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BARS, OVALS, AND LENSES IN EARLY-TYPE DISK GALAXIES: PROBES OF GALAXY EVOLUTION

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ABSTRACT

The origin of S0 galaxies is discussed in the framework of early mergers in a cold dark matter cosmology, and in a scenario where S0s are assumed to be former spirals stripped of gas. From an analysis of 127 early-type disk galaxies (S0–Sa), we find a clear correlation between the scale parameters of the bulge ($r_{\rm eff}$) and the disk ($h_{\rm R}$), a correlation which is difficult to explain if these galaxies were formed in mergers of disk galaxies. However, the stripping hypothesis, including quiescent star formation, is not sufficient to explain the origin of S0s either, because it is not compatible with our finding that S0s have a significantly smaller fraction of bars (46% ± 6%) than their assumed progenitors, S0/a galaxies (93% ± 5%) or spirals (64%–69%). Our conclusion is that even if a large majority of S0s were descendants of spiral galaxies, bars and ovals must play an important role in their evolution. The smaller fraction particularly of strong bars in S0 galaxies is compensated by a larger fraction of ovals/lenses (97% ± 2% compared to 82%–83% in spirals), many of which might be weakened bars. We also found massive disklike bulges in nine of the S0 galaxies, which might have formed at an early gas-rich stage of galaxy evolution.

Key words: galaxies: bulges – galaxies: evolution – galaxies: structure

1. INTRODUCTION

The formation of S0 galaxies is generally discussed in the framework of mergers of disk galaxies within a lambda cold dark matter (ΛCDM) cosmology. Alternatively, they can be viewed as former spirals where star formation has ceased and gas lost by stripping mechanisms. However, less attention has been paid to the role of bars in the evolution of these galaxies. Bars are known to be efficient drivers of gas toward the central regions of galaxies, and in the presence of nuclear bars (Shlosman et al. 1989) or nuclear spirals, a central starburst might occur. Numerical simulations (Athanassoula 2003; Martinez-Valpuesta et al. 2006) also predict that bars evolve due to angular momentum transfer between the bar and a massive or centrally concentrated halo, leading to more prominent bars. Indeed, there is observational evidence that bars in early-type disk galaxies might be more evolved than bars in spiral galaxies. They are longer (Elmegreen & Elmegreen 1985; Laurikainen et al. 2007), more massive, and have more frequently double-peaked Fourier amplitude profiles (Laurikainen et al. 2007) and ansae-type morphologies (Laurikainen et al. 2007; Martinez-Valpuesta et al. 2007). In the above simulation models, these features can be interpreted as indices of evolved bars.

Lenses are features commonly observed in S0 galaxies, but are sometimes also seen in early-type spirals. They are defined as components with a shallow or constant surface brightness profile and a sharp outer edge. Lenses are a fundamental part of the original classification of S0s (Sandage 1961), although they were not recognized initially with their own type symbol. Ovals are global deviations of the disk from the axisymmetric shape. In distinction to bars they have lower ellipticities and generally lack Fourier terms of higher order than $m = 2$.

We emphasize the importance of ovals and lenses for understanding bar-induced galaxy evolution. Kormendy (1979) showed that 54% of barred galaxies of types SB0–SBa have lenses. The actual frequency of lenses in nonbarred S0s was not determined at that time, although strong lenses were known to exist in such galaxies (Kormendy 1984; Sandage & Brucato 1979). Our recent studies (Laurikainen et al. 2005, 2007) have confirmed that lenses are common in nonbarred S0s. It was first suggested by Kormendy (1979) that lenses might be destroyed or weakened bars. If bars evolve in the Hubble sequence, and lenses are indeed weakened bars, at some stage one would expect the fraction of lenses to exceed the fraction of bars. It is also challenging to explain the origin of the multiple bars, ovals, and lenses seen in single S0s and for which no explanation has yet been given in the current paradigm of galaxy formation.

