Decreased Frequency of Strong Bars in S0 Galaxies: Evidence for Secular Evolution?

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ABSTRACT

Using data from the Near-Infrared S0 Survey (NIRS0S) of nearby, early-type galaxies, we examine the distribution of bar strengths in S0 galaxies as compared to S0/a and Sa galaxies, and as compared to previously published bar strength data for Ohio State University Bright Spiral Galaxy Survey (OSUBSGS) spiral galaxies. Bar strengths based on the gravitational torque method are derived from 2.2μm K_s-band images for a statistical sample of 138 (98 S0, 40 S0/a,Sa) galaxies having a mean total blue magnitude $< B_T > \leq$12.5 and generally inclined less than 65^o. We find that S0 galaxies have weaker bars on average than spiral galaxies in general, even compared to their closest spiral counterparts, S0/a and Sa galaxies. The differences are significant and cannot be due entirely to uncertainties in the assumed vertical scale-heights or in the assumption of constant mass-to-light ratios. Part of the difference is likely due simply to the dilution of the bar torques by the higher mass bulges seen in S0s. If spiral galaxies accrete external gas, as advocated by Bournaud & Combes, then the fewer strong bars found among S0s imply a lack of gas accretion according to this theory. If S0s are stripped former spirals, or else are evolved from former spirals due to internal secular dynamical processes which deplete the gas as well as grow the bulges, then the weaker bars and the prevalence of lenses in S0 galaxies could further indicate that bar evolution continues to proceed during and even after gas depletion.

Subject headings: galaxies: spiral; galaxies: photometry; galaxies: kinematics and dynamics; galaxies: structure

1. Introduction

Bars are the most important type of perturbation found in common among spiral and S0 galaxies. In spiral galaxies where interstellar gas is plentiful, a bar can be a major engine of gas-dominated secular evolution, leading to radial gas flows, circumnuclear starbursts, and possibly pseudobulges made of disk material (Kormendy & Kennicutt 2004=KK04). In S0 galaxies, secular evolution is a different issue, because such systems generally have far less interstellar gas than spirals, and thus one must turn to possible interactions between the stellar components, to external interactions, or to the possible relationship between S0s and spirals, for evidence of secular evolution.

Of particular interest is how the properties of bars in S0 galaxies might differ from those in spirals. Bars in early-type spiral galaxies have for some time been reported to be stronger and longer than those in later-type galaxies (Elmegreen & Elmegreen 1985). However, such an assessment is usually based on contrast: the relative m=2 Fourier intensity amplitude, A_2, is stronger for early-type barred galaxies (Laurikainen et al. 2007), but when the *forcing* due to a bar is taken into account, the bars of early-type spirals actually come out weaker than those in later-type spirals (Buta, Laurikainen, & Salo 2004; Laurikainen, Salo, & Buta 2004). This is because bar strength is a relative parameter that depends on the radial forcing due to the axisymmetric background (Combes & Sanders 1981). The axisymmetric contribution to the potential of early-type galaxies tends to be strong due to the presence of more massive bulges (Laurikainen et al. 2004, 2007).

Until recently, there has been no detailed study capable of reliably assessing how the distribution of bar strengths in S0 galaxies might differ from those in both early and late-type spirals. Our goal in this paper is to examine this question using data from the Near-Infrared S0 Survey (NIRS0S, Laurikainen et al 2005; Buta et al. 2006), a statistically well-defined K_s-band imaging survey of 183 S0 to Sa galaxies selected from the Third

Reference Catalogue of Bright Galaxies (RC3, de Vaucouleurs et al. 1991). The NIRS0S was carried out from 2004-2009 at several major observatories, and some analysis of the data has been presented by Laurikainen et al. (2005, 2006, 2007, 2009, 2010a), focussed mainly on bulge properties of early-type galaxies as opposed to later types. We wish to examine the implications of the distribution of bar strengths in S0 galaxies as compared to that for spirals, in order to (1) further explore the possible relationship between the two classes of objects, and (2) deduce the evolutionary history of bars in the absence of long-term gas flow.

