STELLAR, GAS AND DARK MATTER CONTENT OF BARRED GALAXIES

Bernardo Cervantes Sodi
Institute of Radioastronomy & Astrophysics
UNAM
WORK IN COLLABORATION WITH:

- Changbom Park (KIAS, Seoul)
- Cheng Li (Tsinghua Univ., Beijing)
- Lixin Wang (SHAO, Shanghai)
- Osbaldo Sánchez García (UNAM, Morelia)

Cervantes Sodi, B., & Sanchez Garcia, O., 2016, in preparation
• Brief introduction on the fraction of barred galaxies in the local Universe
• Expectations from simulations
• Bar fraction as a function of stellar-to-halo mass ratio using three different halo mass estimates
• Bar fraction as a function of HI gas richness
• General conclusions
In the local universe ~30-50% of spirals are barred galaxies

Cervantes Sodi et al. 2013
Galaxy Zoo (Masters et al. 2010)

Wilman & Erwin 2012
Neverthe-
less, it is by no means clear that this mechanism is unimportant. We have so far discussed only isolated galaxies. Let us now turn to the effect of interactions and mergings. The number of interactions are known to increase dramatically with redshift (e.g., Kartaltepe et al. 2007 and references therein). Interactions and merging activity are most likely to influence (heat up) the less massive galaxies. It is precisely in such galaxies that we see significantly lower bar fractions compared to the high-mass galaxies at the highest redshifts (Figs. 3 and 4). Although indirect, there is observational evidence that later type and less massive systems are dynamically hotter. The top row of panels in Figure 1 of Kassin et al. (2007) clearly shows that late-type spirals and irregulars have larger disordered motions compared to early-type spirals particularly at high redshifts. These are precisely the type of systems within which we find fewer bars. Moreover, in the same figure, the higher mass galaxies also have a higher fraction of ordered motions than disordered motion, although the trend is hard to see in the relatively modest sample size in the high-redshift bins. These data suggest that the lack of bars may therefore be related to the dynamic hotness and the mass surface density of these disks. We are currently identifying bars and measuring the bar fraction in this sample of galaxies and should be able to provide a direct answer for the said hypothesis (Sheth et al. 2008).

Simulations show that interactions speed up bar formation in direct encounters, but have little effect in retrograde ones (Toomre & Toomre 1972; Noguchi 1987; Gerin et al. 1990; Steinmetz & Navarro 2002), in good agreement with observations (Kormendy & Norman 1979; Elmegreen & Elmegreen 1982). Thus one might have expected higher rates of bar formation at high \( z \), where interactions are common. On the contrary, it is possible for mergings to destroy or severely weaken the bar, without destroying the disk (e.g., Berentzen et al. 2004 and references therein). More modeling needs to be done before we can say with any certainty what the combined effect of interactions and mergings is. Note that we discarded from our statistics obviously interacting systems based on tidal features or obvious distortions. However, if a galaxy is weakly interacting, it would be difficult to distinguish it from a noninteracting system; this is already the case even in the local universe. So our sample of galaxies is most likely probing quiescent, postmerger or weakly interacting disks.

5.3. The Downsizing nature in Formation of Galactic Structure

Galaxy ''downsizing'' was coined by Cowie et al. (1996) to refer to an evolutionary history in which the most massive galaxies formed first. There is strong observational evidence for the...
A NUMERICAL STUDY OF THE STABILITY OF FLATTENED GALAXIES: OR, CAN COLD GALAXIES SURVIVE?*

J. P. OSTRIKER
Princeton University Observatory

AND

P. J. E. PEEBLES
Joseph Henry Laboratories, Princeton University

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During the first rotation time period the system of particles goes from a symmetric disk to a highly nonaxisymmetric "barlike" structure, which tends to dissolve and approach rough axial symmetry again. After one orbital period $t$ is roughly comparable to what was indicated as the critical value in analytic studies of fluid models. When a small halo is introduced, this sequence is reproduced in a less pronounced way. When the halo mass is larger, the disk develops random kinetic energy in a manner reminiscent of two-body relaxation processes but does not show a violent instability. For the chosen forms of density distribution in disk and halo components, a halo mass of $1$ to $2\frac{1}{2}$ times the disk mass appears to be required to reduce the initial value of $t$ to the stable range $t \approx 0.14$. 
Numerical experiments on the stability of exponential discs.

Propose a stability criterion: which is basically a ratio between mass of the halo to the mass of the disc.

