</td>
</tr>
<tr>
<td><strong>LEDAR</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unbarred</td>
<td>88% (15)</td>
<td>12% (2)</td>
</tr>
<tr>
<td>Barred</td>
<td>73% (44)</td>
<td>27% (16)</td>
</tr>
<tr>
<td>Total</td>
<td>77% (59)</td>
<td>23% (18)</td>
</tr>
</tbody>
</table>

*Notes.—Sample fraction and total number of galaxies with and without a clearly identified NC, sorted by bar classification. For comparison, we have listed the statistics for both the RC3 and LEDA databases.*

**Presence of NC not affected by a bar**

*Böker et al. 2004*
A sample of 38 S0-Sa low inclination barred galaxies: found 25-40% had nuclear bars regardless of primary strength.
Double-Barred Galaxy Statistics

Secondary bars are sub-kpc and no larger than ~15% of $a_B$
The Furthest Double-Barred Galaxy

\[ z = 0.15 \]

Lisker et al. 2006
Double-Barred Galaxies at High $z$

Data: Erwin 2004

Detection limit for GOODS data:
2.5 PSF = 0.28”

COSMOS

Lisker et al. 2006
How to Measure Angular Frequency

\[ m = \Omega_p \sin i \]

Tremaine & Weinberg 1984
Loop Orbit Shape Prediction

Maciejewski & Sparke 2000
Gas Need Not Be Present

Inner bars seen in NIR (Mulchaey et al. 1997; Laine et al. 2002)

No CO found in a sample of S2Bs down to $3 \times 10^7 \, M_\odot$ or less (Petitpas & Wilson 2004). This includes NGC 2950 (also lacks HI detection)

Petitpas & Wilson 2004
Gas Infall by Rigidly-Rotating Nuclear Bars

Assumed that the primary and nuclear bar are both rotating as rigid objects with a constant shape.

Maciejewski et al. 2002
Although our conclusions are based on purely dynamical considerations, they nevertheless naturally fit the context of a broader physical picture. How can the separation of scales be achieved in a physical configuration? In a pure stellar system, this probably can be obtained through a restrictive set of initial conditions only, i.e., the system is preset to develop double bars (e.g., Friedli & Martinet 1993). A more general way is to invoke the gas redistribution in the galaxy and its accumulation within the central few hundred pc as a precondition to formation and dynamical decoupling of the secondary bars (e.g., Shlosman et al. 1989; Friedli & Martinet 1993; Knapen et al. 1995; Heller, Shlosman, & Englmaier 2001). The secondary bars in this latter scenario require a gravitational runaway in the gas to initiate the decoupling. When the gas gravity triggers the cascade of smaller bars, the phenomena are expected to be transient because of the finite gas supply and dissipation present. Stellar secondary bars in this picture are by-products of the runaway, through stellar capture and induced star formation in the gas. These two processes can regulate the parameters of the inner bar so as to be in a critical state of “marginal” self-gravity, which also happens to be dynamically long-lived. This can explain the remarkable frequency of double-barred systems, despite their a priori improbability.
Simple Orbit Integrations

Nuclear bar support

Large Liapunov expts

El-Zant & Shlosman 2003
Louis-Gerhard Theorem

Assume 2 triaxial stellar systems in rigid rotation

$$\rho_i = \rho_i^M + \rho_i^Q(3 \cos^2 \theta - 1) + \rho_i^Q \sin^2 \theta \cos 2\phi_i(t)$$

Use Poisson eqn. and Boltzmann eqn. to obtain

$$0 = (2\omega_1 G - \delta \omega H) \sin 2\delta \phi$$

$$0 = [2\omega_2 G - \delta \omega (G + H)] \sin 2\delta \phi$$

with

$$G = \int \rho_1^Q \Phi_2^Q r^2 \, dr$$

$$H = \int \rho_1^Q \frac{\partial \Phi_2^Q}{\partial r} r^3 \, dr$$
Louis-Gerhard Theorem

\[ 0 = (2\omega_1 G - \delta \omega H) \sin 2\delta\phi \]

\[ 0 = [2\omega_2 G - \delta \omega (G + H)] \sin 2\delta\phi \]

In general: \( G \neq 0, H \neq 0 \)

\[ \Rightarrow \delta\omega = 0 \text{ and } \phi = 0, \pi/2 \ldots \]

Rigid rotation is possible only if both components have the same angular velocity and their long axes in the equatorial plane are parallel or orthogonal

Louis & Gerhard 1988
Long series of failures to form S2Bs in collisionless simulations

Shlosman (2002): “The presence of gas appears to be imperative for” nuclear bars to form.