2. Data and Sample

The NIRS0S was designed to complement and overlap the *Ohio State University Bright Spiral Galaxy Survey* (OSUBSGS, Eskridge et al. 2002), a sample of 205 spirals over the type range S0/a to Sm, with a comparable-sized sample of early-type galaxies in the type range $S0^-$ to Sa. Owing to the lesser abundance of S0 galaxies compared to spirals among bright galaxies, the selection criteria of the NIRS0S could not be made identical to those of the OSUBSGS. The latter used a magnitude limit of $B_T \leq 12.0$, while the NIRS0S uses a limit of $< B_T > \leq 12.5$, where $< B_T >$ is the weighted mean of the mostly photoelectrically-determined B_T magnitudes in RC3 and photographic magnitudes (m_B) on the same scale listed in the same catalogue[6]. The OSUBSGS had no inclination limit, but the NIRS0S galaxies were restricted to $\log R_{25} \leq 0.35$ in order to minimize deprojection

[6]This definition for the sample slightly differs from that used by Buta et al. (2006), who adopted only a photoelectric $B_T \leq 12.5$. The reason for using $< B_T >$ is that many southern galaxies only have total V photoelectric magnitudes in RC3, but all have m_B, allowing a better definition of the sample.

uncertainties. This limit nevertheless failed to exclude some edge-on S0s, and even some galaxies just below the limit were found to be too inclined to reliably deproject. In addition, NIRS0S includes 19 galaxies classified as types E or E^+ in RC3, but which are instead classified as S0s in the *Revised Shapley-Ames Catalogue* (RSA, Sandage & Tammann 1981). We also included NGC 6482, which satisfies the NIRS0S magnitude and diameter restrictions, but which is classed as E^+ in the RC3 and E2 in the RSA. Our analysis shows it to be an S0. The final sample includes 183 early-type galaxies and is listed in Table 1. All details connected with the NIRS0S, including the public availability of the images, will be presented by Laurikainen et al. (2010b).

Buta et al. (2006) showed that the typical NIRS0S galaxy has an absolute blue magnitude M_B^o of −20.0, comparable to the OSUBSGS bar strength sample (Buta et al. 2004). Dwarfs are greatly under-represented in both samples and do not form part of our analysis (see, e. g., Marinova & Jogee 2007).

3. Estimation of Bar Strengths

We measure bar strengths from the maximum tangential forcing relative to the mean background radial forcing (Combes & Sanders 1981) using a polar grid method (Salo et al. 1999; Laurikainen & Salo 2002, 2005). A deprojected near-infrared image is converted to a gravitational potential assuming a constant mass-to-light ratio, and from this potential the maximum ratio of the tangential to mean radial force, $Q_T(r)$, is derived as a function of radius r (an example is shown in Figure 4 of Buta et al. 2005). The maximum of this function is called Q_g, which is equivalent to the maximum gravitational torque per unit mass per unit square of the circular speed. We use the polar grid approach (as opposed to the Cartesian method used by Quillen, Frogel, & Gonzalez 1994) because it is less sensitive to noise and provides more stable values of $Q_T(r)$ versus r. For the whole NIRS0S sample, these functions will be presented by Salo et al. (2010).

Although color-dependent mass-to-light ratio corrections can be made based on empirical formulae from Bell & de Jong (2001), we have made no such corrections for the NIRS0S sample, and in any case the impact of such corrections on bar strength estimates is small for early-type galaxies because color gradients in such galaxies are generally small (e.g., de Vaucouleurs et al. 1991). A more important problem could be the contribution of dark matter to the axisymmetric background potential. We showed in Buta, Laurikainen, & Salo (2004) that corrections to Q_g for dark matter, based on a "universal rotation curve" (Persic, Salucci, & Stel 1996), are relatively small for the high luminosity OSUBSGS spirals. In the case of S0s, the situation is likely to be similar. For example, Williams et al. (2009) analyzed rotation data for 14 S0s as compared to 14 Sa, Sb spirals and found no systematic difference in the dark matter contents.