In this Letter, the origin of S0 galaxies is discussed, based on an analysis of 127 early-type disk galaxies (Laurikainen et al. 2005, 2006): N(S0) = 82, N(S0/a) = 18, and N(Sa-Sab) = 27. Although by far most S0s might be the descendants of spiral galaxies, we present evidence that bars, ovals, and lenses have played an important role in their structure formation and evolution. Support for the stripped spiral hypothesis is provided by a clear correlation between bulge and disk scale parameters (Section 4). The role of bars in structure formation is evidenced by the large number of ovals+lenses (interpreted as weakened bars) in S0s, and by the massive disklike bulges found in nine of the galaxies (Sections 3 and 5). The studied galaxies are part of a magnitude-limited Near-IR S0 galaxy survey (NIRS0S), which has the following selection criteria: $B_{\rm T} \leqslant 12.5$, inclination $\leqslant 65°$, and Hubble type $-3 \leqslant T \leqslant 1$ (Laurikainen et al. 2005; Buta et al. 2006). More than half of the 184 NIRS0S galaxies are currently analyzed, which form an adequate sample to study the structural components of these galaxies.

2. TWO EXAMPLES OF OVAL/LENS-DOMINATED GALAXIES

We show two-dimensional decompositions of the surface brightness distribution for two oval/lens-dominated galaxies, with the following aims: (1) to show how to identify lenses in galaxies, (2) to stress the importance of accounting for bright ovals/lenses while deriving the parameters of the bulge, and (3) to demonstrate the complexity of some S0 galaxies that needs to be explained by galaxy evolutionary models. Our

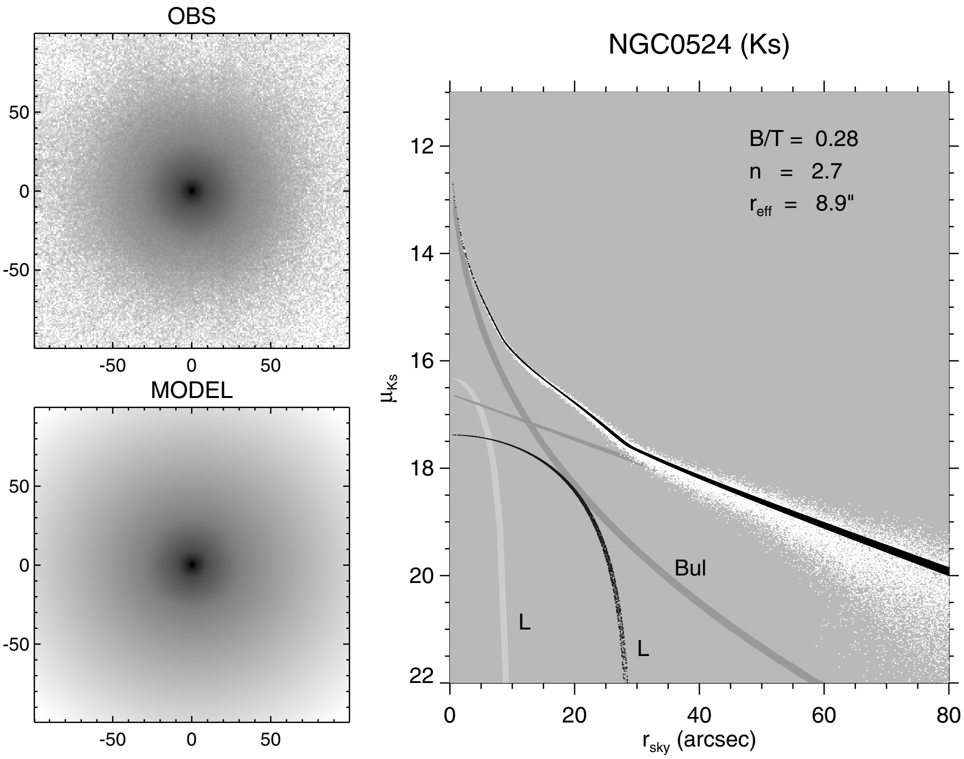

Figure 1. Two-dimensional multicomponent decomposition for NGC 524. The small white dots show the pixel values in the observed image and the other symbols show the model functions: the dark gray lines are for the Sersic bulge (Bul) and the exponential disk, and the small black dots show the final model. Lenses (L) are shown by the large black dots and by shadowed light gray. The upper-left panel shows the observed K_s-band image and the lower panel is the fitted model image.

