DARK MATTER HALOS OF BARRED DISK GALAXIES

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Received 2014 September 18; accepted 2015 May 26; published 2015 July 6

ABSTRACT

We use a large volume-limited sample of disk galaxies drawn from the Sloan Digital Sky Survey Data Release 7 to study the dependence of the bar fraction on the stellar-to-halo mass ratio, making use of a group catalog, and we identify central and satellite galaxies in our sample. For the central galaxies in the sample we estimate the stellar-to-halo mass ratio \( M_\star/M_h \) and find that the fraction of barred galaxies is a strong function of this ratio, especially for the case of strong bars. Bars are more common in galaxies with high \( M_\star/M_h \) values, as expected from early theoretical works that showed that systems with massive dark matter halos are more stable against bar instabilities. We find that the change of the bar fraction with \( M_\star/M_h \) and \( M_h \) is stronger if we consider a relation with the form \( \bar{f}_{\text{bar}} = \bar{f}_{\text{bar}}(M_\star^\alpha/M_h^\beta) \), with \( \alpha = 1.5 \), and that the bar fraction is largely independent of other physical properties such as color and spin parameter when \( M_\star^{3/2}/M_h \) is fixed. With our sample of galaxies segregated into centrals and satellites, we also compare the fraction of barred galaxies in each group, finding a slightly higher bar fraction for satellites when compared with centrals at fixed stellar mass, but at fixed color this difference becomes very weak. This result, in agreement with previous studies, confirms that the bar fraction does not directly depend on the group/cluster environment, but the dependence exists through its dependence on internal morphology.

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

1. INTRODUCTION

A substantial percentage of disk galaxies at low redshift are known to host stellar bars (e.g., de Vaucouleurs et al. 1991; Eskridge et al. 2000; Nair & Abraham 2010; Lee et al. 2012, henceforth Lee+12). These prominent non-axisymmetric structures are believed to have an important influence on galaxy evolution, such as redistributing mass and angular momentum between the constituents of the galaxies (Friedli & Benz 1993; Debattista & Sellwood 2000; Athanassoula 2002; Martinez-Valpuesta et al. 2006), promoting the formation of spiral arms and rings (Lindblad 1960; Toomre 1969; Sanders & Huntley 1976; Schwarz 1981), fueling gas to the centers of the galaxies (Shlosman et al. 1989; Friedli & Benz 1993), and helping in the build-up of pseudo-bulges (Sheth et al. 2005; Laurikainen et al. 2007; Okamoto 2013).

Just as bars act as major agents of secular evolution of their hosting galaxies (Athanassoula et al. 2013; Cheung et al. 2013; Sellwood 2014), the internal physical characteristics of their hosting galaxies play a major role in determining the presence and evolution of bars. Using extensive samples of galaxies, at both low and at high redshifts, a number of important studies have examined the dependence of the disk bar fraction \( \bar{f}_{\text{bar}} \) on different physical properties. While some early studies (Aguerri et al. 2009; Barazza et al. 2009) found that bars are mostly located in blue, low concentrated galaxies with low luminosities and masses, more recent studies report the opposite. In general, the fraction of barred galaxies is higher in luminous, more massive galaxies, than in their less massive, fainter counterparts (Nair & Abraham 2010; Lee+12; Masters et al. 2012; Oh et al. 2012; Wang et al. 2012). This non-monotonic behavior of the bar fraction is also found as a function of galaxy color; with the bar fraction increasing considerably when moving from blue to red systems (Nair & Abraham 2010; Masters et al. 2011; Lee+12; Oh et al. 2012). Masters et al. (2012) reported a lower bar fraction in gas-rich disk galaxies than gas-poor ones, and Wang et al. (2012) found that galaxies with strong bars present an enhanced central star formation rate or a star formation rate that is suppressed when compared to the mean, highlighting the important role that bars have in the quenching of star formation. Finally, the bar fraction is higher and the bars are longer in early-type spirals, with more prominent bulges and higher concentrations, than in late-type spirals (Elmegreen & Elmegreen 1985; Martin 1995; Erwin 2005; Laurikainen et al. 2007; Hoyle et al. 2011).