In this study we compare bar strengths of S0s with those we obtained previously for spirals (Buta et al. 2004, 2005; Laurikainen et al. 2004). In barred spirals, Q_g includes contributions from both the bar and the spiral. Therefore, for OSUBSGS spirals we also use bar strengths in which the spiral contribution is eliminated using the Fourier-based method of Buta, Block, & Knapen (2003), which leads to individual estimates of the bar strength, Q_b, and the spiral strength, Q_s. In S0 galaxies, spiral structure is absent, $Q_b = Q_g$, and the two parameters can be used interchangeably. This is also not a bad approximation even for spirals. For example, Figure 5 of Buta 2004 shows a separation for the SB0/a galaxy NGC 4596 where the arms are too weak to make Q_b different from Q_g. Also, Figure 26 of Buta et al. (2009) shows that even for stronger spirals, the difference between Q_g and Q_b is generally small. Q_g and Q_b values for spirals in the OSUBSGS are provided by Laurikainen et al. (2004) and Buta et al. (2005), respectively.

An important parameter in bar strength studies is the vertical scale height, h_z, a quantity which can only be reliably measured in edge-on galaxies, and which impacts the forcing in the plane used for estimating bar strengths. In our previous analyses of OSUBSGS spiral galaxies, we assumed an exponential vertical density distribution and derived h_z as a type-dependent fraction of the radial scale length h_R, based on a study by de Grijs (1998). For types Sa and earlier, Sab to Sbc, and Sc and later we used $h_z = h_R/4$, $h_R/5$, and $h_R/9$, respectively. The de Grijs analysis includes very few early-type galaxies, and for them we have used $h_z = h_R/4$ in order to make a comparison with spirals. Values as low as $h_R/2$ or $h_R/3$ are also possible for S0s from de Grijs's analysis.

The vertical scale height is the largest source of uncertainty in the gravitational torque method (see Laurikainen & Salo 2002). Because of this, we also consider a different approach (Speltincx et al. 2008): instead of scaling h_z from the radial scale length, we scale it from the $\mu_{K_s} = 20.0$ mag arcsec^{-2} isophotal radius, r_{K20}, based on *Two-Micron All-Sky Survey* (2MASS; Skrutskie et al. 1997) surface photometry provided on the NASA/IPAC Extragalactic Database (NED) [7] website. We use scalings $h_z/r_{K20} = 0.05$, 0.10, and 0.20, and examine the full impact of h_z assumptions on the distribution of early-type galaxy bar strengths.

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[7]The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

4. Analysis

4.1. Sample Rejections

Of the 183 NIRS0S galaxies listed in Table 1, 174[8] were observed in our program (the objects not observed are indicated in Table 1.) Of those observed, 35 had to be rejected from our statistical analysis of bar strengths in early-type galaxies either because they were too inclined in spite of what their catalogued isophotal axis ratio implied, were interacting or peculiar, or were members of close pairs where the two components were difficult to separate. Nearby dwarfs such as NGC 205 and NGC 5206 were also rejected. Of these, only NGC 5206 was actually observed. Also, galaxies that, in the decomposition analysis of Laurikainen et al. (2010a), could be fitted either by a single Sérsic function, or a combination of a Sérsic function and some central component, were rejected. Some of these are likely to be true elliptical galaxies, although at least two of these cases (NGC 439 and 3706) are probably not ellipticals. Table 1 identifies all the rejected galaxies and gives the basis for the rejection. Our final sample for the bar strength analysis consists of 138 galaxies.

4.2. Distribution of Bar Strengths

Our final statistical sample of 138 NIRS0S galaxies is comparable in size to the 147 OSUBSGS galaxies used for bar and spiral strength studies by Buta et al. (2005). Of the

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[8]This number excludes 31 additional S0-Sa galaxies that are outside the formal definition of the sample.

138 galaxies, 98 are classified as E-S0$^+$ in RC3 [9], while 40 are types S0/a and Sa. The latter types include 18 in common with the OSUBSGS (24 for the whole sample of 183 galaxies).

