ON THE FRACTION OF BARRED SPIRAL GALAXIES

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ABSTRACT

We investigate the stellar masses of strongly barred spiral galaxies. Our analysis is based on a sample of ~14,000 visually classified nearby galaxies given by Nair & Abraham. The fraction of barred spiral galaxies is found to be a strong function of stellar mass and star formation history, with a minimum near the characteristic mass at which bimodality is seen in the stellar populations of galaxies. We also find that bar fractions are very sensitive to the central concentration of galaxies below the transition mass but not above it. This suggests that whatever process is causing the creation of the red and blue sequences is either influencing, or being influenced by, structural changes which manifest themselves in the absence of bars. As a consequence of strong bar fractions being sensitive to the mass range probed, our analysis helps resolve discrepant results on the reported evolution of bar fractions with redshift.

Key words: galaxies: fundamental parameters – galaxies: photometry – galaxies: structure

1. INTRODUCTION

Understanding the role of bars in galaxy formation is central to understanding the evolution of galaxies. Bars are important structures that help to redistribute angular momentum between baryonic and dark matter components in disk galaxies (Weinberg 1985; Debattista & Sellwood 2000; Athanassoula 2002) thereby driving their secular and dynamic evolution (Kormendy & Kennicutt 2004). Bars are thought to drive spiral arms (Lindblad 1960; Toomre 1969; Sanders & Huntley 1976) and ring structures (Schwarz 1981; Buta & Combes 1996; Martinez-Valpuesta et al. 2006). They transport gas/matter to the centers of galaxies (Knapen et al. 1995; Hunt & Malkan 1999) and help to build bulges (Laurikainen et al. 2007) and possibly trigger active galactic nucleus (AGN) activity (Laine et al. 2002; Knapen et al. 2000; Laurikainen et al. 2004).

The importance of bars in galaxy evolution has motivated a number of recent studies. In a comprehensive investigation of the fraction of barred spirals as a function of cosmic epoch, Sheth et al. (2008) used a sample of 2000 galaxies from the Hubble Space Telescope COSMOS survey (Scoville et al. 2007) to show that the bar fraction decreases with redshift, as claimed by Abraham et al. (1999) and van den Bergh et al. (2002; but see Elmegreen et al. 2004 and Jogee et al. 2004). In addition, SE08 also find that the bar fraction of spiral galaxies is a strong function of stellar mass, color, and bulge prominence such that more massive, redder, concentrated galaxies have a larger bar fraction than less massive, bluer, disky galaxies. These observations are rather different from those presented by Barazza et al. (2008, hereafter BJ08), who examined a sample of ~2000 galaxies from the Sloan Digital Sky Survey (SDSS) in the redshift range between 0.01 and 0.03. In sharp contrast with SE08, these authors claim that bar fractions increase with decreasing mass and bluer colors (corresponding to late-type galaxies).

Can the observations of SE08 and BJ08 be reconciled? One possibility is that the different claims represent an evolutionary effect. This seems unlikely because the trends reported by SE08 apply equally well in the lowest redshift bin of that investigation.

A more promising explanation lies in the fact that, for obvious reasons, magnitude-limited surveys of high-redshift galaxies will always tend to probe more massive galaxies than those probed by low-redshift surveys. Therefore, the stellar mass ranges spanned by the galaxies in SE08 and BJ08 only partially overlap. SE08 is not sensitive to galaxies with stellar masses $M < 10^{10.2} M_\odot$ (thus missing many dwarf systems), while BJ08 is not sensitive to galaxies with stellar masses $M > 10^{10.5} M_\odot$ (thus missing the most luminous and massive objects in the local universe). It therefore seems quite conceivable that the apparent discrepancy in these studies is due to differences in the stellar mass ranges being probed.

To test this hypothesis, and to learn more about the nature of barred spiral galaxies at a range of masses, we use the sample of 14,034 visually classified galaxies from Nair & Abraham (2010, hereafter Paper I). The reader is referred to Paper I for details but in summary all spectroscopically targeted galaxies from the SDSS DR4 (Stoughton et al. 2002; York et al. 2000), with an extinction-corrected $g$-band magnitude $g < 16$ at redshifts between 0.1 and 0.1, were visually classified by one of the authors (P.N.) using the Carnegie Atlas of Galaxies (Sandage & Bedke 1994) as a visual training set. Comparisons of our classification with the Third Reference Catalog of Bright Galaxies (RC3; de Vaucouleurs et al. 1991) for the ~1700 objects in common showed excellent agreement with a mean deviation of 1.2 T-Types. Bars in our sample were visually identified and are equivalent to “strong bars” in the RC3 catalog (as noted in Paper I). In order to simplify our investigation, we restrict ourselves to disk galaxies (which we define to be S0 galaxies and later with axial ratios $b/a > 0.4$). The bar fraction for this sample is ~30%, with 2312 barred galaxies. We use the stellar masses derived by Kauffmann et al. (2003a) for the following analysis.

