Evidence for Secular Evolution of Disc Structural Parameters in Barred Galaxies

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Abstract

We address the effects of bar-driven secular evolution in discs by comparing their properties in a sample of nearly 700 unbarred and barred (42 ± 3 per cent of the population) massive disc galaxies ($M_\star \geq 10^{10} M_\odot$). We make use of accurate structural parameters derived from bulge/disc/bar decompositions to show that, as a population, barred discs tend to have fainter central surface brightness ($\Delta_{\mu_0} \approx 0.25$ mag in the $i$-band), and disc scale lengths that are larger by a factor $\approx 1.15$ than those of unbarred galaxies. The corresponding distributions of $\mu_0$ and $h$ are statistically inconsistent at the 5.2 $\sigma$ and 3.8 $\sigma$ levels, respectively. Bars rarely occur in high-surface brightness discs, with less than 5 per cent of the barred population having $\mu_0 < 19.5$ mag arcsec$^{-2}$ – compared to 20 per cent for unbarred galaxies. They tend to reside in moderately blue discs, with a bar fraction that peaks at $(g-i) \approx 0.95$ mag and mildly declines for both bluer and redder colours. These results demonstrate that bars induce noticeable evolution in the structural properties of galaxy discs, in qualitative agreement with longstanding theoretical expectations.

Key words: galaxies: structure – galaxies: evolution – galaxies: formation – galaxies: fundamental parameters – galaxies: photometry – galaxies: spiral

1 INTRODUCTION

Secular processes are expected to have played a significant role in establishing the current properties of massive disc galaxies. These are dynamically evolved systems, as evidenced by the presence of a population of discs at $z \sim 1$ with similar scale lengths (Lilly et al. 1998; Simard et al. 1999; Barden et al. 2005) and bar fraction (Jogee et al. 2004; Sheth et al. 2008) to what is found in the Local Universe. This suggests that the quiescent phase of massive disc evolution started at least 8 Gyr ago, thus leaving ample time for secular mechanisms to operate (but see Hammer et al. 2005).

Bars perhaps provide the most clear evidence of the impact of secular evolution on disc galaxies. Analytical and numerical calculations show that they drive a significant amount of mass and angular momentum redistribution in the disc (Hohl 1971; Sellwood & Wilkinson 1993; Athanassoula 2003; Martinez-Valpuesta et al. 2006), funneling material towards the galaxy inner regions that can result in enhanced gas and stellar densities – thus possibly fueling nuclear starbursts and AGNs (Shlosman et al. 1989) and leading to the formation of central bulge-like components (Kormendy & Kennicutt 2004; Debattista et al. 2006). Furthermore, the angular momentum exchange between the inner and outer disc can lead to increased disc scale lengths, and the development of mass profile breaks at large radii (Valenzuela & Klypin 2003; Debattista et al. 2006).

It is precisely the amount of angular momentum exchanged within the galaxy that determines the bar strength, and this ultimately depends on the mass and velocity distributions of the material in the disc and spheroidal (bulge plus halo) components (Athanassoula 2003). Once formed, these non-axisymmetric perturbations appear to be long-lived, surviving buckling instabilities and the growth of a significant central mass concentration (> 10%, and perhaps up to 20% of the original disc mass; Shen & Sellwood 2004; Athanassoula et al. 2005; Debattista et al. 2006). On the other hand, Bournaud et al. (2003) suggest that a substantial gas component in the disc (~7% of the total visible mass) might lead to the weakening, or even destruction of the bar due to the angular momentum exchange resulting from gas inflow. However, this effect is significantly reduced when a responsive dark matter halo model is considered (Berentzen et al. 2007).