On their simulations, discs with $t^* > 1.1$ where stable against bar instability.
Using a live halo

Massive Disc

Massive Halo

Massive Halo

Massive Disc

Athanassoula & Misiriotis 2002, Athanassoula 2012
Figure 2. Circular velocities of all models at $t = 0$ after halo relaxation in the frozen disk potential. Each panel displays the stellar disk rotation curve (red, long dashed), halo (blue, dashed), and the total curve (black, solid).

(A color version of this figure is available in the online journal.)

We take a closer look at these trends in Section 4. When we decided to create one-parameter sequences naturally leads to a wide spectrum of bar properties and can include some of the extreme behavior.

Some clear trends of the bar strength behavior can be observed along each of the sequences defined in Section 2.2. First, in all models, except the two exclusions mentioned above, $A_2$ and $A_{2b}$ have saturated by $t \sim 230$. Because $A_{2b}$ is tailored for the bar, the saturation of this parameter is more obvious (more about this in Section 3.3). Second, making the inner halo less massive (i.e., less centrally concentrated), either by reducing the total halo mass or by increasing the size of the central core ($M_h$ and $\gamma$, respectively), results in a shorter rise time of the bar instability and hence brings up the bar earlier.

Third, increase in the mass of the inner halo and decrease in the outer one has the most dramatic effect on the bar strength, substantially increasing the timescale of the bar instability. This hints at DM mass concentration being important rather than the total halo mass. Varying the mass of the outer halo alone has a much smaller effect on the bar. Finally, in all one-parameter sequences, the first $A_2$ or $A_{2b}$ peak forms a progressively more extended plateau for less concentrated halos, respectively. Again $T_{16}$ is an exclusion.

Furthermore, $A_2$ and $A_{2b}$ show high-frequency variability in some models (e.g., Figure 4), being strongest in models SD, C30, and T22. This variability can also be seen in $R_b$ and $\Omega_b$ evolution, the bar length and its pattern speed. This variability is limited to the time of the bar secular growth and dies out with saturation of the bar strength, $A_2$ and $A_{2b}$. These oscillations coincide in time with the presence of four short arms located close to the bar end, and two spirals in the outer disk beyond the bar radius. Both sets of spirals have pattern speeds larger than $\Omega_b$.

Villa-Vargas, Shlosman & Heller 2010

SD - Standard model
M70 - 70% halo mass of SD
M40 - 40% halo mass of SD
### KIAS Galaxy Catalog

**SB0**
- J121016.23-015934.89
  - RCS: S0
  - NA10: NB (30)
- J11241.92+013114.83
  - RCS: E
  - NA10: NB (Sa)
- J015110.71-010141.08
  - RCS: B
  - NA10: NB (30/a)
- J063726.59+002008.06
  - RCS: S0
  - NA10: NB (30)

**SB1**
- J12847.31+000910.59
  - RCS: Sa/Sb
  - NA10: NB (30)
- J143933.12+020010.83
  - RCS: SB1
  - NA10: NB (Sa)
- J110748.15+021823.98
  - RCS: B
  - NA10: NB (30/a)
- J111956.58+542748.50
  - RCS: S0
  - NA10: SB (30/a)

**SB2**
- J112416.63+003907.44
  - RCS: SB/S0
  - NA10: NB (30)
- J122055.69+033929.33
  - RCS: S0
  - NA10: NB (30)
- J101720.99+142746.54
  - RCS: SB/S0
  - NA10: NB (30)
- J134105.20+050020.89
  - RCS: S0
  - NA10: NB (30)

**SB3**
- J081341.02+455827.46
  - RCS: SB/S0
  - NA10: NB (30)
- J140908.50+014206.28
  - RCS: SB/S0
  - NA10: NB (30)
- J091814.20+453208.16
  - RCS: SB/S0
  - NA10: NB (30)
- J110842.81+444838.35
  - RCS: SB/S0
  - NA10: NB (30)

**Lee et al. 2012**
Last year we studied the bar fraction as a function of $M_*/M_h$.

Stellar mass estimates from VAGC from the MPA/JHU SDSS database (Kauffmann et al. 2003; Brinchmann et al. 2004).

Halo mass estimates from Yang et al. (2007) group catalog.