2. STELLAR MASS AND COLOR DISTRIBUTIONS

Figure 1 shows the fraction of barred spiral galaxies as a function of mass and ($g-r$) color for our sample of disk objects.
The top row shows a histogram of the number of bars, while the bottom row shows the fraction of barred systems in each mass bin. Error bars on the fractions have been computed assuming binomial statistics. For the sake of clarity, we have excluded bins with fewer than 10 barred objects. The distribution is keyed to galaxy type where S0+Sa galaxies are represented by the red curve, Sb galaxies by the purple curve, and Sc+Sd galaxies by the blue curve. The figure clearly shows that the bar fraction of local galaxies is bimodal with respect to stellar mass and color, with fewer than 10 barred objects. The distribution is keyed to galaxy type where S0+Sa galaxies are represented by the red curve, Sb galaxies by the purple curve, and Sc+Sd galaxies by the blue curve. The figure clearly shows that the bar fraction falls steeply from low masses to intermediate masses, $M\sim 10.2$, and rises slowly and plateaus thereafter. With $(g-r)$ color, we find that the bar fraction decreases from bluer colors to intermediate colors, $(g-r)\sim 0.5$, and rises slowly thereafter.

The results just described give us some insight into the importance of potential systematic effects which may be relevant for understanding results from other surveys. For example, a decreasing bar fraction from low to intermediate masses is also seen by BJ08. However, BJ08 find that the bar fraction continues to decrease with increasing mass from log($M/M_\odot$) $\sim 9$ to log($M/M_\odot$) $\sim 10.7$, a range over which BJ08’s data become sparse, while our own data show a slightly increasing/constant bar fraction over this mass range, we conclude that the apparent discrepancy in the results of SE08 and BJ08 in this mass regime is probably due to the fraction of barred spiral galaxies being a strong function of stellar mass, with these surveys preferentially sampling below and above the characteristic mass. Since our own data show a slightly increasing/constant bar fraction over this mass range, we conclude that the apparent discrepancy in the results of SE08 and BJ08 in this mass regime is probably due to the fraction of barred spiral galaxies being a strong function of stellar mass, with these surveys preferentially sampling below and above the characteristic mass of log($M/M_\odot$) $\sim 10.2$ at which the bar fraction is at its minimum.

Our result also provides a possible solution to the discrepancy between the redshift evolution found by Sheth et al. (2008) and the works by Jogee et al. (2004) and Elmegreen et al. (2004). SE08 find that the bar fraction strongly decreases as a function of redshift. Their sample probes $M_v < -21.7$ at $z \sim 0.9$ and log($M/M_\odot$) $> 10.2$, whereas Jogee et al. (2004) find a near-constant bar fraction using fainter samples with $M_v < -19.3$ and $M_v < -20.6$. Most likely, Jogee et al. (2004) sample further down the mass function, averaging over both the low-mass and high-mass peaks, whereas Sheth et al. (2008) are restricted to the high-mass peak (log($M/M_\odot$) $> 10.2$). Thus, the redshift evolution of the bar fraction is most likely driven by the mass dependence of the bar fraction.
evolution of bar fractions needs to be studied carefully, both above and below the transition mass.

3. DISCUSSION

Our central conclusion is that the fraction of barred spiral galaxies is strongly dependent on the mass and star formation history of galaxies. This conclusion naturally leads us to wonder whether our observations can be used to constrain scenarios for bar growth and/or destruction. As has already been noted, a number of galaxy properties, such as color (Strateva et al. 2001; Baldry et al. 2004), luminosity (Balogh et al. 2004), mass, surface mass density (Kauffmann et al. 2003b), and size and concentration (Shen et al. 2003), exhibit bimodal characteristics. The fact that bimodality is manifested in so many parameters is perhaps not surprising given the strong internal correlations between them. To this list of bimodal properties an additional morphological signature, namely the bar fraction, can now be added. A minimum in the fraction of barred spiral galaxies occurring at the same mass at which bimodality manifests itself in stellar populations suggests that whatever process is causing the creation of the red and blue sequence is either influencing, or being influenced by, structural changes in the galaxies in which bars become rarer.