decompositions use a Sersic function for the bulge, allowing for its flattening and deviation from elliptical isophotes, an exponential function for the disk, and either a Sersic or Ferrers function for the bars, ovals, and lenses. In this study, two types of bulges are considered: (1) classical elliptical-like bulges (with Sersic index n near 4) and (2) disklike pseudobulges (with smaller Sersic index), formed mainly from the disk material via central star formation. However, the vertically thick boxy/peanut structures in barred galaxies (often also called bulges; Athanassoula 2003) are considered here as part of the bar. Such structures, and nuclear bars and rings, are not counted to the flux of the bulge in our decompositions.

The galaxies and their decompositions are shown in Figures 1 and 2: NGC 524 is dominated by two almost circular lenses, whereas NGC 5365 has two oval-shaped components, both ovals with an embedded bar. The lenses in NGC 524 are directly visible in the image, and show in the surface brightness profile as distinct exponential subsections. The best fit is obtained by an $n = 2.8$ Sersic bulge and two flat Ferrers functions (Ferrers index = 1) for the lenses, implying a fairly small bulge-to-total flux ratio $B/T = 0.28$. For NGC 5365, the inner bar/oval system is fitted by a single Sersic function and the outer one with a single Ferrers function, leading to a fairly exponential bulge ($n = 2.0$) and a small $B/T = 0.17$. Counting all the flux above the exponential disk as a bulge would lead to a considerable overestimate of the bulge flux ($B/T \sim 0.5$ in two-component fits), in accordance with Laurikainen et al. (2005) who showed that by omitting the bar/oval in the decomposition the B/T-flux ratio is overestimated, regardless of whether one-dimensional or two-dimensional decompositions are used. It is challenging to explain how these kinds of multiple ovals/lenses form in S0 galaxies and how they are related to the evolution of bars. In Section 6, they will be discussed in the context of cosmologically motivated simulations by Heller et al. (2007).

3. WEAK BARS INSIDE THE LENSES

Although bars in S0 galaxies are on average fairly prominent, weak bars are detected inside the ovals/lenses in eight of the galaxies: NGC 484, NGC 507, NGC 1161, NGC 1351, NGC 2768, NGC 2902, NGC 3998, and NGC 7377. All these galaxies are classified as nonbarred (de Vaucouleurs et al. 1991; RC3) and no bar is directly visible in the K_s-band image. However, a weak, genuine bar is visible in the residual image after subtracting the bulge model obtained from our decomposition (see Figure 3 for NGC 3998). Taking into account that the evolution of bars and bulges might be coupled, it is interesting to look more closely at the properties of the bulges of these galaxies.

We find fairly small Sersic indices for the bulges in these nine galaxies ($\langle n \rangle = 2.5$), similar to the typical values recently found for S0 galaxies in decompositions where a multicomponent approach is used (Laurikainen et al. 2005, 2007; Gadotti 2008). However, their average bulge-to-total flux ratio ($\langle B/T \rangle = 0.44$) is higher than average for their Hubble type, which for S0–S0/a galaxies ~0.25–0.28 (Laurikainen et al. 2005, 2007; Gadotti 2008). In Section 6, we will discuss that the weak bars, and probably also the massive, fairly exponential bulges in these galaxies might be a manifestation of bar-induced secular evolution.