In regards to the formation of bars in disk galaxies, the halos in which these galaxies are embedded play a major role. According to the early simulations by Ostriker & Peebles (1973), a cold stellar disk will experience bar instabilities if the ratio of total kinetic energy to the total potential energy exceeds 0.14. The presence of a massive halo, supported by random orbital motions, helps to stabilize the disk by increasing the potential energy, being a more efficient large halo than a centrally concentrated one (Hohl 1976). Efstathiou et al. (1982) reached a similar conclusion studying a set of N-body simulations and proposing a stability criterion that requires a massive halo component to provide stability against bar formation (see also Christodoulou et al. 1995). This same stability criterion is reported (Yurin & Springel 2014) to be a good predictor for the formation of bar in the full cosmological context. The inclusion of other components, such as bulges, diminished the importance of the stabilizing effect of the halo (Athanassoula & Sellwood 1986). However, Athanassoula (2002, 2003) found stronger bars in halo-dominated models than in their disk-dominated counterparts when a live halo is
implemented. More recently, DeBuhr et al. (2012) studied gravitational interactions between live stellar disks and their dark matter halos, finding the stellar-to-halo mass ratio to be a primary factor to follow bar formation and evolution, with systems showing stronger stability against bar formation in lower mass disks for a given halo mass.

An interesting case of study in this regard are low surface brightness galaxies (LSB), that are expected to be stable against bar formation due to low disk self-gravity and high dark matter content. Numerical experiments trying to simulate the formation of bars in such systems face difficulties due to the low disk masses and if they are successful, the bars they generate are small and unstable, leading to the formation of bulge-like structures (Mihos et al. 1997; Mayer & Wadsley 2004).

Halo shape has also repercussion on the fate of stellar bars. When compared with axisymmetric halos, triaxial halos induce early bar formation (Athanassoula et al. 2013), but at later stages damp the growth and strengthening of the bar (Berentzen et al. 2006; Athanassoula et al. 2013). Only recently, numerical simulations have addressed the influence of rotating halos in the formation and growth of bars (Saha & Naab 2013; Long et al., 2014), finding that spinning halos promote bar formation, but their growth in size and strength gets quenched with increasing spin, explaining why $f_{\text{bar}}$ decreases with increasing $\lambda$ (Cervantes-Sodi et al. 2013).

Recently, there have been several works studying the environmental dependence of barred galaxies. When the environment is characterized in terms of the distance to the nearest neighbor, the likelihood of galaxies hosting bars shows a systematic decrease as the distance decreases (Lee+12; Casteels et al. 2013; Lin et al., 2014), suggesting that close encounters suppress the formation of bars and/or destroy them. If the local environmental density is considered, most of the studies show an independence of barred galaxies with environment (Giordano et al. 2010; Martínez & Muriel 2011; Lee+12; Marinova et al. 2012). Skibba et al. (2012) introduced the use of a mark clustering statistic in their calculation of the correlation function, which helped them to find a positive overclustering, from projected separations of 150 kpc $h^{-1}$ to 3 Mpc $h^{-1}$, for barred, bulge-dominated galaxies. Analyzing a particular halo occupation model, they argue that their finding suggest that the barred galaxies in their sample are central galaxies in low mass dark matter halos or satellite galaxies in more massive halos, hosting galaxy groups. A result in the same line is reported by Lin et al. (2014) for the case of their early-type barred galaxies, that are more strongly clustered on scales from a few 100 kpc up to 1 Mpc, than the unbarred early-type galaxies.

In this paper we study the dependence of the bar fraction on the stellar-to-halo mass ratio as well as differences on the bar fraction for central and satellite disk galaxies. In Section 2 we describe the volume-limited sample. The main results and discussion are presented in Section 3. Lastly we summarize our general conclusions in Section 4. Throughout this paper, we use a cosmology with density parameter $\Omega_m = 0.3$, cosmological constant $\Omega_\Lambda = 0.7$ and Hubble constant written as $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$, with $h = 0.7$.