It has been shown by Elmegreen & Elmegreen (1985, 1989) that the characteristics of bars themselves change along the Hubble Sequence. Bars in early-type galaxies are longer, stronger, show a flatter light profile, and a strong correlation with grand design two-spiral arm structures compared to bars in late-type galaxies which show an exponential light profile and more multiple-armed or flocculent-arm structure. This bimodality in bar type may be directly related to the mass bimodality in the fraction of barred spirals. To illustrate this, Figures 2 and 3 show representative examples of bars below and above the transition mass threshold of $\log(M/M_\odot) \sim 10.2$ sorted by increasing mass. The first noticeable difference between the two panels is the color of the galaxy, where the lower mass galaxies are blue while the higher mass galaxies are red, as expected. Galaxies in the higher mass bin have definite bulges while those in the lower mass bin have no bulge or a very tiny bulge and more flocculent arm structure. There is a possible indication of increasing bulge presence with mass in low-mass barred galaxies. If this is the case we would expect bar fraction to be keyed to central concentration, which is an easily measurable (albeit crude) proxy for bulge strength.

To test this idea, Figure 4 shows the fractional histograms relating the bar fraction to mass keyed to $(g-r)$ color (left panel) and concentration3 (right panel) for objects in our sample. We find blue objects occupy the low-mass peak and redder objects occupy the high-mass peak as expected. From the right panel of

3 Defined as the ratio of flux within an inner and outer elliptical aperture determined from the sky-subtracted, intensity-weighted, second-order moment of the image. The major and minor axes of the outer aperture are normalized so that the total area within the ellipse is the area of the galaxy. The inner aperture is defined by scaling these axes down by a factor of 3.
Figure 4. Bar fraction as a function of mass keyed to color (left) and concentration (right) in three quantile bins. Blue (small dash) indicates the lowest quantile, purple (dotted) the intermediate range, and red (dashed) the highest quantile.

Figure 5. Bar fraction as a function of central concentration keyed to (left) stellar mass, where the blue (dotted) curve shows galaxies below the transition mass and red (dashed) curve shows galaxies above the transition mass, and (right) Hubble type.

Figure 4, we find that the low-mass peak is dominated by low-concentration galaxies but low-concentration galaxies span the whole range in mass. What is more interesting is that for objects with log(M/M⊙) < 10.2 (low-mass peak), at a given stellar mass the bar fraction decreases as concentration increases, while in the high-mass peak (log(M/M⊙) > 10.2) the reverse is true: as concentration increases, the bar fraction increases. (It should be noted that the bar fractions are roughly the same in the two highest concentration bins although there is a slight mass dependence.) This can be seen more clearly in Figure 5 which shows bar fraction versus concentration keyed to (left) two mass bins and (right) galaxy type. For low-mass galaxies bar fraction decreases with concentration, whereas for high-mass galaxies the bar fraction dependence is more complicated. These trends are clearer with Hubble type. Bar fractions in Sbc and later galaxies clearly decrease with increasing central concentrations, whereas they increase for Sab and earlier types. Sb galaxies appear to be a bridge between the two populations.

The different ways in which bar fraction varies with central concentration (and type) above and below log(M/M⊙) ∼ 10.2 suggests that bar formation (or destruction) may be operating in fundamentally different ways in these two mass regimes. Do numerical simulations shed any light on these conclusions? 3.1. Bar Destruction Mechanisms in the Low-mass Peak