Figure 1a,b shows histograms (both differential and cumulative) of the Q_g relative frequency distributions of the S0 and S0/a,Sa subsets of NIRS0S, and already it is evident that low Q_g values are more abundant for S0s than for early-type spirals. For 98 S0s, $< Q_g >$ =0.09±0.06 (stand. dev.), while for 40 S0/a and Sa galaxies, $< Q_g >$ = 0.16±0.11 (stand. dev.). A Kolmogorov-Smirnov test yields a D parameter (the maximum difference between the normalized cumulative distributions) of 0.34 for these subsamples, and the corresponding probability P=0.002 indicates that the null hypothesis that the two distributions come from the same parent population is rejected at a high significance level. When the total sample of 138 S0-Sa galaxies (Figure 1c,d) is compared with the distribution of Q_g values for 129 OSUBSGS galaxies (Buta et al. 2004, 2005), it is evident that S0s lack the extended "tail" of high Q_g (Q_b) values noted by Block et al. (2002) for OSUBSGS spirals. The Kolmogorov-Smirnov D parameter is 0.51 for these cumulative distributions, $P<10^{-3}$, and the null hypothesis is again rejected. The OSUBSGS subset is restricted to the type range Sab to Sm in order to exclude the 18 OSUBSGS S0/a and Sa galaxies in common with the NIRS0S sample.

Figure 2 compares only the NIRS0S S0s with both Q_g and Q_b distributions for 147 OSUBSGS S0/a-Sm spirals. The Q_b parameter is based on bar-spiral separations as described by Buta et al. (2005). The presence of spiral torques exaggerates the difference between S0s and OSUBSGS spirals because Q_g is affected by spiral arm torques, but when bar strength Q_b alone is used, the distributions are still significantly different. For the comparison with Q_b, the Kolmogorov-Smirnov D=0.37, while for the comparison with Q_g,

[9]In conflicting cases where a galaxy was classified as type E in RC3 but S0 in the RSA, the RSA type is adopted.

the Kolmogorov-Smirnov is stronger at D=0.55. The corresponding P in each case is less than 10^{-3}, and the null hypothesis is again rejected. The comparison with the OSUBSGS Q_b values is most fair since Q_g for S0s will generally be a bar or oval strength without significant contributions from spiral arms.

The differences found, between S0s and OSUBSGS spirals on one hand, and between NIRS0S S0s and S0/a,Sa galaxies on the other, were previously highlighted in a preliminary analysis of S0 bar strengths by Buta et al. (2008). In that analysis, based partly on Sloan Digital Sky Survey (SDSS) i-band images, no S0 galaxy having $Q_g > 0.25$ was found. Of the three galaxies that have $Q_g > 0.25$ in our current analysis, two [NGC 4596 ($Q_g = 0.28$) and 4608 ($Q_g = 0.26$)] are reclassified as S0/a galaxies by Buta et al. (2007), and the third (NGC 4984) is classified as Sa in the RSA.

Figure 3 shows histograms of the distribution of bar strengths for the same galaxies as in Figures 1 and 2, for the alternative three values of the assumed scaleheight of the exponential vertical density profile, in terms of fractions of the isophotal radius r_{K20}. Of these, the one that is most like our $h_z = h_r/4$ plots is for $h_z = 0.10r_{K20}$, showing that our result is not sensitive to how we define the scale height. The values $h_z = 0.05r_{K20}$ and $0.20r_{K20}$, are selected to logarithmically bracket this value. These highlight the significance of the assumed thickness: as h_z increases, the relative frequency of strong bars decreases. If h_z is as large as $0.20r_{K20}$, there would be little skewness or extended tail in the distribution of early-type galaxy bar strengths.

This analysis can also give us an indication of what a factor of 2 uncertainty in the assumed average h_z can do to the distributions. A Kolmogorov-Smirnov comparison between the $h_z = 0.05r_{K20}$ and $h_z = 0.10r_{K20}$ distributions gives a D-parameter of 0.16 with a probability P=0.05 that the null hypothesis is rejected, more than a factor of 100 poorer than the comparison shown in Figure 2a,b gives. Comparison between the $h_z = 0.10r_{K20}$

and $h_z = 0.20r_{K20}$ distributions gives a similar result. Thus, even a factor of 2 uncertainty in the assumed average h_z would *not* rule out as significantly that the samples come from the same parent population.