The importance of bars in galaxy evolution studies does not only stem from the fact that they can significantly impact the evolution of a given galaxy, but also because such
structures are rather common in disc galaxies. Visual classification using photographic plates yields a bar fraction of 65 per cent in the RC3 catalogue (de Vaucouleurs et al. 1991), and recent optical studies indicate that approximately half of all massive disc galaxies contain bars (Marinova & Jogee 2008; Menéndez-Delmestre et al. 2007; Buta et al. 2010). The fraction of strong bars increases substantially in dust-penetrating near-infrared wavelengths, but the total bar fraction does so only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009). Since only slightly, as compared to the RC3 (Eskridge et al. 2009).

It is however now clear that the bar fraction in the Local Universe is a strong function of the galaxy stellar mass (Méndez-Abreu et al. 2010; Nair & Abraham 2010; Cameron et al. 2011), and thus consistent results can only be obtained when comparing samples well matched in $M_*$. Even though wavelength coverage, detection technique, and possibly to a larger extent sample selection, all play a role in the detection of bars in disc galaxies, most studies point to fractions ~50 per cent in $L > L^*$ galaxies.

The picture that emerges from theoretical work is corroborated, at least qualitatively, by a number of observational results. The bar-driven redistribution of angular momentum affects the interstellar medium in galaxies, resulting in flatter chemical abundance gradients in barred galaxies (Martin & Ros 1994; Zaritsky et al. 1994), as well as higher central concentrations of molecular gas (Sakamoto et al. 1994; Sheth et al. 2003). More recently, evidence has been found that the gas brought to the centre by bars is efficiently transformed into stars. Ellison et al. (2011) present indication that the current star formation rate at the centre is higher in massive barred galaxies. Coelho & Gadotti (2011) show that the distribution of mean stellar ages in bulges of massive barred galaxies shows a peak at low ages that is absent for their unbarred counterparts (see also Pérez & Sánchez-Blázquez 2011).

Yet investigation of the effects of bar-driven secular evolution on the structural properties of discs is currently lacking in the literature. In this Letter we fill this gap by comparing the disc properties in sample of nearly 700 barred and unbarred galaxies.

2 GALAXY SAMPLE

The sample used here is the one presented in Gadotti (2009). It contains all galaxies in the SDSS-DR2 with stellar masses $M_*/10^{10} M_\odot$ from Kauffmann et al. (2003), at redshift $0.02 \leq z \leq 0.07$, and with axial ratio $b/a > 0.9$. These criteria provide a sample which is both representative and suitable for 2D bulge/disc/bar decomposition. The redshift range allows for enough spatial resolution, while selecting face-on galaxies minimizes dust and projection effects, and eases the identification of bars. The reader is referred to that paper for a detailed discussion of selection effects.

Through multi-band (gri) 2D decomposition, Gadotti (2009) provides accurate structural parameters for the three components (when necessary) — including the central surface brightness, scale length, integrated colour and stellar mass of the disc component, as well as the galaxy bulge-to-total ratio. Despite of the inherent complexity of bulge/disc/bar decompositions, Gadotti (2004). Appendix A) shows that disc structural parameters are particularly stable, and therefore both $h$ and $\mu_0$ can be robustly derived even in the presence of a bar. Moreover, it is important to recall that failing to account for the contribution of the bulge results in structural parameters corresponding to a maximum disc, and therefore our multi-component fits provide the least biased results. In this Letter we focus on structural parameters derived from fits in the $i$-band, as it is the least affected by dust and recent star formation. Disc stellar masses were obtained from disc luminosities and mass-to-light ratios in the $i$-band, the latter derived from the integrated $(g−i)$ disc colour and the relation determined by Kauffmann et al. (2007). In order to select a clean sample of disc galaxies, only systems having $B/T < 0.8$ have been considered.

To verify whether a galaxy is barred, typical bar signatures were searched for through the inspection of each galaxy image, isophotal contours and a pixel-by-pixel radial intensity profile. It should be noted that due to the limited spatial resolution of SDSS images we miss most bars with semi-major axis shorter than $L_{bar} \approx 2h$, which are mainly found in very late-type spirals (later than Sc; Elmegreen & Elmegreen 1983) and are usually not detected in most recent studies (e.g., Barazza et al. 2008; Aguerri et al. 2009). Gadotti (2011) presents a detailed analysis of the structural properties of the bars in this sample.

