ON THE GALACTIC SPIN OF BARRED DISK Galaxies

Bernardo Cervantes-Sodi1, Cheng Li1, Changbom Park2, and Lixin Wang1

1 Partner Group of the Max Planck Institute for Astrophysics and Key Laboratory for Research in Galaxies and Cosmology of Chinese Academy of Sciences, Shanghai Astronomical Observatory, Nandan Road 80, Shanghai 200030, China; bernardo@shao.ac.cn
2 Korea Institute for Advanced Study, Dongdaemun-gu, Seoul 130-722, Korea

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ABSTRACT

We present a study of the connection between the galactic spin parameter ($\lambda_d$) and the bar fraction in a volume-limited sample of 10,674 disk galaxies drawn from the Sloan Digital Sky Survey Data Release 7. The galaxies in our sample are visually classified into one of three groups: non-barred galaxies and galaxies hosting long or short bars, respectively. We find that the spin distributions of these three classes are statistically different, with galaxies hosting long bars having the lowest $\lambda_d$ values, followed by non-barred galaxies, while galaxies with short bars present typically high spin parameters. The bar fraction presents its maximum at low to intermediate $\lambda_d$ values for the case of long bars, while the maximum for short bars is at high $\lambda_d$. This bimodality is in good agreement with previous studies finding longer bars hosted by luminous, massive, red galaxies with a low content of cold gas, while short bars were found in low luminosity, low mass, blue galaxies that were typically gas rich. In addition, the rise and fall of the bar fraction as a function of $\lambda_d$, within the long-bar sample shown in our results, can be explained as a result of two competing factors: the self-gravity of the disk that enhances bar instabilities and the support by random motions, instead of ordered rotational motion, that prevents the formation/growth of bars.

Key words: galaxies: fundamental parameters – galaxies: general – galaxies: spiral – galaxies: statistics – galaxies: structure

Online-only material: color figures

1. INTRODUCTION

If we take a look at an image of a galaxy such as NGC 1300, a special feature that immediately catches our attention is the prominence of the bar. At the same time, we can find galaxies of similar mass and overall morphology with no signs of bars. The presence of such prominent non-axisymmetric features must certainly shape the structure and secular evolution of the host galaxies by exerting tidal torques that lead to a redistribution of the galactic constituents (Friedli & Benz 1993).

Through analytical and numerical calculations, previous studies have shown that bars produce a redistribution of mass and angular momentum in the galactic disk (Hohl 1971; Weinberg 1985; Debattista & Sellwood 2000; Athanassoula 2002; Martinez-Valpuesta et al. 2006; Hwang et al. 2013). Stellar density waves can be driven by galactic bars, leading to the formation of spiral arms (Lindblad 1960; Toomre 1960; Elmegreen & Elmegreen 1985) and ring structures (Schwartz 1981; Buta & Combes 1996). Bars can also funnel material toward the galaxy center, especially for the case of the collisional gas component that can dissipate energy during shocks and flow inward (Shlosman et al. 1989; Friedli & Benz 1993). This inflow can produce an accumulation of material in the central region that can help in the build-up of disk-like bulges or pseudo-bulges (Sheth et al. 2005; Laurikainen et al. 2007; Okamoto 2013). This process may be most prominent in the case of early-type galaxies where bars appear larger (Elmegreen & Elmegreen 1985, 1989; Erwin 2005). As a result of these gas inflows, higher molecular gas concentrations are found in the central regions of barred galaxies (Sakamoto et al. 1999; Sheth et al. 2005), as well as younger populations in the bulges of barred galaxies when compared with unbarred ones (Coelho & Gadotti 2011). Numerical simulations by Friedli et al. (1994) show not only inflow, but also outflow induced by the bar; these flows can facilitate the chemical mixing and triggered star formation reported in observational studies (Hummel et al. 1990; Huang et al. 1996; Ellison et al. 2011).

If bars funnel gas inward and most massive galaxies host super-massive black holes (SMBHs), a natural consequence would be enhanced active galactic nucleus (AGN) activity. Mechanisms such as “bars within bars” (Shlosman et al. 1989, 2000) and nuclear spirals (Martini & Pogge 1999; Márquez et al. 2000) have been suggested to transport gas to the vicinity of the SMBH, but in this respect no consensus has been reached. Some authors propose the presence of bars as a triggering factor for AGN activity (Knapen et al. 2000; Laine et al. 2002; Laurikainen et al. 2004), while others are more skeptical (Moles et al. 1995; Mulchaey & Regan 1997; Lee et al. 2012b; Oh et al. 2012).