2. THE GALAXY SAMPLE

The sample used in this work comes from a previous work by Lee+12. It is a volume-limited sample complete down to a $r$-band absolute magnitude brighter than $M_r = -19.5 + 5 \log h$ and within the redshift range $0.02 \leq z \leq 0.05489$, drawn from the Sloan Digital Sky Survey Data Release 7 (DR7: Abazajian et al. 2009). The original catalog contains 33,391 galaxies that are classified into early (E/S0) and late (Sa to Sd) types by segregating them in the color versus color gradient and concentration index planes (Park & Choi 2005) plus an additional visual inspection.

The identification of stellar bars is done by visual inspection of $g + r + i$ combined color images from the SDSS website using Visual Tools. To avoid selection biases by inclination, the sample of late-type galaxies is limited to systems with $i$-band isophotal axis ratio $b/a > 0.6$, where $a$ and $b$ are the semimajor and semi-minor axes. From this requirement we restrict our study to 10,674 late-type galaxies. When a stellar bar is identified, it is further classified as a strong bar if it is larger than one quarter of the size of their host galaxies, or as a weak bar otherwise. As presented in Lee+12, our classification shows a good agreement with the classification performed by Nair & Abraham (2010). Among the 10,674 late-type galaxies in our sample, 23.8% (2542 galaxies) host strong bars and 6.5% (698 galaxies) host weak bars, giving a bar fraction of 30.4%, a value in good agreement with studies that detect bars by visual inspection, with typical values between 25% and 36% (Nair & Abraham 2010; Giordano et al. 2011; Masters et al. 2011; Oh et al. 2012). Furthermore, the bar fraction distribution of our sample shows dependencies with stellar mass, color, and concentration index, in qualitative and quantitative good agreement with the findings of Nair & Abraham (2010), Masters et al. (2011), and Oh et al. (2012). For a more detailed description of the galaxy catalog and comparisons of the classification with previous studies (de Vaucouleurs et al. 1991; Nair & Abraham 2010), we refer the reader to Lee+12 and Park & Lee (2014 in preparation).

The physical properties required for this study, such as $r$-band absolute magnitude $M_r$, stellar mass $M_*$ and $u - r$ color are extracted from the Korea Institute for Advanced Study Value-Added Galaxy Catalog (Choi et al. 2010), the New York University Value-Added Galaxy Catalog (NYU-VAGC; Blanton et al. 2005) and the MPA/JHU SDSS database (Kauffmann et al. 2003; Brinchmann et al. 2004).

To obtain estimates of the parent halo mass, we match the galaxies in our sample with an updated version of the galaxy group catalog of Yang et al. (2007), finding a match for 91.5% of the galaxies in our sample without any apparent bias. The groups in this catalog are identified by applying a “friends of friends” halo finder algorithm to the SDSS DR7, with galaxies redshifts in the range $0.01 \leq z \leq 0.20$ and masses as low as $10^{11.5} h^{-1} M_\odot$. The halo mass estimates in the catalog are obtained by ranking the galaxy groups by their total stellar mass or luminosity, and assuming a one-to-one relation between the total stellar mass/luminosity of the groups and $M_\ast$. Given that in our study we are interested in the dependence of the bar fraction on the stellar mass to halo mass ratio, we opt for the $M_\ast$ estimates by ranking total luminosity of the galaxy groups, in order to avoid introducing an intrinsic bias, but similar results are obtain if we adopt the ranking by stellar masses, or even by employing a different group/cluster catalog (i.e., Tempel et al. 2014), where the virial masses are obtain through dynamical considerations.
3. RESULTS AND DISCUSSION

3.1. Central Galaxies

Given that our interest is to study the dependence of the likelihood of galaxies hosting bars on their stellar-to-halo mass ratio, in this subsection we will include only central galaxies for which we have estimates of their respective halo masses.