4. COMPARISON OF THE SCALE PARAMETERS OF THE BULGE AND THE DISK

The scale parameters of the bulge and the disk are sensitive to the evolutionary processes of galaxies during their cosmic

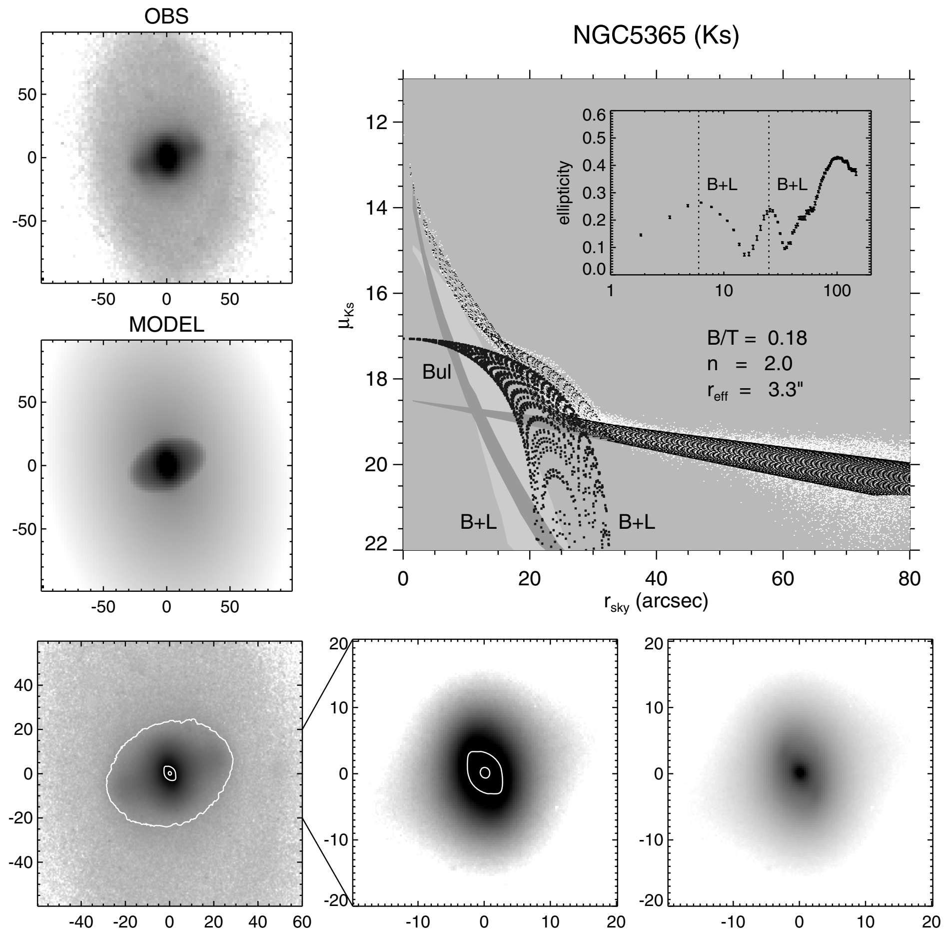

Figure 2. Decomposition for NGC 5365. The symbols are as in Figure 1. The galaxy has two bars embedded in ovals, both components being fitted by a single function (B+L). The three lower panels show the observed image in different scales. Left: the scale is selected to show the primary bar, whereas the isophotes show the nuclear bar and the weak oval surrounding the primary bar. Middle: the bright inner oval, and an isophote indicating the nuclear bar. Right: the nuclear bar. In the ellipticity profile, the two bar+oval systems have nearly the same ellipticity.