Some numerical simulations (Hasan & Norman 1990; Norman et al. 1996; Athanassoula et al. 2005) show bar weakening, and in some cases dissolution, by a central mass concentration (CMC) or gravity torques (Bournaud et al. 2005). In order to explain the large proportion of barred galaxies observed in different observational surveys, mechanisms such as the dissolution and reformation of bars as recurrent transient structures has been proposed (e.g., Combes 2000; Bournaud & Combes 2002), as well as the survival of bars in the presence of a CMC (Shen & Sellwood 2004; Debattista et al. 2006).

Recently, the relevance of bars in galaxy evolution has motivated a large number of studies. The fraction of barred galaxies found in optical images varies depending on the method used to identify galaxies with bars and on sample selection, with a typical fraction between 30% and 50% (Barazza et al. 2008; Aguerri et al. 2009; Nair & Abraham 2010; Lee et al. 2012a, henceforth Lee+12). The fraction of barred galaxies appears even higher when near-infrared (NIR) images are used, as weak bars are no longer obscured by dust and are therefore more easily identified (Marinova & Jogee 2007; Menéndez-Delmestre et al. 2013).
2007) since they appear as strong bars in NIR wavelengths (Buta et al. 2010). Analyses of the bar fraction in the Hubble Deep Fields found a dramatic drop of barred systems at $z > 5$ (Abraham et al. 1999; van den Bergh et al. 2002), later confirmed by Sheth et al. (2008) studying a sample of luminous face-on spirals from the 2 deg$^2$ Cosmic Evolution Survey. However, results from other studies report the contrary, a constant bar fraction, at least since $z \leq 1$ (e.g., Elmegreen et al. 2004; Jogee et al. 2004). Sheth et al. (2008) also find that the bar fraction in spiral galaxies is a strong function of stellar mass, color, and bulge prominence, as the fraction increases for more massive, luminous redder systems, with a slight preference for bulge-dominated galaxies. Using a smaller sample of $\sim 190$ galaxies from the Coma Cluster, Méndez-Abreu et al. (2010) found that bars are hosted by galaxies in a tight range of luminosities ($-20 \lesssim M_r \lesssim -17$) and masses ($10^{9} \lesssim M_*/M_\odot \lesssim 10^{11}$). Nair & Abraham (2010) also report this strong dependence on mass, but given that their sample contains low-mass galaxies, they are able to assess that the bar fraction is bimodal in mass. There is a high bar fraction at the low-mass end, mostly in late-type spirals, a decrease of the bar fraction in intermediate mass galaxies (log($M/M_\odot$) $\approx 10.2$), and an increase in the bar fraction again at the high-mass end, where this time most of the barred galaxies are early-type spirals. Recently Lee+12 found that the bar fraction strongly depends on color, with the fraction increasing significantly with redder colors for the case of long bars; an opposite trend is found for galaxies hosting short bars (Buta et al. 2010). Analyses of the bar fraction in the Hubble (2007) since they appear as strong bars in NIR wavelengths. In a previous study, Athanassoula & Sellwood (1986) showed that velocity dispersion has an important influence on bar stability. In their study, they presented a disk with no halo, which was stable because of its high velocity dispersion.

In the present study, we will investigate further if the spin parameter has any direct effect on the presence of bars in disk galaxies. The format of the paper is as follows. In Section 2, we describe the model to infer the spin parameter for disk galaxies in our sample. The sample is described in Section 3. In Section 4, we present our general results of the dependence of the bar fraction on the galactic spin. A discussion regarding our results is presented in Section 5, followed by our conclusions in Section 6.

2. ESTIMATION OF THE GALACTIC SPIN PARAMETER

To account for the spin of disk galaxies, we use the $\lambda$ spin parameter as defined by Peebles (1971):

$$\lambda = \frac{L}{GM^{2/3}},$$

where $E$, $M$, and $L$ are the total energy, mass, and angular momentum of the configuration, respectively. In order to estimate this parameter for the galaxies in our sample, we adopt the model by Mo et al. (1998), as we did in Hernandez & Cervantes-Sodi (2006). Here, we briefly recall the main ingredients of the model. In the framework of the CDM scenario for galaxy formation, primordial density fluctuations give rise to haloes of dark matter of mass $M_\odot$, within which gas condenses and forms rotationally supported disks of maximum circular velocity $V_d$. The disk is expected to be thin and present an exponential surface density profile:

$$\Sigma(r) = \Sigma_0 e^{-r/R_d}.$$  

where $\Sigma_0$ is the central surface density and $R_d$ is the disk scalelength. The corresponding mass is

$$M_d = 2\pi \Sigma_0 R_d^2,$$

which is a fraction $f_d$ of the total halo mass

$$M_d = f_d M.$$  

We describe the dark matter halo by a truncated singular isothermal sphere of radius $R_H = MG/V_c^2$, where $\lambda = \lambda'$, with

$$\lambda' = \frac{L}{\sqrt{2}MV_cR_H},$$

as defined by Bullock et al. (2001). The dark matter halo is responsible for establishing a rigorously flat rotation curve along the disk, from where the angular momentum of the disk is

$$L_d = 2M_dV_cR_d.$$  

Assuming that the specific angular momentum of the disk is a fraction $f_d$ of that of the halo, we can express Equation (5) as

$$\lambda = \left(\frac{\sqrt{2}}{G}\right)\left(\frac{f_d}{f_d}\right)R_dV_d^2M^{-1}.$$  

We define $\lambda_d$ as the product $\lambda_d = \lambda f_d$. In the case of both components, baryons and dark matter, having the same specific angular momentum, $\lambda_d$ becomes $\lambda$ and we recover...
the expression we used to assess the spin of disk galaxies in previous works, i.e., Hernandez & Cervantes-Sodi (2006) and Cervantes-Sodi et al. (2012). The input parameters to estimate the spin of disk galaxies in Equation (7) are the disk scalelength $R_d$, the disk mass $M_d$, the circular velocity $V_d$, and the disk mass fraction $f_d$. $R_d$ is measured from the Sloan Digital Sky Survey (SDSS) $i$-band. As an estimation for the disk mass, we use the stellar mass obtained from the MPA/JHU DR7 VAGC, which is based on fits to the SDSS five-band data with the model of Bruzual & Charlot (2003; see also Kauffmann et al. 2003). Given that the location of a galaxy in the Tully–Fisher (TF) relation does not depend on the presence of a bar (Courteau et al. 2003; Sheth et al. 2012), we determine confidently $V_d$ by the $r$-band Tully–Fisher relation from Pizagno et al. (2007) for all the late-type galaxies in the sample. Finally, following Gnedin et al. (2007), we derive the disk mass fraction in terms of the stellar surface density using

$$f_d = f_0 \left( \frac{M_* R_d^{-2}}{10^{9.2} M_\odot \text{kpc}^{-2}} \right)^p,$$

(8)

where $p = 0.2$ and $f_0$ is chosen using the Milky Way as a representative example. In Cervantes-Sodi et al. (2008), we proved the accuracy of our estimation of $\lambda$ by comparing the estimation using Equation (7) to values arising from numerical simulations of different authors. The result was a one-to-one correlation with a small dispersion and no bias, leading to typical errors of less than 30%. Our estimate of $\lambda$ has also been used by other groups who found it appropriate for different kinds of studies (e.g., Puech et al. 2007; Gogarten et al. 2010; Muñoz-Mateos et al. 2011).

One would expect that galaxies with low spin parameters, being more compact and self-gravitating, would be more prone to global instabilities. A simple criterion for the instability of a thin exponential stellar disk was proposed by ELN82 using a set of N-body experiments; these authors found that a bar instability occurs if

$$\epsilon_c \equiv \frac{V_d}{(GM_d/R_d)^{1/2}} < 1.1,$$

(9)

where $\epsilon_c$ is a measure of the self-gravity of the disk. This value of 1.1 should be compared to the value of a self-gravitating exponential disk: 0.63. By combining Equations (7) and (9), we obtain

$$\epsilon_c^2 = \frac{\lambda_d}{\sqrt{2} f_d}.$$

(10)

In this context, we expect to find an increase in the fraction of barred galaxies as we move from galaxies with high to low spin parameters.

3. DATA

The sample of galaxies analyzed in this work comes from a previous study by Lee+12. It is a volume-limited sample of galaxies extracted from the SDSS DR7 (Abazajian et al. 2009) with absolute $r$-band magnitudes brighter than $M_r \leq -19.5 + 5 \log h$ within the redshift range $0.02 \leq z \leq 0.05489$. A total of 33,391 galaxies were identified from the Korea Institute for Advanced Study Value-Added Galaxy Catalogue (Choi et al. 2010). Given that we focus our analysis on late-type galaxies, we divide this main sample into early- and late-type galaxies using the prescription of Park & Choi (2005), where galaxies are segregated according to their morphology in color versus color gradient and concentration index space. An additional visual inspection was performed to improve the accuracy of the morphology classification.