Galaxies are grouped according to their common halos.
Halo mass is assigned to each group.
The most massive galaxy is defined as the central one.
Cervantes Sodi et al. 2015
Cervantes Sodi et al. 2015

Graph showing the relationship between $f_{\text{bar}}$ and $\log M_*/M_h$ for different categories: All, Strong, and Weak.
Cervantes Sodi et al. 2015
Díaz-García et al. (2016)

- Using near-infrared photometry (S4G).
- HI line widths from the literature to estimate dynamical masses within optical radius.
- No dependence on $M_h$ at fixed $M^*$.
• Using the same galaxy sample for bar classification (Lee et al. 2012)

• HI line width estimates from ALFALFA for a more direct and homogeneous approach to estimate dynamical masses

• We looked to the dependence of the bar fraction on disk-to-halo mass fraction and gas content.
TWO DIFFERENT HALO MASS ESTIMATORS

- The dynamical mass within the HI disk radius

\[ M_{\text{dyn}} = \frac{R_{\text{HI}}V_{\text{rot}}^2}{G}. \]

- Given that we don’t count with the HI disk radius, we estimated it through (Broelis & Rhee 1997):

\[ \log M_{\text{HI}} = 1.96 \log D_{\text{HI}} + 6.52, \]

Lelli, McGaugh & Schombert (2016) half the intrinsic scatter of the BTF
• The halo mass computed using the estimate by van den Bosch (2002):

\[ M_{\text{halo}} = 2.54 \times 10^{10} M_\odot \left( \frac{r_d}{\text{kpc}} \right) \left( \frac{V_{\text{rot}}}{100 \text{ km s}^{-1}} \right)^2 \]
3. RESULTS AND DISCUSSION

3.1. Bar fraction as a function of mass

We start our analysis by looking at the dependence of the bar fraction $f_{\text{bar}}$ as a function of different masses defined for our sample. In Figure 1a, we show the dependence of the bar fraction on stellar mass for strong and weak bars, as well as for strong plus weak bars, with the well known trend of higher $f_{\text{bar}}$ for galaxies with high stellar masses (Masters et al. 2012; Oh et al. 2012; Skibba et al. 2012; Cervantes Sodi et al. 2013; Cervantes Sodi 2016, submitted).
The fraction of barred galaxies $f_{\text{bar}}$ as a function of:

(a) stellar-to-dynamic mass ratio $M_*/M_{\text{dyn}}$,
(b) baryonic-to-dynamic mass ratio $M_{\text{baryon}}/M_{\text{dyn}}$,
(c) stellar-to-halo mass ratio $M_*/M_{\text{halo}}$,
(d) baryonic-to-halo mass ratio $M_{\text{baryon}}/M_{\text{halo}}$.

Gavazzi et al. 2015), at least for the case of strong bars, an expected result given that bars form earlier in massive galaxies, as previously shown by Sheth et al. (2008) and Kraljic, Bournaud & Martig (2012). Error bars in all figures denote the estimated 1σ confidence intervals based on the bootstrap resampling method. The corresponding result using the baryonic mass is presented in Figure 1b, where is noticeable a slight increase of the bar fraction for increasing baryonic mass, but the trend is less dramatic than the one present as a function of stellar mass. This might be due to the fact that an increase in $M_{\text{baryon}}$ can be the result of an increase of $M_*$ but also and increase of $M_{\text{gas}}$, and as will be discussed in section 3.3, an increase of $M_*$ promotes the growth of the bar, but an increase of $M_{\text{gas}}$ hinders the growth of the bar.

To study the dependence of the bar fraction on the halo mass, we employ two estimates. We calculate the dynamical mass $M_{\text{dyn}}$, as the mass responsible for establishing a flat rotation curve with amplitude $V_{\text{rot}}$ within the HI disk radius:

$$M_{\text{dyn}} = R_{\text{HI}} V_{\text{rot}}^2 G.$$  \(4\)

Given that we do not count with rotation curves, we follow Broeils & Rhee (1997) to estimate the radius of the HI disk ($R_{\text{HI}}$) in terms of the HI mass using one of the tightest scaling relations of galaxy disks (Lelli, McGaugh & Schombert 2016):

$$\log M_{\text{HI}} = 1.96 \log D_{\text{HI}} + 6.52,$$  \(5\)

with $R_{\text{HI}} = D_{\text{HI}}/2$.

The fraction of barred galaxies as a function of dynamical mass is shown in Figure 1c, where $f_{\text{bar}}$ seems to be independent of $M_{\text{dyn}}$.