The susceptibility of bars to destruction by a central mass concentration (CMC) has been studied in many simulations (Norman et al. 1996; Athanassoula & Misiriotis 2002; Shen & Sellwood 2004; Hozumi & Hernquist 1999; Bournaud et al. 2005; Athanassoula et al. 2005; Curir et al. 2008a). Most simulations agree that it is possible to destroy or severely reduce a bar in different circumstances, though the results on the actual mass of the central concentration required to destroy a bar varies, and is usually much higher than log(M/M⊙) ∼ 10.3. The CMC can be due to stellar mass but also due to the buildup of gas and dust. It has been shown that barred galaxies have a larger concentration of CO (Sheth et al. 2005; Sakamoto et al. 1999) and polycyclic aromatic hydrocarbon emission (Regan et al. 2006) than unbarred galaxies. Some simulations suggest that while the growth of the CMC may not completely dissolve a bar (Shen & Sellwood 2004) the gas flow to the center aided by the bar is itself responsible for bar destruction (Friedli & Benz 1993). Bournaud et al. (2005) suggest the transfer of angular momentum between the infalling gas and the bar can severely weaken the bar. These two processes, the buildup of a CMC and the transfer of angular momentum from infalling gas to bars in stellar-mass-dominated systems, could account for the decrease in bar fraction we observe in low-mass galaxies. Athanassoula et al. (2005) find that “massive disk” (or late-type) galaxies are very prone to bar dissolution where even a 5% CMC can destroy a bar and a 1% mass concentration can considerably weaken exponential bars. Curir et al. (2008b) find that bars are more easily destroyed in their simulations of log(M/M⊙) ∼ 10.3 galaxies than in their lower mass (log(M/M⊙) ∼ 9.7), dark-matter-dominated galaxies, which agree with our results.

Another possible explanation for our results might be found in the local environment of galaxies, which seems particularly relevant to understanding bars in low-mass/low-concentration galaxies. The halo and gas play a very important role in such systems where they tend to dominate the dynamics.
simulations show that low-mass, gas-dominated galaxies are very prone to instabilities and bar formation. This could explain why the bar fraction is higher in the low-mass, blue peak as opposed to the high-mass, red peak. A possible trigger could be minor satellite impacts (10:1 ratio) which have been shown to cause bar instabilities in axisymmetric disks (Dubinski et al. 2008). In addition, asymmetries in the dark matter distribution or internal instabilities have also been considered as mechanisms for triggering bar instabilities (Curir et al. 2008b). As the galaxy converts more of its gas to stars, it becomes harder for bars to be triggered by instabilities, thus naturally explaining the trend of lower bar fraction with increasing stellar mass in the low-mass peak.

### 3.2. Bar Formation Mechanisms in the High-mass Peak

At the high-mass end, a number of numerical simulations suggest bars in galaxies with massive halos remain stable once formed (Athanassoula et al. 2005). In the low-redshift universe, we find a near-constant bar fraction at masses greater than 10.4 (log units), as does SE08. However, SE08 also find that this slope evolves with redshift where the highest mass objects have the highest bar fraction at $z \sim 1$ and intermediate-mass objects build up their bar fraction between $0 < z < 1$. Thus, it appears the bar formation mechanism in the high-mass peak is either more efficient or more stable for higher mass galaxies than for the intermediate-mass galaxies (in contrast to the low-mass peak). If we assume that this is true then perhaps bars forming in high-redshift galaxies with intermediate masses ($10.0 < \log(M/M_☉) < 10.5$) do not have halos with sufficient mass to prevent destruction by processes such as merging or gas inflow. These galaxies have not yet had the opportunity to build a stabilizing halo through a steady diet of low-mass mergers or through infall into a larger group. In a companion paper (in preparation), we will study the effect of environment and AGN on bar formation/destruction.

### 3.3. Evolution of Bar Fraction

Identifying the causes of bar destruction will be very important to understanding the redshift evolution of barred galaxies and possibly the formation of the red and blue sequences. This may be testable in a fairly straightforward way, if we note that there appears to be two methods for destroying bars in low-mass galaxies. The first is related to increasing galaxy mass and the second to increasing central concentration. Numerical simulations have shown that exponential bars common in low-mass galaxies are prone to bar destruction as the central concentration increases, while flat surface density strong bars which occupy high-mass galaxies are not destroyed by a CMC, but may have their bars shortened (Athanassoula et al. 2005). This suggests that an analysis of bar sizes as a function of cosmic epoch, Hubble type, and environment might prove interesting.

### 4. CONCLUSIONS

We find that the fraction of barred spiral galaxies is a strongly bimodal function of stellar mass, with a minimum near $\log(M/M_☉) \sim 10.2$. This is also the characteristic mass at which bimodality is seen in the stellar populations of galaxies. This suggests that whatever process is causing the creation of the red and blue sequences is linked in some way to the formation (or destruction) of bars. Because estimates of the local barred galaxy fraction depend sensitively on the stellar mass range being probed, our results suggest that inconsistencies in the reported fractions of barred spiral galaxies can be understood rather simply as a selection effect in which surveys have obtained different results because they have been probing galaxies in different stellar mass ranges.

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