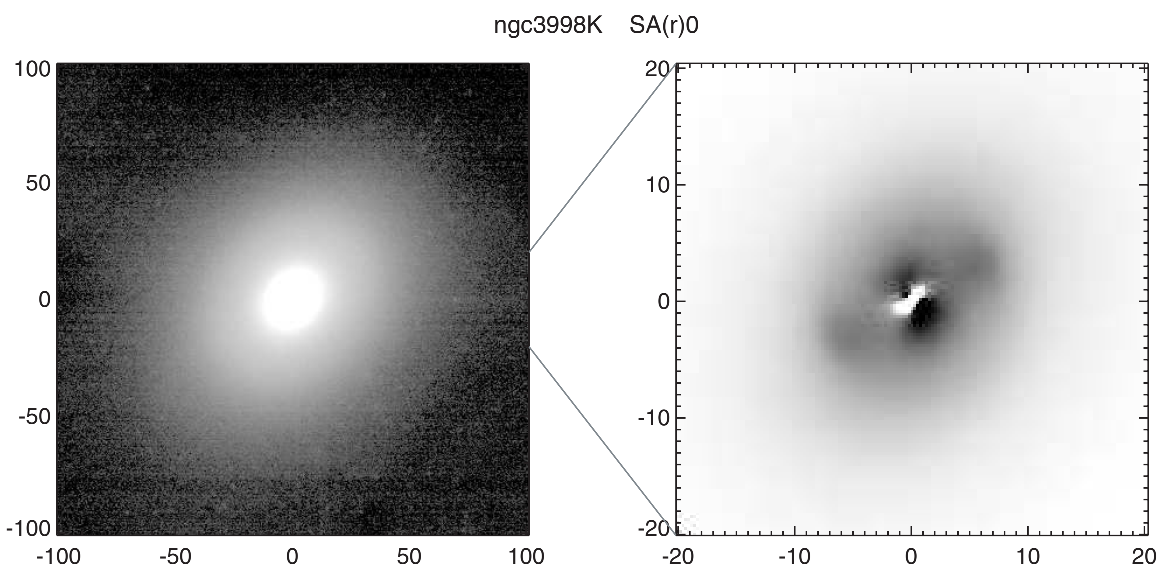

Figure 3. Left: the original K_s-band image of NGC 3998. Right: the residual image after subtracting the bulge model obtained from our two-dimensional decomposition. The bright lens at $r < 12''$ was fitted by a Ferrers function. The scale is in arcseconds.

history, and therefore offer an independent test of the importance of secular processes in S0s. A correlation between the scale parameters is expected in models where the bulges were formed in slow secular processes (reviewed by Kormendy & Kennicutt 2004), whereas no correlation is expected in models where the bulges were formed either in a fast dissipative collapse (Eggen

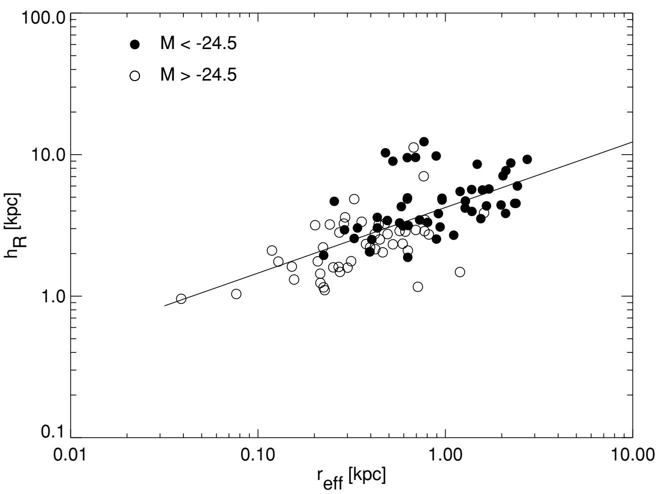

Figure 4. Intrinsic scale length of the disk as a function of the effective radius of the bulge. Two K_s-band magnitude bins are shown ($H_0 = 75$ km s^{-1} Mpc^{-1} is assumed). The line shows the fit $\log h_R = 0.62 + 0.46 \log r_{\rm eff}$.

et al. 1962), or by mergers of large (Toomre & Toomre 1972; Springel & Hernquist 2005) or small galaxies (Abadi et al. 2003).