There can be little doubt that thickness effects contribute part of the difference we find between spiral and S0 bar strengths. Even so, thickness can't fully explain the differences because even S0/a and Sa galaxies have stronger bars on average than S0s.

5. Discussion

Our study is the first to use the relative torque parameter Q_g (Q_b) for large well-defined samples to show the lower strengths of bars in S0 galaxies as compared to spirals. This turns out to be in good agreement with other ways of evaluating bar strength. For example, Laurikainen et al. (2009) compared fractions of bars, ovals, and lenses (in the near-IR) in galaxies of different types, and found that S0 galaxies have a smaller fraction of bars than S0/a galaxies or later spirals. Aguerri et al. (2009) used isophotal ellipse fits (in the optical) to come to the same conclusion. Our goal in this section is to examine several possible reasons for why the distributions of bar strengths in spirals and S0s are so different. In particular, we are interested in how the distributions connect to the possibility that spirals are the progenitors of S0s, an idea which originally came from comparison of the frequencies of S0s in clusters and in the field (Dressler 1980).

5.1. Do S0s have the bar strengths expected for systems not accreting any gas?

One way to interpret a distribution of bar strengths was discussed by Bournaud & Combes (2002), who used simulations to investigate the possibility that a galaxy may have multiple bar episodes during a Hubble time. If bar strength is a parameter that varies over time, then the relative frequency of galaxies in each bin must tell us the relative amount of time a galaxy spends in a given bar state (non-barred, weakly-barred, or strongly-barred). The bar state is something that could evolve due to gas accretion from external sources. Bars first grow, perhaps by swing amplification (Combes 2000) or by transferring angular momentum to a halo (Athanassoula 2003), and then drive gas into the center, building up a central mass concentration. This helps to heat the disk and weakens or destroys the bar. If there is gas accretion, the disk can be cooled to the point of instability to a new bar, as shown by Bournaud & Combes (2002). According to Block et al. (2002), gas accretion produces an extended "tail" to the distribution of bar strengths, while lack of gas accretion leads to a higher relative frequency of axisymmetric states than does gas accretion. The distribution of bar strengths in S0 galaxies, within the Bournaud & Combes framework, seems to support the idea that these galaxies have not accreted any external gas for a long time, while spirals have accreted gas. However, it remains to be determined in this framework what systematic environmental differences result in differences in gas accretion efficiency. S0s may in general have only a small amount of cool gas, but this does not explain why S0s have not accreted more gas.

5.2. Are weaker bars in S0s due mainly to more massive bulges and thicker disks?

S0 galaxies may not be directly comparable to the non-accreting models of Bournaud & Combes, which still have interstellar gas and spiral structure. An alternative interpretation is that S0s have weaker bars on average because they have more massive bulges than spirals (Laurikainen et al. 2004, 2007). This dilutes the tangential forces, making even a relatively strong-looking (high relative m=2 Fourier amplitude or high maximum ellipticity) bar come out weak (see Figures 8 and 10 of Laurikainen, Salo, & Buta 2004 for illustrations of this dilution effect between early- and late-type spirals). As a check of how much this effect plays a role, we analyzed the SB0 galaxy NGC 7155 from Buta et al. (2009), using similar techniques as for formal NIRS0S galaxies. The bar strength is derived from a deprojected image obtained by first subtracting a spherical bulge model, deprojecting the disk component structures, and then adding back the bulge. The bar strength obtained for this galaxy using such an image is 0.19. According to Figure 1 of Laurikainen et al. (2007), an Sbc galaxy has about half the K_s-band bulge-to-total luminosity ratio as a typical S0. In order to simulate this, we add back to NGC 7155's disk component the same bulge model scaled down by a factor.of 2. This yielded a bar strength of 0.26, 37% larger than for the actual bulge model. Since the strongest RC3 S0 bars have $Q_g \leq 0.3$, this kind of effect would translate to a spiral maximum equivalent $Q_g \leq 0.4$, while the actual spiral Q_g can be as high as 0.7 (e.g., Laurikainen et al. 2004; Buta et al. 2009).