Figure 1(a) shows the well known dependence of $f_{\text{bar}}$ on stellar mass (Méndez-Abreu et al. 2010; Nair & Abraham 2010; Masters et al. 2012; Oh et al. 2012; Cervantes-Sodi et al. 2013) for the central late-type galaxies in our sample, with an increase of the bar fraction with increasing stellar mass for the case of strong bars, while weak bars show the opposite trend, an increase of $f_{\text{bar}}$ for decreasing stellar mass. Figure 1(b) shows the dependence of $f_{\text{bar}}$ on the host halo mass. Similar to the case of stellar mass, we find that strong bars tend to be more common in galaxies with massive halos (contrary to the results of Martínez & Muriel 2011, who found no dependence on halo mass), while weak bars show almost no dependence of $f_{\text{bar}}$ on halo mass. Given that more massive stellar disks reside in more massive halos, this dependence of the bar fraction on $M_h$ is not surprising. A more interesting feature to explore is the dependence of the bar fraction on the stellar-to-halo mass ratio. As can be seen in Figure 1(c), for the case of strong bars, galaxies with high $M_*/M_h$ ratios ($\geq 1.8$) have much higher bar fraction than systems that are more dominated by dark matter. Weak bars present only a weak dependence but in the opposite direction, with $f_{\text{bar}}$ increasing with decreasing $M_*/M_h$.

It is interesting to check if this dependence is visible at fixed stellar mass. In the top panels of Figure 2 we present the bar fraction in the $M_h$ versus $M_*$ plane, for the full sample of barred galaxies (strong plus weak bars, left panel), strong (central panel) and weak (right panel) bars separately. We use a spline kernel to get a smooth transition of $f_{\text{bar}}$, dividing the parameter space into $20 \times 20$ bins, and requiring at least 15 galaxies per bin to estimate the bar fraction. The first thing to note is that even at fixed stellar mass, there is a strong variation of $f_{\text{bar}}$ with halo mass, and the dependence is particularly clear for the case of strong bars, with $f_{\text{bar}}$ increasing with decreasing $M_h$ at fixed $M_*$, although the dependence is more dramatic fixing the halo mass and looking at the increase of $f_{\text{bar}}$ with increasing stellar mass. Weak bars are found in galaxies with low $M_*$ and $M_h$ values.

For the cases of the full sample and the restricted subsample of strong bars, we find that the bar fraction presents a secondary maximum at high halo mass ($M_h \gtrsim 10^{13}M_\odot$) and relatively low stellar mass ($M_* \lesssim 10^{11.2}M_\odot$). These systems are actually central galaxies of rich groups, where the stellar mass refers to the central galaxy only, but the total halo mass refers to the mass of the parent halo plus the satellite systems. In this sense, the value obtained through our estimate for the $M_*/M_h$ represents only a lower value or the real one. Besides, in these rich groups, other mechanisms might be taking place changing the likelihood of galaxies hosting bars.

With the most massive galaxies populating the most massive halos and at the same time being in general redder and with a higher $M_*/M_h$ than less massive galaxies, it is important to check if the dependence of the bar fraction on $M_*/M_h$ is not only a reflection of the dependence of $M_*/M_h$ on color. Figure 2 middle panels show the co-dependence of the bar fraction on color and $M_*/M_h$. As reported by previous studies (Nair & Abraham 2010; Lee+12), we detect a strong dependence on color, with strong bars preferentially in red galaxies and weak bars in blue systems. The contour colors indicate a stronger dependence on color than on the stellar-to-halo mass ratio, but even at fixed $u - r$ color there is a clear dependence on $M_*/M_h$, especially for values of $M_*/M_h \gtrsim 1.7$ with an increase of $f_{\text{bar}}$ for increasing $M_*/M_h$ at any $u - r$ value.