As a second estimate for the halo mass we turn to the study by van den Bosch (2002), where he explored different virial mass estimators for disk galaxies using models for the formation of these kind of galaxies. The best estimator, with the smallest scatter, is a combination of circular velocity and disk scale radius $r_d$, of the form:

$$M_{\text{halo}} = 2.54 \times 10^{10} M_* r_d^{100 \, \text{km} \, \text{s}^{-1}}.$$  \(6\)

The result using $M_{\text{halo}}$ (Figure 1d) is very similar to the one using $M_{\text{dyn}}$, with little or no dependence of the bar fraction on either of these mass estimates, a result in agreement with Martínez & Muriel (2009) and Wilman & Erwin (2012) who found no evidence of bars preferring any particular halo mass.
amplitude of the disc surface density. The bars are not destroyed by the buckling but continue to grow until the present day. Bars are largely absent when the disc mass is reduced by a factor of 2 or more; the relative disc-to-halo mass is therefore a primary factor in bar formation and evolution. A subset of the discs is warped at the outskirts and contains prominent non-coplanar
haloes, etc. Irrespective of these factors, it appears that the strength of the disc self-gravity relative to the supporting spheroidal potential is by far the most decisive parameter for governing stability against the formation of strong bars. We note that this therefore can-

![Graph showing bar strength against Q_bar.](image)
Sellwood 2016

Models with near uniform central rotation and that lack an extended halo

*Red for $M_h/M_d = 2$
*Green for $M_h/M_d = 3$
*Blue for $M_h/M_d = 4$
*Cyan for $M_h/M_d = 5$

Bar growth slows down with increasing halo mass.
We conclude that, in order to develop strong bars, discs must be locally and globally dominant; in other words, they must con-
$f_\text{bar}$ vs. HI gas mass fraction

![Graph showing $f_\text{bar}$ vs. log ($M_{\text{HI}}/M_\star$)]

Cervantes Sodi 2016, submitted
Masters et al. 2012

- Barred galaxies consume their atomic gas more quickly
- Increasing the atomic gas content in a disc galaxy inhibits bar formation
\[ \log (W(\text{H}\alpha) + 1) [\text{Å}] \]

\[ \log \frac{M_{\text{HI}}}{M_*} \]

Strong
Weak
Unbarred

\[ \log \text{sSFR} [\text{yr}^{-1}] \]

\[ \log \frac{M_{\text{HI}}}{M_*} \]
\[ t_{\text{cons}} = \frac{M_{\text{HI}}}{SFR} \]
Vera, Alonso & Coldwell 2016

Unbarred -> yellow
Weak       -> blue
Strong     -> black

Galaxies with strong bars show low star formation efficiency and older stellar populations.
This bimodal behavior was noted by Berentzen et al. (2007) and Villa-Vargas, Shlosman & Heller (2010). In gas-rich models, with $f_g \gtrsim 15\%$, the peak is lowered gradually for $\epsilon_{grav} \sim 0.05$ and $\Delta t \sim 0.1$, it lies in the range $\sim 10\%$–$12\%$ for $\epsilon_{grav} = 0$ and stays constant or rises in the latter disks. In the secular phase, $\Omega_{b}$ nearly always rises in the gas-rich models and the secular bar growth of the gas-poor ones. Models SD_G50S2 and SD_G15S3 lie close to this borderline, thus, in the gas-poor models, the bar tumbling slows down, while in the gas-rich models it stays nearly constant. Although in no way does this figure account for dynamical softening, it provides a hint to what one can expect for the anti-correlation with $\epsilon_{grav}$.

Gas fraction

Dynamical softening
The time evolution of the bar strength is shown for all runs in Figs. 7 and 10. The four panels show the time evolution of the bar strength for runs with different gas fractions and halo shapes. The top-left panel shows the bar strength for runs with 0% gas and a spherical halo, the top-right panel shows the bar strength for runs with 20% gas and a triaxial halo, the bottom-left panel shows the bar strength for runs with 50% gas and a spherical halo, and the bottom-right panel shows the bar strength for runs with 75% gas and a triaxial halo. The bars grow in strength over time, with the most significant growth occurring during the first 2-3 Gyr. The bars then reach a plateau and gradually decrease in strength over the remaining 5-6 Gyr. The growth and decay of the bars are sensitive to the initial gas fraction and halo shape, with higher gas fractions and triaxial halos leading to stronger and more transient bars.
CONCLUSIONS

• The bar fraction increases with increasing stellar mass.

• At fixed stellar mass, the bar fraction decreases with increasing halo mass. This result is reproduced using three different halo mass estimates.

• Our study suggests that massive dark matter halos help to stabilize galaxies against the formation and/or growth of bars.

• In a similar way, we conclude that the strong anti-correlation between the likelihood of a galaxy hosting a bar with the gas richness of the galaxy results form the inhibiting effect the gas has in the formation of bars.
Thanks and

Happy day of the dead