Our final sample consists of 291 barred and 393 unbarred disc galaxies, corresponding to a bar fraction of 42 ± 3 per cent (binomial 90% uncertainty) — in excellent agreement with previous studies (e.g., Aguerri et al. 2009). Both subsamples are perfectly matched in disc stellar mass, with 2.5, 50 and 97.5 per cent quantiles of $[0.5,7,2.5] \times 10^{10} M_\odot$ and $[0.4,6.6,5] \times 10^{10} M_\odot$ for barred and unbarred galaxies, respectively.

3 PROPERTIES OF DISCS IN BARRED AND UNBARRED GALAXIES

Figure 1 reveals the striking differences of the structural scaling relations of galaxy discs in barred and unbarred galaxies. Panels 1a and 1b show, respectively, the $i$-band disc central surface brightness ($\mu_0$) and scale length ($h$) as a function of disc stellar mass, while panel 1c depicts the bivariate distribution of the two former quantities. Isocontours in all panels enclose 25, 75 and 95 per cent of each population. There are several remarkable features worth discussing. First, panel 1a shows that the distribution of disc central surface brightness is significantly different for barred and unbarred galaxies, in
Figure 1. Structural scaling relations of discs in barred and unbarred galaxies. In all panels isocontours enclose 25, 75 and 95 percent of each population. a) Disc central surface brightness, $\mu_0$, as a function of disc stellar mass. b) The disc scale length vs stellar mass relation. c) Joint $\mu_0$-$h$ relation for both subsamples. All parameters are derived from fits to the $i$-band images. It is clear that discs in barred galaxies are characterised by having fainter central surface brightness and larger scale lengths. Note the lack of bars in galaxies having compact, high surface brightness discs. Shaded regions indicate discs where we likely miss more than half of the bars because of their small length.

the sense that at a given disc stellar mass barred galaxies tend to have fainter $\mu_0$ values – note how all isocontours extend towards much brighter $\mu_0$ for unbarred galaxies than for barred ones. Notably, the reduction in surface brightness is accompanied by an increase of disc scale length (panel 1b), resulting in markedly dissimilar distributions in the $\mu_0$-$h$ plane (panel 1c). While unbarred galaxies populate the high-surface brightness and small-scale lengths parameter space, barred galaxies are essentially absent from this region – only 5 per cent of all barred galaxies have $\mu_0 < 19.5$ mag arcsec$^{-2}$, while this fraction increases up to 20 per cent for unbarred discs. One potential explanation for the lack of bars in these discs is that they have semi-major axis lengths $L_{\text{bar}} \lesssim 2$ kpc and thus remain undetected. Gadotti (2011) shows that there is a tight relation between $L_{\text{bar}}$ and $h$, with a median ratio $L_{\text{bar}}/h = 1.5$ that appears to be independent of disc scale length within this sample. This implies that we likely miss more than half of the bars in discs having $h \lesssim 1.33$ kpc. The shaded areas in Fig. 1 highlight this region of incompleteness, and show that the paucity of bars in high surface brightness discs is real. First, we still detect bars in these small discs, but they only occur in the lowest surface brightness systems. Second, panel 1c shows that bars are still missing in larger discs having $\mu_0 < 19.5$ mag arcsec$^{-2}$, where bar non-detection is not an issue. The remarkable result is the paucity of long bars in these systems, and the evidence that barred discs extend towards the large-$h$, faint-$\mu_0$ region of the plot.