Galaxies are classified by visual inspection of $g + r + i$ combined color images into long-barred, short-barred, and non-barred systems. A galaxy with a bar that is larger (shorter) than one quarter the size of its host galaxy is classified as long-barred (short-barred). Visual classification is more robust for face-on galaxies, where we also avoid internal extinction effects that would provide an underestimation of $V_d$ when using the TF relation. To this end, we limit our sample to galaxies with minor-to-major axis ratio $b/a > 0.6$. Our final sample contains 10,674 late-type galaxies, 3,240 with long bars and 698 with short bars. As described in Lee+12, this classification shows good agreement with the classification performed by Nair & Abraham (2010) considering the galaxies in common between the two samples; our sample shows only a relatively small fraction of galaxies with short bars when compared with theirs due to a slightly stricter criterion. Figure 3 of Lee+12 also shows some examples of late-type galaxies with long and short bars. For a more detailed description of the sample and comparisons of the classification with previous work, we refer the reader to Lee+12.

4. RESULTS

4.1. Dependence of the Bar Fraction on Galactic Spin

Using our $\lambda_d$ estimate from Equation (7), we calculate the spin parameter for all the galaxies in our sample and look at the empirical distributions $P(\lambda_d)$ of each of the subsamples divided according to their morphology. Figure 1(a) shows the spin distribution of disk galaxies in the sample divided into non-barred galaxies, barred galaxies, and those hosting long and weak bars. Theoretical (Shaw et al. 2006) and empirical (Hernandez et al. 2007) distributions of $\lambda_d$ are traditionally described by a log-normal function of the form

$$P(\lambda_d, \sigma_{\lambda_d}; \lambda_d) d\lambda_d = \frac{1}{\sigma_{\lambda_d} \sqrt{2\pi}} \exp \left[ -\frac{\ln^2(\lambda_d/\lambda_{d1})}{2\sigma_{\lambda_d}^2} \right] d\lambda_d.$$

(11)

The parameters describing the different $\lambda_d$ distributions in Figure 1(a) are listed on Table 1. The four distributions are statistically drawn from different underlying distributions, as confirmed by Kolmogorov–Smirnov tests; significance levels are >99% for all cases. This result shows that long bars are preferentially found in low-spinning galaxies, while short barred galaxies have high spins compared with non-barred galaxies. In Figure 1(b), we present the bar fraction as a function of $\lambda_d$, where we can clearly see two peaks, one at intermediate-low $\lambda_d$ and then an increase for galaxies with high spin. Error bars in Figure 1 and subsequent figures denote the estimated 1σ confidence intervals based on the bootstrapping resampling method.

| Sub-sample | $\lambda_{d1}$ | $\sigma_{\lambda_d}$ |
|------------|---------------|-------------------|
| Non-barred | 0.045         | 0.545             |
| Barred     | 0.039         | 0.507             |
| Long       | 0.035         | 0.449             |
| Short      | 0.061         | 0.419             |
Again dividing the sample into long and short bars, we identify the first maximum with the increase of the fraction of long bars, while the second increase of the bar fraction is due to short bars. As expected, the bar fraction is higher for galaxies with low spin parameters, although this result is only for the case of long bars; the opposite case is observed for galaxies with short bars, with the bar fraction increasing with increasing \( \lambda_d \). If we look at the bar fraction as a function of the disk self-gravity parameter \( \epsilon_c \) (Figure 2(b)), we see that only long bars fulfill the ELN82 stability criterion, while the frequency of short bars increases for galaxies that are expected to be stable against bar formation. It is worth noting that the bar fraction drops for vanishing spin while still fulfilling the ELN82 stability criterion.

The difference of the \( \epsilon_c \)-distributions for the different subsamples shown on Figure 2(a) when compared with the \( \lambda_d \) distributions on Figure 1(a) comes from the dependence on the disk mass fraction as estimated using Equation (8). Typically, the long-barred galaxies have larger \( f_{d,0} \) values than weak-barred or unbarred galaxies. The case of using a constant dark matter fraction produces a qualitatively similar result as the dependence of the bar fraction on \( \lambda_d \), only quantitatively enhancing the difference in the \( \lambda_d \) distributions for the long- and short-barred galaxies. We present our results using this more conservative approach.