The radial scale length of the disk, h_R, and the absolute magnitude, M, in the K_s-band are calculated in the following manner:

$$h_{\rm R,intr}\,({\rm kpc}) = h_{\rm R,obs} \times D\,({\rm kpc})/c_1,$$

$$M_{\rm intr} = m_{\rm obs} - m_{\rm ext} - c_2 - (5 \times \log D\,({\rm Mpc})) - 25.0,$$

where the internal dust correction for h_R, $c_1 = [1.02 - 0.13 \times \log(\cos i)]$, is from Graham & Worley (2008). For M, the internal dust correction is $c_2 = [0.11 + 0.79 \times (1 - \cos i)^{2.77}]$, taken from Driver et al. (2008). For galaxy distance D we use $H_o = 75$ km s^{-1} Mpc^{-1}, and Galactic extinction, $m_{\rm ext}$, is from Schlegel et al. (1998). For the effective radius of the bulge, $r_{\rm eff}$, no internal dust correction was made. The subscripts obs and intr refer to measured and intrinsic values, respectively. We find a clear correlation between $r_{\rm eff}$ and $h_{\rm R,intr}$, with the coefficient of correlation of 0.66, at the significance level of 7×10^{-14} (Figure 4). The correlation is independent of the applied corrections. The correlation is found to be the same for bright ($M < -24.5$) and faint ($M \geqslant -24.5$) galaxies. This contradicts the recent result by Barway et al. (2007) who found an anticorrelation for bright S0s and a positive correlation for faint S0s. This different result is most probably due to the deeper images and the more homogeneous database used in the present study. Note also that the scale parameters in Barway et al. were derived using simple bulge–disk decompositions, whereas we use a multicomponent approach. The correlation we find for S0s is similar to that found previously for spiral galaxies (Courteau et al. 1996; Carollo et al. 2007), and for 14 SB0 galaxies (Aguerri et al. 2005).

5. FREQUENCY OF BARS, OVALS AND LENSES

Finally, we compare the fractions of galaxies with bars and ovals/lenses in different Hubble types. If S0s were simply stripped spirals one would expect similar bar fractions in S0s and in their spiral progenitors. In Table 1, we use RC3 family classes for calculating bar fractions in different Hubble-type bins: for S0–S0/a galaxies the whole NIRS0S sample of 184 galaxies is used, whereas for spirals we use the similarly sized Ohio State University Bright Spiral Galaxy Sample (OSUBSGS; Eskridge et al. 2000). We find that S0s (46% ± 5%) have bars (SB+SAB) less frequently than S0/a galaxies (77% ± 9%) or spirals (61%–70%). The values for spirals are in agreement with those found previously by other authors (Knapen et al. 2000; Eskridge et al. 2000; Laurikainen et al. 2004; Menńdez-Delmestre et al. 2007; Marinova & Jogee 2007). The bar fractions for S0 and S0/a galaxies in the subsample of 127 NIRS0S galaxies (38 ± 5% and 76 ± 10%, respectively) are nearly the same as for the complete NIRS0S sample. In Table 1, the fractions of multiple bars are calculated in respect of the total number of barred galaxies, while all the other values are given in respect of the total number of galaxies within the Hubble-type bin. The uncertainties are estimated from $\Delta p = \sqrt{(1-p)p/N}$, where p denotes the fraction in question in a sample of N systems.

We then use A_2, the maximum $m = 2$ Fourier density amplitude in the bar region, normalized to $m = 0$, to study the three bar strength bins within each Hubble-type bin. For the OSUBSGS, we use the values from Laurikainen et al. (2004), whereas for S0 and S0/a galaxies they were calculated in this study in a similar manner. As a lower limit for the barred galaxies we use $A_2 = 0.1$. We confirm the above result that S0 galaxies have a smaller fraction of bars than S0/a galaxies or spirals. We find that (1) Sc-Scd spirals have the largest number of weak bars ($A_2 = 0.1$–0.3) and the smallest number of strong bars ($A_2 > 0.6$), and that the fraction of strong bars increases toward the S0/a galaxies. This is in agreement with the previous studies showing that the prominence of bars increases toward the early-type disk galaxies. (2) Quite interestingly, although the fraction of strong bars increases from late-type spirals toward S0/a galaxies, it suddenly drops from 38 ± 9% to 10 ± 3% for S0s.