In Cervantes-Sodi et al. (2013) we studied the dependence of the bar fraction on the spin parameter $\lambda_d$ using the same
To estimate the \( \lambda_d \) we used a simple model introduced by Hernandez & Cervantes-Sodi (2006) with which we are able to give a first order estimate of the spin in terms of the disk scalelength \( R_d \), the circular velocity \( V \), the mass of the stellar disk \( M_d \), and the disk mass fraction \( f_d \). For a detailed description of the model we refer the readers to Cervantes-Sodi et al. (2013). As a result, we found that the bar fraction strongly depends on the spin, with the \( f_{\text{bar}} \) maximum at low to intermediate \( \lambda_d \) values for the case of strong bars, while the maximum for weak bars is at high \( \lambda_d \). With \( \lambda_d \) being proportional to the stellar-to-halo mass ratio in our estimate, it is interesting to look if the bar fraction shows a dependence on the spin, even at fixed \( M_* / M_h \). The only difference between present estimate for \( \lambda_d \) with the one in Cervantes-Sodi et al. (2013) is that we are using \( M_* / M_h \) from the group catalog, instead of the estimate by Gnedin et al. (2007).

Figure 2 bottom panels show \( f_{\text{bar}} \) in the \( \lambda_d \) versus \( M_* / M_h \) plane. It is evident that the dependence is stronger with \( M_* / M_h \) than with \( \lambda_d \), but still at fixed \( M_* / M_h \) there is a variation of the bar fraction with the spin parameter. For the case of strong bars (middle panel) with low to intermediate values of \( M_* / M_h \), at fixed \( M_* / M_h \), the bar fraction increases for decreasing \( \lambda_d \), while strong bars with heavy stellar disks appear to be more frequently found on high spinning galaxies. As discussed in Cervantes-Sodi et al. (2013), we expect galaxies with low spin values to be more prone to develop bar instabilities due to their

![Figure 2](image_url)
self-gravitation, while high spinning galaxies are more extended with sparse disks that suppress and/or damp global instabilities. This naturally explains the behavior found in light disks, but disks with high stellar-to-halo mass ratios are already massive enough to develop bar instabilities. For these systems with heavy disks in relation to their halos, the increase of \( \lambda_d \) prevents them from becoming supported by random motions instead of ordered rotation which in turn increases the formation/growth of bars, hence the increase of \( f_{\text{bar}} \) with increasing \( \lambda_d \). Weak bars (Figure 2, bottom right panel) have their maximum occurrence at low \( M_*/M_h \) ratios and high \( \lambda_d \) values, in agreement with recent numerical experiments (DeBuhr et al. 2012) where weak bars appear only in marginally stable systems.

The purpose of plotting a line with slope 1.5 in the log \( M_h \) versus log \( M_*/ \) plane in Figure 2 first panel is to make evident that moving perpendicular to this line we get the most dramatic change in \( f_{\text{bar}} \), also shown in Figure 3, with a strong increase of \( f_{\text{bar}} \) with increasing \( M_*/M_h \). Weak bars (Figure 2, bottom right panel) have their maximum occurrence at low \( M_*/M_h \) ratios and high \( \lambda_d \) values, in agreement with recent numerical experiments (DeBuhr et al. 2012) where weak bars appear only in marginally stable systems.

A plausible explanation for the strong dependence of the bar fraction on this ratio might arise from the stability criterion proposed by Efstathiou et al. (1982). Using a set of N-body simulations, they found that their systems were stable against bar formation if

\[
e_c \equiv \frac{V_{\text{max}}}{(GM_d/R_d)^{1/2}} < 1.1, \tag{1}
\]

where \( V_{\text{max}} \) is the maximum rotation curve velocity, and \( M_d \) and \( R_d \) refer to the mass of the disk and the disk scalelength, respectively. In this sense, \( e_c \) is a measure of the self-gravity of the disk, very similar to the stability criterion proposed by Ostriker & Peebles (1973) in terms of the ratio of kinetic energy of rotation to total gravitational energy. If we consider a dark matter halo with an isothermal density profile responsible for establishing a rigorously flat rotation curve along the disk, then \( V_{\text{max}} \sim (M_h/R_h)^{1/2} \), and if \( R_d \) is independent of \( M_d \), then \( e_c \sim M_h/M_d^{3/2} \). This simple analysis presents the same functional dependence we obtain from our observational sample and tells us that it comes from the different density distributions of dark matter and stars, and reflects the stabilizing effect the halo provides to the disk of stars against bar formation.