Friedli & Martinet (1993): “It seems difficult to form nuclear bars inside primary bars without calling on dissipative processes."

"In summary, in the set of simulations performed without any dissipative components, we generally observe that the first bar formed remains stable over many Gyr and a second bar never appears. The appearance of two almost simultaneous bars with different extension, albeit possible, only corresponds to transient state converging rapidly to one unique bar."
Sellwood & Merritt (1994):
Discovered that counter-rotating disks may produce counter-rotating large-scale bars

Friedli (1996):
Restricted counter-rotation to an inner disk and got an S2B

Davies & Hunter 1997
First Successful Simulations

Rautiainen & Salo 1999
A pseudo-bulge is a bulge formed by internal (secular) evolution, such as gas inflows from large scale bars, spirals etc. A growing body of evidence suggests that this is an important channel of bulge formation.
QuickTime and a
YUV420 codec decompressor
are needed to see this picture.

Debattista & Shen 2007
Non-Uniform Rotation

Debattista & Shen 2007
Non-Uniform Rotation

Debattista & Shen 2007

Is such rotation able to fuel gas to the centre more effectively?
“The circumnuclear regions (of a few kiloparsec in size) in all candidate double-barred galaxies of our sample (except NGC 5566) are dynamically decoupled, because deviations of the gaseous/stellar dynamical axes relative to the lines of nodes or elliptical peaks of $\sigma$ are detected on our 2D maps. Various peculiar structures (inner polar and coplanar disks, mini-spirals) were revealed. Such a large fraction of peculiar structures is not surprising, because different structural features can produce twists of the inner isophotes. However, we have not found any kinematic features connected with inner (secondary) bars. This cannot be explained by the limited angular resolution of our kinematic data, because we confirm definitively the nuclear mini-bars (without large bars) in NGC 3368 and NGC 3786. We see two possibilities to explain this.

Firstly, it is possible that the twist of the inner isophotes of galactic images has no connection with a dynamically decoupled inner bar. In this case a "secondary bar" is an illusory structure, and different reasons may cause the isophotal distortion: inner disks or rings, nuclear spirals etc. Indeed, Shaw et al. (Shaw et al.1993) had constructed a model where the inner twist of the stellar isophotes is triggered by a secular evolution of the gaseous component in a single-barred gas-rich galaxy. See also papers by Friedli et al. (1996), Moiseev (2001), and Petitpas & Wilson (2002) where various mechanisms are considered for an isophotal twist explanation.

Secondly, the kinematics of the inner bar in a double-barred galaxy differs essentially from single-bar dynamics. In this case, the deviations of $PA_k$ and the peaks of the velocity dispersion must be interpreted in a different manner than in this paper. For example, in their last work Corsini et al. (2003) have measured different pattern speeds for secondary and primary bar-like structures in NGC 2950. However, $PA_k$ of the stellar velocity field coincides with the line of nodes. New self-consistent models of barred galaxies must be used to investigate this phenomenon.”

Moiseev et al. 2004
"Wozniak et al. (1995) and Friedli et al. (1996) explained the inner PA turn, and the peak, at r<6'', as a secondary bar. Surprisingly, this `bar" does not distort the circular rotation of stars in the circumnuclear region. The PA\textsubscript{k} of the stellar velocity field coincides with PA\textsubscript{0} of the line of nodes.

We do not detect any non-circular motions in this velocity field despite the strong turn of isophotes at these radii. There are sharp elliptical structures decoupled in the stellar velocity dispersion map at r=1-5''. It is extended along PA \textasciitilde 150°, which is the direction of the major axis of the primary (external) bar."

Moiseev et al. 2004
Simulation Kinematics

Shen & Debattista 2008
Triaxial bulges rotate rapidly

Kormendy 1982
Triaxial Bulges

\[ \langle B/A \rangle = 0.85 \]

Méndez-Abreu et al. 2007
SMBH Growth

Shlosman et al. (1989) proposed that nuclear bars lead to AGN fueling while Begelman et al. (2006) propose that SMBHs can form directly from nuclear bars.

Sellwood & Moore (1999) propose that a first generation of bars is weakened by a growing SMBH. Subsequent bars do not feed SMBHs as efficiently because an ILR is present. A prediction of this model is that in DM dominated systems, if a bar cannot form than a SMBH cannot form.
Barred Galaxies & the M-σ Relation

Tremaine et al. 2002