De Grijs (1998) showed that on average, S0s have thicker disks than late-type spirals. For a given mass, this implies less tangential forcing in the plane. The effect of the disk thickness on Q_g was estimated by Laurikainen & Salo (2002): calculating two extreme cases for the SBab galaxy NGC 1433, h_z=h_R/2.5 and 10, changes Q_g from 0.4 to 0.5.

The combination of more massive bulges and thicker disks can therefore account for some of the difference in average bar strength between S0s and spirals. However, it is not likely to account for all of the difference because other methods of estimating bar strength also indicate that S0 bars are weaker on average than bars in spirals. Aguerri et al. (2009) used the ellipticity-based f_{bar} parameter of Abraham & Merrifield (2000) to show, for an SDSS volume-limited sample, that S0 bars have a lower median f_{bar} than early- or late-type spirals. Aguerri et al. (2009) tested the impact of the bulge on bar ellipticities, and concluded it had no affect on their result that S0 bars are weaker than spiral bars.

5.3. S0s as Transformed Spirals

One of the main conclusions of Laurikainen et al. (2010a) is that the specific photometric properties of S0 bulges and disks (e.g., Sérsic n, correlation of bulge and disk scale lengths) favor the idea that S0s in general are evolved from spiral progenitors (see also Dressler et al. 1997; Bekki et al. 2002; Shioya et al. 2004; van den Bergh 2009; and also Burstein et al. 2005 for a counter-argument). The main problem with this interpretation is that S0 bulges are more massive than spiral bulges, yet the present interstellar gas content of spirals is insufficient to account for such masses (KK04). This could simply mean that S0s had more gas-rich progenitors than present-day spirals, or that another mechanism, unrelated to gas flow, could have caused pre-existing disk stars to become part of a pseudobulge. For the latter, KK04 suggested that a bar buckling instability might be relevant, although this mechanism mostly raises the stars away from the disk plane, but does not necessarily lead to the radial migration of the stars which is needed to build up the kind of central mass that would significantly dilute Q_g. The concept of the bulge in the buckling process is different from the kind of bulge we are concerned with. A bulge created by buckling is actually part of the bar, as discussed in many simulation studies (e.g., see review by Merrifield 1995).

If S0s are mainly spirals that have been stripped of (or used up, or lost) all or most of their gas, then they should evolve as purely stellar systems. Block et al. (2002) have noted: "In the absence of gas, the dynamics of disks is different: pure stellar bars are very robust, and can endure for one Hubble time, contrary to bars in spirals. In S0s, bars are not destroyed, and no mechanism is needed to explain bar reformation." This suggests that once the gas is gone, no further evolution of the bar would be possible and the galaxy would maintain the bar strength it had after the gas was removed. Thus, whatever bar is left is not destroyed any further, and S0 galaxies would be preserving a type of "fossil" bar.

The more massive bulges in S0s nevertheless suggest, either that S0s are not stripped spirals, or that secular evolution does occur in S0s, including bar evolution. These bulges, which make S0 bars systematically weaker compared to spirals, could be explained if there existed an effective mechanism which allows the bulge to continue to grow from disk material during, or even after, the gas depletion process. One such mechanism, the potential-density phase shift (PDPS) mechanism, was proposed by Zhang (1996, 1998, 1999). According to the PDPS mechanism, inward movement of the *stellar* component could still occur as long as the bar wave mode has a small amount of skewness (i.e., can be thought of as a very open spiral). Just like a spiral, bar skewness would introduce a phase shift between the density and potential of the bar, causing stellar material (as well as gas) to slowly move inward inside corotation and outward outside corotation, with the result of slow secular mass increase in the bulge and a spreading outward of the disk. A by-product of the radial mass redistribution induced by the PDPS mechanism is the secular heating of the disk stars in all three spatial dimensions, which also leads to the growth of the bulge (Zhang 1999).