These differences can be more clearly appreciated in Fig. 2 where we show the normalised distributions of $\mu_0$ and $h$ for our two populations (panels 2a and 2b, respectively). The central surface brightness distribution of discs in unbarred galaxies peaks at a moderately more luminous value, and features a distinct extended tail towards brighter $\mu_0$. A Kolmogorov-Smirnov test rules out the null hypothesis that the two distributions are drawn from the same parent population at the 5.2$\sigma$ level. The distributions of disc scale lengths for both populations are also inconsistent at the 3.8$\sigma$ level according to the KS test. The two distributions would however be statistically indistinguishable if barred galaxies had 0.25 mag brighter central surface brightness and 15 per cent smaller scale lengths. It is important to note that, despite the high statistical significance of the differences here reported, there is considerable scatter at a given disc stellar mass: $\sigma_{\mu_0} \approx 0.5$ mag and $\sigma_h \approx 1.10$ kpc.

Aside from the structural scaling relations, we investigate the stellar population properties of discs in our sample of barred and unbarred galaxies. Fig. 3 presents the relation between the disc stellar mass and its integrated $(g-i)$ colour, while panel 3b shows the corresponding normalised colour distributions. The disc colour distribution appears to be marginally bimodal for both populations but, remarkably, their peaks differ from $(g-i) \approx 1.25$ for unbarred galaxies to $(g-i) \approx 0.95$ for barred ones. The dark gray curve in Fig. 3 shows the bar fraction as a function of disc colour (only for bins having more than 5 galaxies), while the light gray curves correspond to the binomial 90% confidence intervals. Bars tend to reside in moderately blue discs, with a fraction that peaks at $\approx 55$% at the previously mentioned value and mildly declines for both bluer and redder discs – in qualitative agreement with previous work (Aguerri et al. 2004; Masters et al. 2011). The fraction of bars in galax-

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Figure 2. Normalised distributions of disc central surface brightness (a) and disc scale lengths (b) for barred and unbarred galaxies. According to a Kolmogorov-Smirnov test, the corresponding distributions of $\mu_0$ and $h$ are statistically inconsistent at the 5.2$\sigma$ and 3.8$\sigma$ levels, respectively. As a population, discs in barred galaxies tend to have $\approx 0.25$ mag fainter central surface brightness and $\approx 15$ per cent larger disc scale lengths.
ies with very blue colours is probably a lower limit (cf. Nair & Abraham 2010), as we recall that these late-type systems can contain small bars that are undetected in our images.

4 DISCUSSION AND CONCLUSIONS

We have shown that barred and unbarred $M_\ast > 10^{10} M_\odot$ galaxies are characterised by distinct distributions of disc structural parameters. As a population, barred discs tend to have fainter central surface brightness ($\Delta \mu_0 \approx 0.25$ mag in the $i$-band) and disc scale lengths that are larger by a factor $\approx 1.15$ than those of unbarred galaxies. This value is close to, but slightly lower than, that predicted by the numerical simulations of Valenzuela & Klypin (2003), where discs were found to increase their scale lengths by factors 1.2–1.5 due to the transfer of angular momentum that accompanies the formation of a bar. Nevertheless, the moderate increment of scale lengths revealed by the data has to be thought of as a lower limit to the actual effects of bar-driven secular evolution. The reason is twofold.

First, it is important to recall that bars are not the only drivers of disc secular evolution. In fact, any type of non-axisymmetric perturbation—including spiral arms, oval distortions and triaxial dark matter haloes—can also modify the properties of discs (e.g., Kormendy & Kennicutt 2004; Sellwood 2010), but they generally operate on longer timescales. It is therefore possible that secular evolution has also occurred, to some degree, in our sample of unbarred galaxies.

Second, our disc structural parameters come from fitting one single exponential to the surface brightness profile, with no distinction between different disc Freeman types (Freeman 1970). This can slightly bias our recovered parameters, resulting in marginally brighter $\mu_0$ and smaller $h$ in the case of Type II profiles with outer truncations – which occur far more often than single exponential, Type I profiles (e.g., Pohlen & Trujillo 2006). This is indeed supported by the recent analysis of disc properties in S\textsuperscript{4}G galaxies (Sheth et al. 2014). Muñoz-Mateos et al. (in preparation) find that, when allowing for outer profile breaks, disc scale lengths in barred galaxies are, on average, a factor $\approx 1.8$ larger than those without bars – but, as in our case, the scatter at fixed $3.6 \, \mu$m magnitude is large.