We also find that (3) S0 galaxies have a larger fraction of ovals/lenses than S0/a galaxies (97 ± 2% versus 82 ± 9%), and that (4) S0/a galaxies have a larger fraction of multiple bars than earlier or later-type galaxies (see Laine et al. 2002; Erwin & Sparke 2002). The fraction of ovals/lenses is found to be the same for barred and for nonbarred S0-S0/a galaxies (82 ± 4% vs. 86 ± 6%, respectively). Although ovals and lenses might have different light distributions, they are not distinct enough to be considered separately in our statistics.

6. DISCUSSION AND CONCLUSIONS

In the current paradigm of galaxy formation, ΛCDM, the spheroidal components of galaxies were formed through mergers of disk galaxies: dry mergers are suggested to lead to the formation of elliptical galaxies, whereas mergers of gas-poor with gas-rich galaxies lead to the formation of bulges in the disk-dominated galaxies (Khockfar & Burkert 2003; Naab et al. 2006). Minor mergers are actually more common in the universe and they are suggested to form even 55% of the spheroid stars from accreted satellites (Abadi et al. 2003). In ΛCDM, the disks form after a major merger when hot gas in the halo settles into the disk (Kauffmann et al. 1999; Springel & Hernquist 2005). In this picture, every dark matter halo is expected to possess a substantial pressure-supported classical bulge with elliptical-like photometric properties (Steinmetz & Navarro 2002). Although many observations support this scenario it is also faced with severe problems; for example, the bulges, not only in spiral galaxies, but even in S0 galaxies are fairly disklike and have smaller bulge-to-total flux ratios than predicted by cosmological models. Our finding that *the scale parameters of the bulge*

Table 1
Bar Fractions Using RC3 Family Classes for the Complete NIRS0S+OSUBGS Samples

Bar Index (1)	$S0^-$, $S0^0$, $S0^+$ (%) (2)	S0/a (%) (3)	Sa, Sab (%) (4)	Sb, Sbc (%) (5)	Sc, Scd (%) (6)
B+AB (RC3)	46 ± 5%	77 ± 9%	65 ± 7%	70 ± 6%	61 ± 7%
B (RC3)	27 ± 4%	50 ± 10%	30 ± 7%	39 ± 6%	27 ± 6%
AB (RC3)	19 ± 4%	27 ± 9%	35 ± 7%	31 ± 6%	34 ± 7%
A (RC3)	53 ± 5%	22 ± 9%	35 ± 7%	28 ± 5%	38 ± 7%
All bars ($A_2 > 0.1$)	53 ± 6%	93 ± 5%	65 ± 7%	69 ± 6%	64 ± 7%
Strong ($A_2 > 0.6$)	10 ± 3%	38 ± 9%	26 ± 7%	23 ± 5%	11 ± 4%
Medium ($A_2 = 0.31$–0.6)	33 ± 6%	44 ± 9%	35 ± 7%	34 ± 6%	26 ± 6%
Weak ($A_2 = 0.1$–0.3)	9 ± 4%	10 ± 5%	5 ± 4%	11 ± 4%	28 ± 6%
Ovals/lenses	97 ± 2%	82 ± 9%	83 ± 7%		
Multiple bars (among barred)	21 ± 6%	40 ± 12%	26 ± 8%		

Note. The A_2 fractions for S0 and S0/a galaxies, and the statistics for ovals/lenses and multibars have been derived from the NIRS0S subsample of 127 galaxies.

(r_{eff}) and the disk (h_R) are well correlated for S0s, provides an additional problem for ΛCDM: such a correlation would be difficult to explain if the formation of bulges and disks in S0 galaxies were decoupled.