4.2. Joint Dependence of the Bar Fraction on the Galactic Spin and Other Galaxy Properties

Previous work has already shown the dependence of the occurrence of bars on different galaxy properties such as luminosity, mass, color, concentration, and gas content. On the other hand, we have also found correlations of the spin parameter with mass (Cervantes-Sodi et al. 2008), color (Hernandez & Cervantes-Sodi 2006), and gas mass fraction (Cervantes-Sodi & Hernandez 2009), among other parameters. For reference, Figure 3 shows the bar fraction as a function of absolute magnitude, stellar mass, color, and concentration index, reproducing the findings of Lee+12 and Lee et al. (2012b). Long bars are preferentially found in luminous, massive, red, highly concentrated galaxies (with low i-band inverse concentration indices \( c_{in} = R_{50}/R_{90} \)), while short-barred galaxies are preferentially found in blue, less massive galaxies with low concentration indices. Within the magnitude limit of our sample, these distributions are in agreement with previous findings (e.g., Nair & Abraham 2010; Méndez-Abreu et al. 2010).

To disentangle the dependence of the bar fraction on the spin and other crucial physical parameters, we look at the bar fraction in two parameter spaces involving the spin and other physical properties. We use a cubic B-spline kernel to obtain a smooth distribution of \( f_{bar} \), calculating the ratio of the weighted number of barred galaxies to the total number of weighted galaxies using a fixed-size smoothing scale.

Figure 4 (top panels) presents the bar fraction in \( \lambda_d \) versus \( M_r \) space. The first fact to notice is that even at fixed \( M_r \) there is a strong variation of \( f_{bar} \) as a function of galactic spin for both cases of short as well as long bars. For the case of long bars (middle column), it is clear that there is a maximum for bright galaxies with low spin parameters, although the bar fraction decreases for the brightest low-spinning galaxies of the sample.
It is also worth noting that the contours elongated in the $M_*$ direction show that the $f_{\text{bar}}$ values for long bars show a stronger dependence on $\lambda_d$ than on $M_*$. The case of short bars is less clear; at fixed $M_*$ there is a trend of increasing $f_{\text{bar}}$ with increasing $\lambda_d$, but no clear trend is found at a fixed spin.

The brighter a galaxy is the more massive it is, especially if we look at absolute magnitudes in redder bands where the underlying stellar mass distribution is better traced and is less affected by current bursts of star formation. In Figure 4 (second row), we present the bar fraction in $\lambda_d$ versus $M_*$ space. The $f_{\text{bar}}$ values for long bars show a gradual increase with increasing stellar mass with a maximum at $11 \times 10^{10} M_\odot$ and then a slight decrease for the most massive galaxies in our sample. With massive galaxies having, in general, low spin parameters, this maximum corresponds to low-spinning galaxies, but at fixed stellar mass we can still notice a strong dependence on $\lambda_d$. Actually, for the most massive galaxies in our sample, those with moderately high $\lambda_d$ values are more prone to hosting long bars. The symmetry of the contours for the case of long bars tells us that the dependence on the spin parameter is as important as the dependence on stellar mass. Short bars are mostly present in low-mass, high-spin galaxies.

The third row of Figure 4 presents the bar fraction in $\lambda_d$ versus $u-r$ space. The double dependence on the chosen parameters is again noticeable. Although we can find blue galaxies with low spin parameters that fulfill the stability criterion for the formation of bars (Equation (9)), in our sample, the long bar fraction of these galaxies is low when compared with red galaxies where $f_{\text{bar}}$ increases. Among red galaxies, systems with high spins present the highest bar fractions. This result is also the case of short bars, but they reside in blue galaxies.

In the last row of Figure 4, we present the bar fraction in $\lambda_d$ versus $c_{\text{in}}$ space. It is clear in this case that once we fix a specific value for $\lambda_d$, there is very little variation of the bar fraction with concentration index, with the exception of the less concentrated systems, especially for the case of long bars. Given this fact, we can attribute the dependence of $f_{\text{bar}}$ on $c_{\text{in}}$ directly to the spin of the galaxies.