For completeness, we also explore the behavior of \( f_{\text{bar}} \) in two-dimensional planes, choosing one of the axes to be \( M_*/M_h \), to check if at fixed \( M_*/M_h \) we can still find a dependence of the bar fraction on other physical parameters. Our result is presented in Figure 4. We can see that in all cases (stellar mass, color, and spin), the color contours denoting the bar fraction are almost entirely horizontal in the areas most densely populated by galaxies, implying that the bar fraction at fixed \( M_*/M_h \) is practically independent of stellar mass, color, and spin where the bulk of the galaxy population resides. This independence is particularly interesting for the case of color, for which previous studies have always found a strong dependence, even after fixing other quantities; i.e., Nair & Abraham (2010) found that, at fixed color, the bar fraction still presents a dependence on stellar mass and morphological type; Masters et al. (2012) found a dependence of the bar fraction on color at fixed absolute magnitude, and fixing the color they also found a dependence on the gas mass fraction; and Lee+12 found a dependence on \( u-r \) color at fixed absolute \( r \)-magnitude, concentration index, and velocity dispersion. Our result using central galaxies indicates, contrary to previous findings, that at fixed \( M_*/M_h \), the dependence of the bar fraction on color becomes much weaker, with the only exception of extreme red galaxies with \( u-r \gtrsim 2.6 \). Our result stresses the primary role that this parameter plays on establishing the conditions for the presence of bars in disk galaxies, giving observational support to theoretical works (i.e., Yurin & Springel 2014) that conclude that after the Efstathiou et al. (1982) stability criterion, the importance of other physical parameters appear to be of secondary importance.

### 3.2. Central Plus Satellite Galaxies

Before carrying on with our study using satellite galaxies, we consider it important to explore what would be the result of studying the dependence of the bar fraction on the stellar-to-halo mass ratio using the full sample of galaxies, centrals plus satellites, although in this case the halo mass estimate for satellites does not correspond to their own dark matter halo, but that of their central galaxy. If we compare this result of Figure 5 with 1(c) we notice that the strong dependence is blurred in some degree, making less obvious the dependence of \( f_{\text{bar}} \) on \( M_*/M_h \), helping us to explain why this dependence has not been detected in previous works, where the distinction between centrals and satellites has not been taken into account (Martínez & Muriel 2011).

The weak correlation between \( f_{\text{bar}} \) and the stellar-to-halo mass ratio for the full sample is consistent with previous studies that have found no obvious dependence of galaxy clustering on the presence of a bar (e.g., Li et al. 2009; Martínez & Muriel 2011; Lin et al. 2014). Our analysis indicates that such dependence may be seen if the analysis was restricted to central galaxies only. This is certainly an interesting topic worthy of more work in future.

For galaxies in the satellite subsample, the stellar-to-halo mass ratio lacks importance, given that the halo mass estimate corresponds to the parent halo of the most luminous galaxy in the group, and we do not count with any estimate for the mass of the subhalo hosting the satellite galaxy in question. In turn, we look at differences on the bar fraction between central and satellite galaxies.
In a previous work using an extended sample from which our present sample is a subset, Lin et al. (2014) studied the environment of barred galaxies including early- and late-type galaxies. They found early-type barred galaxies to be more strongly clustered on scales from a few 100 kpc to 1 Mpc when compared to early-type galaxies without bars. Furthermore, they reported that for early-type galaxies, the fraction of central galaxies is smaller if they host a bar, which indicates that the likelihood for early-type galaxies to host a bar depends on the location within the dark matter halos. This result goes in the same line as the one reported by Skibba et al. (2012), that shows a significant environmental correlation of barred, bulge-dominated galaxies on the same scales. Instead, when exploring the correlation function for the late-type galaxies of their sample, Lin et al. (2014) found that the correlation function does not show any dependence on the presence of bars, and that the ratio of central-to-satellite systems for barred and unbarred late-type galaxies was very similar, about ~27%. In the present work, we look at differences of $f_{\text{bar}}$ at fixed stellar mass and color for satellite and central galaxies in our sample, that corresponds to the late-type subsample of Lin et al. (2014).