In any case, our fits provide the optimal average exponential profile between small and large radii, and thus allow for a direct comparison with the numerical simulations by Debattista et al. (2006). Not surprisingly, they find that the amount of evolution in their simulated discs depends critically on the initial disc kinematics. The density profiles of highly unstable discs (low Toomre’s $Q$) evolve dramatically compared to more stable initial configurations, resulting in final scale length differences of factors $\gtrsim 2$ even for models with nearly identical initial angular momentum. The general situation is of course more complex than this, and the specific density profile evolution in their simulations is determined by the phase-space distributions of the stellar disc and the dark matter halo – resulting in scale lengths changing by factors 1.0–2.4. As Debattista et al. (2004, 2006) point out, this has the important consequence that direct estimates of dark matter halo spin parameters from measured disc scale lengths can be rather uncertain.

Our results support their claims, but suggest that the amount of scale length evolution due to bar formation is only moderate. A simple back-of-the-envelope argument appears to be consistent with this idea. If secular mechanisms were to increase disc scale lengths by a considerable amount—say, factors larger than two—we would then expect to see clear signs of evolution in the mass-size relation of discs between redshifts $0 < z < 1$. Yet observations support mild to no evolution at all (Lilly et al. 1998; Simard et al. 1999; Barden et al. 2003) and this, in turn, is consistent with real discs being reasonably stable ($Q \gtrsim 1.5$; e.g., Kregel et al. 2002). If this is the case, and considering all the assumptions involved, it is most likely that the uncertainties derived from mapping halo spin to disc scale lengths are not dominated by secular evolution effects – but they certainly are a contributing factor.

It is not yet clear if there exists one single condition determining whether a galaxy will be bar-stable or not. Athanassoula (2008) shows that simple criteria that do not fully capture the complexity underlying bar formation [e.g., the Efstathiou et al. (1982) criterion] generally fail to correctly predict disc stability. Instead, numerous factors come into scene in order to stabilise a disc against non-axisymmetric perturbations. Thus, galaxies with very weak or no bars must have either a kinematically hot disc and/or a significant central mass concentration and/or a very low relative disc mass and/or be embedded in a quite unresponsive dark matter halo (Athanassoula 2003; Sellwood 2010). From the disc component point of view, a high stellar velocity dispersion can provide significant stabilisation and prevent the formation of a bar for over a Hubble time (Athanassoula & Sellwood 1986). Moreover, Sellwood & Evans (2001) show that a steeply rising inner rotation curve is sufficient to bar-stabilise a disc, regardless of the dark matter content. In this context, the realisation in Fig. 4 that compact, high-surface brightness discs do not host bars – or if they do, they are rather small– is intriguing, and it is tempting to think of these systems as having...
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a high rate of shear at the centre capable of (almost) fully stabilising the disc. Kinematical studies of these galaxies are highly desirable in order to test this hypothesis and clarify their lack of bars.

Finally, basic stability criteria and numerical simulations suggest that bars are more easily triggered in gas-rich (i.e., cold), star-forming discs. This provides a natural explanation for the preferential occurrence of bars in moderately blue discs, but the exact shape of the bar fraction distribution deserves further investigation. Even though such an analysis is beyond the scope of this Letter, one can naively think that gas consumption through star formation leads to redder and kinematically hotter (more bar-stable) discs. In this context, the declining fraction towards bluer colours has probably to be understood in terms of a selection effect, such that these galaxies contain smaller bars that remain undetected in our images.

We have shown that bars drive noticeable structural evolution of galaxy discs, confirming longstanding analytical and numerical predictions. Detailed structural decomposition of galaxies provides one of the most powerful diagnostics for galaxy evolution studies, allowing for direct, quantitative comparisons with theory and simulations.

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