4.3. Dependence of the Bar Fraction on Random Motions

As shown in Figure 1, the dependence of the bar fraction on the spin parameter is different for long and short bars. For the case of galaxies with long bars, the bar fraction reaches its maximum at intermediate-low $\lambda_d$ values. Since it is the self-gravity of the disk that drives dynamical instabilities responsible for the formation of the bar, galaxies with low spin, being less dispersed, will be more prone to hosting a bar. Our finding of a decreasing bar fraction with increasing $\lambda_d$ is in good agreement with the vanishing bar fraction in galaxies expected to be stable against bar formation, as accounted for by the ELN82 stability criterion.

It is important to point out that the maximum bar fraction is at low spin values, but as we approach spin values of zero, the bar fraction decreases dramatically. These galaxies are expected to be dynamically unstable and prone to the formation of bars as they are the most self-gravitating systems, but at the same time, as their spin value decreases, their rotational support is also diminished and random motions are expected to start dominating. Numerical studies (Athanassoula & Sellwood 1986; Athanassoula 2008) show that disks that are expected to be unstable in terms of the ELN82 stability criterion become stable against bar formation due to their high velocity dispersion, delaying the formation of a bar. Observational results confirm this hypothesis. Das et al. (2008) found in a sample of local
Figure 4. Bar fraction isocontours in $\lambda_d$ vs. $M_r$ (first row), $M_*$ (second row), $u-r$ (third row), and $c_{in}$ (fourth row) space. The left column corresponds to long plus short bars, the middle column corresponds to long bars, and the right column corresponds to short bars. Each panel shows its corresponding $f_{bar}$ range and coding. (A color version of this figure is available in the online journal.)
Sheth et al. (2012) analyzed a sample at higher redshift and found that the central component becomes kinematically hotter. More recently, Cervantes-Sodi et al. (2013) concluded that the decline of the bar fraction in galaxies with centers that are dynamically too hot. Alternatively, Scannapieco & Athanassoula (2012) studied the properties of bars formed in fully cosmological hydrodynamical simulations of Milky Way-mass galaxies. These authors found that the longest bar is formed in a bulge–disk–halo system with the lowest spin parameter and that the shortest bar is found in a galaxy with a disk but no significant bulge and the highest spin parameter. Previous studies have shown similar results (Athanassoula & Misiriotis 2002; Athanassoula 2003); stronger bars reside in galaxies with prominent bulges. Hernandez & Cervantes-Sodi (2006) noticed that galaxies with the largest bulge-to-disk ratio are those with low spin parameters. The corresponding two-dimensional maps for the bar fraction in log(σ) versus log(λ_d) space are shown in Figure 6. In agreement with what we expected, we first notice the anti-correlation between the two physical parameters. For the case of long bars, a clear decrease of the bar fraction, even for low-spinning systems, is observed when σ > 160 km s^{-1}. Although this result cannot be regarded as proof for our hypothesis, given that our λ_d estimation stems from invoking the TF relation and not from a pure kinematic study, this finding can be explained as a result of two competing factors: the self-gravity of the disk that enhances the formation of bars and the support by random motions that works in the opposite direction, preventing bar instabilities.

5. DISCUSSION

Galaxies hosting a short bar have typically higher spins than those hosting long bars or non-barred galaxies, with the bar fraction increasing with increasing λ_d. The presence of these short bars in high λ_d systems contradicts the ELN82 stability criterion, as shown in Figure 2(b) where the bar fraction increases even for galaxies with ϵ_c > 1.1. As pointed out by Sellwood & Moore (1999), while the normal bar instability gives a natural explanation for the presence of strong bars, there is no alternative mechanism to explain the existence of weak bars. Erwin (2005) presents a careful and extensive comparison of bar lengths between observational and numerical results and concludes that the simulations compared with his results tend to produce long bars. Except for two early simulations (Penninger & Friedli 1991; Combes & Elmegreen 1993), no N-body bars are as small as typical Sc–Sd bars that are expected to be in galaxies with high spin parameters.

An extreme case of high spinning systems is low surface brightness galaxies. Simulations with λ_d > 0.04 are able to reproduce some of the physical characteristics of these galaxies such as their surface density profiles and colors (e.g., Jimenez et al. 1998; Kim & Lee 2013). While these systems are expected to be both stable against bar formation due to the low self-gravity of their disks and be dark matter dominated at all radii, some simulations are able to produce bars that display a mild oval distortion (Mihos et al. 1997), with short-lived episodes that finally evolve into a bulge-like structure (Mayer & Wadsley 2004).