The left column of Figure 6 shows $f_{\text{bar}}$ as a function of stellar mass for satellite and central galaxies. For high mass galaxies with $\log M_*/M_\odot \gtrsim 10.5$ at a given stellar mass, the bar fraction of satellite galaxies is higher than the one for centrals, with this effect seen only for the case of...
strong bars. If we instead look at the bar fraction as a function of $u - r$ color (same figure right column), the difference between satellites and centrals vanishes. This can be explained with the satellite population being on average redder at fixed stellar mass than the subsample of central galaxies, due to the harsh group environment where they experience gas stripping (Kimm et al. 2009; Skibba 2009; Weinmann et al. 2010; Zhang et al. 2013), especially for low- to intermediate-mass galaxies. As they lose their gas, their star formation shuts off and the galaxies become red, increasing the likelihood for hosting bars, as bars are more common in red galaxies with low gas content (Lee+12; Masters et al. 2012). In this way the group environment is not directly responsible for an increase on the likelihood of galaxies hosting bars, but indirectly by the dependence of $f_{\text{bar}}$ on color.

Our result might help to explain why some authors find effects of the group/cluster environment on the bar fraction (Andersen 1996), even at fixed luminosity (Méndez-Abreu et al. 2012), while others do not (van den Bergh 2002; Giordano et al. 2011; Martínez & Muriel 2011), demonstrating that is important not only to control luminosity or stellar mass when comparing galaxies in different environments, but also color (see also Lee+12; Lin et al. 2014).

### 4. CONCLUSIONS

Using a volume-limited sample of galaxies with visually identified bars by Lee+12 and the Yang et al. (2007) group catalog to discriminate between central and satellite galaxies and to estimate masses of the parent halos of the groups, we investigated the dependence of the bar fraction on the stellar-to-halo mass ratio, finding that for central galaxies $f_{\text{bar}}$ increases for increasing $M_*/M_h$, even at fixed stellar mass or color. This result is in line with early (Ostriker & Peebles 1973; Efstathiou et al. 1982) and recent (DeBuhr et al. 2012; Yurin & Springel 2014) theoretical works pointing out the stabilizing effect of dark matter halos on stellar disks against bar formation.

Exploring the bar fraction in the log $M_*$ versus log $M_h$ plane, we find that the change of $f_{\text{bar}}$ is the strongest if we consider a relation with the form $f_{\text{bar}} = f_{\text{bar}}(M'_*/M_h)$ with $\alpha = 1.5$. Furthermore, once $M'_*/M_h$ is fixed, the dependence of the bar fraction on stellar mass, color, and spin becomes very weak, with the only exception of galaxies with extreme red colors.

By comparing the bar fraction for central and satellite systems at fixed stellar mass we find that $f_{\text{bar}}$ is higher for satellites with $\log M_*/M_\odot \gtrsim 10.5$, but this difference vanishes when we compare the bar fraction at fixed $u - r$ color. We interpret this as follows: the bar fraction of satellites is higher than that of centrals at given stellar mass (or luminosity) because satellites are redder than centrals on average at this mass range. With $f_{\text{bar}}$ being a strong function of color, the difference of the bar fraction between satellites and centrals is not directly due to the local environment, but indirectly through gas stripping suffered by the satellite population when entering the group/cluster environment, with the subsequent reddening due to quenched star formation. This, in turn, is what enhances the likelihood for galaxies to host bars, given that they are more commonly found in red, gas-poor galaxies.

The authors thank the anonymous referee for useful comments that helped to improve the quality of the paper and clarify our results. B.C.S. thanks Ramin A. Skibba for valuable discussions about our results. C.L. acknowledges the support of the NSFC (grant Nos. 11173045, 11233005, 11325314, and 11320101002) and the Strategic Priority Research Program “The Emergence of Cosmological Structures” of CAS (grant No. XDB09000000). Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation and Participating Institutions, the National Science
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