Alternatively, S0s might be the descendants of spirals whose star formation has faded after consuming the gas or losing it by some stripping mechanism, such as ram pressure stripping (Gunn & Gott 1972), halo stripping (Bekki et al. 2002), or galaxy harassment (Moore et al. 1996). Recent evidence supporting this idea comes from the Tully–Fisher (TF) relation and from the analysis of the properties of globular clusters in galaxies. S0s lie below the spiral galaxies in the TF relation, having lower luminosities (Bedregal et al. 2006). This deviation is explained by the luminosity evolution of spiral galaxies: the transformation from spirals to S0s occurred at various times in the past, and the galaxies have been passively fading ever since. The globular cluster frequency (the number of globular clusters per unit *V*-band luminosity) has been used as an independent estimate of the degree to which the luminosity of S0s has faded relative to that of their spiral progenitors (Aragón-Salamanca et al. 2006; Barr et al. 2007). This estimate is based on the assumption that the frequency of globular clusters is constant during the transformation process. The fact that the bulges in S0 galaxies also have many characteristics of disklike structures, including their kinematic properties (Cappellari et al. 2007), is consistent with this picture. However, if S0s were simply passively formed from S0/a spirals it would be difficult to explain our finding that *the fraction of bars is considerably lower in S0s than in S0/a galaxies, which are expected to be their progenitors in the Hubble sequence.* Bars should be fairly robust structures, evidenced by the fact that the bar fraction, at least in massive luminous spirals, is maintained nearly constant throughout the redshift range $z = 0$–0.84 (Sheth et al. 2008).

Although the hypothesis of S0s as stripped spirals is a promising idea, an important piece of information is still missing in this picture. Indeed, bars are expected to be efficient drivers of galaxy evolution: the angular momentum transfer between gas and stars leads to gas infall and subsequent star formation in the central regions, which can add to the mass of the bulge (Friedli & Benz 1993). If the angular momentum transfer occurs between the bar and the halo, it leads to the evolution of the bar (Debattista & Sellwood 2000; Athanassoula 2003): a bar first grows in mass and length, but if the bulge mass at the same time increases due to the gas infall, this might lead to a subsequent weakening of the bar. Weakening of the bar is most efficient in strong bars with flat-top surface density profiles (Athanassoula et al. 2005), typical for early-type disk galaxies (Elmegreen & Elmegreen 1985). In this study, we have shown indirect observational evidence of such evolution: it is tempting to think that bar weakening due to increased central mass concentration is the explanation for the lower fraction of bars and the larger fraction of ovals/lenses in S0s. We also find that S0 galaxies have a deficiency particularly of the strongest bars, which fits this picture.

A manifestation of bar-induced secular evolution of galaxies is probably also our finding that nine galaxies in our sample have massive disklike bulges ($\langle B/T \rangle = 0.44$, $\langle n \rangle = 2.5$), surrounded by weak bars and lenses. In principle, an increase in bulge mass in these galaxies could have occurred in a similar manner as discussed above. Also, once the bulge mass had increased, the bar might have started to weaken, leaving only a weak bar inside a lens. The lenses surrounding the weak bars can be naturally explained as relics of the evolution of the bar: many barred galaxies have lenses of the same dimension as the bar, aligned with the bar major axis. A problem in this scenario is that normal spiral galaxies do not have enough gas for making such massive bulges by star formation (Kormendy & Kennicutt 2004), at least not without a significant accretion of extragalactic gas to the disk. It is still possible, however, that these galaxies are associated with the formation and evolution of bars at higher redshifts. The role of bars in cosmological simulations has not yet been studied much, but one such attempt has been made by Heller et al. (2007). Their simulations, starting from initial values motivated by cosmological simulations, include star formation, cooling, and feedback. In these simulations, disklike bulges form at early phases of galaxy evolution during the gas-rich epoch in the history of galaxies, being thus capable of accounting for the large bulge-to-total flux ratios of the disky bulges found in some of the S0s. The triaxial halos are the driving force in the formation of primordial bars, which trigger nuclear bars. After 4–5 Gyr, the primary bars are weakened to fat ovals and the nuclear bars are decoupled. These processes might be a key for understanding the multiple bar/oval/lens structures seen in many S0 galaxies.

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