The fact that bars appear short in high-spinning galaxies could be due to the low efficiency of their disks as angular momentum sinks. The disperse disks of these systems are unable to carry away the necessary amount of angular momentum from the bar in order to grow to the extent of typical bars of low-spinning galaxies.

Recently, Scannapieco & Athanassoula (2012) studied the properties of bars formed in fully cosmological hydrodynamical simulations of Milky Way-mass galaxies. These authors found that the longest bar is formed in a bulge–disk–halo system with the lowest spin parameter and that the shortest bar is found in a galaxy with a disk but no significant bulge and the highest spin parameter. Previous studies have shown similar results (Athanassoula & Misiriotis 2002; Athanassoula 2003); stronger bars reside in galaxies with prominent bulges. Hernandez & Cervantes-Sodi (2006) noticed that galaxies with the largest bulge-to-disk ratio are those with low spin parameters, a result that fits in this picture of galaxies with low λ_d values showing longer bars that galaxies with high spins.

The competing effects of self-gravity in the development and growth of bar instabilities and the suppression through random motions in dispersion-dominated systems helps to explain the dependence of the bar fraction on the galactic spin. Given the clear trend for mean λ_d values increasing with later Hubble types (Cervantes-Sodi & Hernandez 2009 and references therein), our results are in good agreement with previous studies regarding the bar fraction as a function of morphological type, in the sense that bars in early-type, low-spinning galaxies are longer than those in late-type, high-spinning ones (e.g., Erwin 2005).
An additional factor that might be playing an important role is the content of cold gas. Galaxies with high spins typically have late-type morphologies, with blue colors and higher gas mass fractions. In these systems, the ELN82 stability criterion might not apply, as pointed out by Christodoulou et al. (1995), due to the large influence the gas has on the formation and development of stellar bars. The threshold value found in simulations varies depending on the amount of gas and the type of cooling that is implemented (Mayer & Wadsley 2004), but in general the gas component severely limits bar growth and evolution (Villa-Vargas et al. 2010), usually producing weak, short-lived bars. Previously, Shlosman & Noguchi (1993) studied the effect of gas on the global stability of a galactic disk embedded in a live halo and they found two different regimes: in a low-gas surface density disk, the radial redistribution of the gas depends solely on the stability of the stellar disk; while for high-gas surface densities, the gas develops inhomogeneities that heat up the stellar component and increase the stability of the system, thereby preventing the growth of bars. This result fits well with our findings, where long bars are hosted by luminous, massive, red galaxies that typically have low gas content, while short bars are found in low-luminosity, low-mass, blue galaxies that are usually gas rich.

In a recent study by Athanassoula et al. (2013), the authors followed the formation and evolution of bars in N-body simulations of disk galaxies with gas where the gas component was modeled as a multiphase medium including star formation, feedback, and cooling. The study showed that in gas-rich simulations, the disk stays axisymmetric longer than in gas-poor simulations. Furthermore, once the bar forms, it grows at a much slower rate. This result explains why fully grown bars are in place earlier in massive red disks than in blue spirals. In a subsequent study, we will investigate the combined effect of the gas content and spin on the bar properties of disk galaxies.

6. CONCLUSIONS

In summary, we report a strong dependence of the bar fraction on the galactic spin of disk galaxies. This dependence on \( \lambda_d \) is different for long and short bars. Long bars are preferentially found in galaxies with low to intermediate \( \lambda_d \) that are more prone to develop bar instabilities due to their self-gravitation. These galaxies are typically massive, luminous, red, gas-poor systems when compared with galaxies hosting short bars. Instead, short bars are mostly found in high-spinning galaxies that at the same time are typically low-mass, faint galaxies rich in cold gas, with blue colors.

The rise and fall of the bar fraction for the case of long bars as a function of \( \lambda_d \) can be explained as the result of two competing factors: the self-gravity of the systems and the support by random motions. At high \( \lambda_d \) values, the decline of the bar fraction is due to the lack of self-gravity, as when the disk is more sparse, global instabilities are suppressed or damped. At low \( \lambda_d \) values, the support of the system by random motions instead of ordered rotation dominates and prevents the formation and growth of bars.

Our finding of short bars being hosted by high-spinning galaxies is in good agreement with previous observational and theoretical studies, considering that these systems are preponderantly blue, gas-rich galaxies. The sparsity of the disk material and the large fraction of gas play an important role in restricting the formation/growth of the bar.

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