Zhang & Buta (2007; their Figure 7 especially) show that slightly skewed bars are indeed present among early-type barred galaxies, making the PDPS mechanism a viable process to consider. The mechanism can operate in any galaxy with a skewed pattern, and is purely gravitational, so it affects both stars and gas. The mechanism is not expected to be important if a bar is perfectly linear or a spiral is very tightly wound (Zhang 2008). Note that the ability of the mechanism to account for the more massive bulges in S0s does not depend on the exact process that depletes the gas in a galaxy. Evolution from a later type system (small B/T ratio) to an earlier type system (larger B/T ratio) follows naturally from the process. If only star formation depletes the gas, then the transition from spiral to S0 could be smooth and the bulges of S0s could then simply be more advanced in an evolutionary sense than those in spirals (Zhang 1999). If another mechanism, such as ram pressure stripping, depletes the gas, the PDPS mechanism could still operate, but the resulting S0 may not have as large a B/T mass ratio as it would have had if star formation depleted the gas.

Studies of the role of a central mass concentration (CMC) in weakening or destroying bars have suggested that a mere buildup of bulge mass would be insufficient for total bar destruction. Shen & Sellwood (2004) used numerical simulations to show that diffuse CMCs are much less effective at destroying bars than extremely dense CMCs. In fact, their simulations did not even use a bulge model, only a disk plus a CMC. If an S0 did develop a massive enough (few percent disk mass) and concentrated enough (supermassive black hole (SMBH)-like) CMC, then its bar could be destroyed in a Hubble time. Athanassoula, Lambert, & Dehnen (2005; see also references therein) showed that a CMC with 10% of the mass of the disk could severely weaken a bar over time even in the presence of a significant halo.

5.4. Bars and Lenses

Evidence that bars can be destroyed or weakened in S0s may come from the existence of lenses. Kormendy (1979) showed that lenses (components of galaxy structure having a shallow brightness gradient interior to a sharp outer edge) are most abundant in SB0-SBa galaxies and much less abundant in later-type barred galaxies, the latter having mostly inner rings. Laurikainen et al. (2009) found lenses in 97% of a subset of 127 NIRS0S galaxies; in that study also, S0/a galaxies included 82% with lenses. Kormendy (1979) suggested that lenses are the products of dissolved or dissolving bars, an idea supported by an observational study of the lens in the $S0^+$ galaxy NGC 1553 (Kormendy 1984) and by numerical simulations such as those of Bournaud & Combes (2002). Numerical simulations by Heller et al. (2007) have also shown that bars can evolve to "fat ovals" over time. If this is indeed a viable origin for lenses, then even if S0s were tied mainly to S0/a progenitors, the lower relative frequency of lenses in S0/a types compared to S0s suggests that bars do not "freeze" after a galaxy is stripped, but continue to evolve towards further dissolution.

Laurikainen et al. (2009) have suggested that the frequent presence of lenses in S0s, of ansae in the bars of many S0s (Laurikainen et al. 2007; Martinez-Valpuesta et al. 2007), and of the double-peaked Fourier profiles in early-type galaxies (Laurikainen et al. 2007), argues that the bars of S0s are simply more evolved than those in spirals. If S0s have spiral progenitors that did not necessarily have lenses at the time the galaxies were stripped or cleaned of gas, then the formation of some lenses had to have occurred *during* the S0 phase, meaning bar evolution must have continued in the absence of much interstellar gas. A caveat connected with the lens issue is that not all lenses are likely to be associated with dissolved bars. In galaxies with multiple lenses, some could represent highly evolved former zones of active star formation, such as inner, outer, and nuclear rings, in addition to highly evolved bars.

6. Conclusions

We have highlighted the significant difference in the distribution of bar strengths between S0 and spiral galaxies. Strong bars having $Q_b > 0.25$ are rare among S0s but relatively common among spirals. Much of the difference can be traced to the more massive bulges and thicker disks on average that characterize S0s as compared to spirals, both of which conspire to make S0 maximum relative gravitational bar torques low compared to spirals. This cannot be the whole reason behind the difference, however, because even when relative bar Fourier contrast, bar ellipticity, and bar fraction are considered, bars are still less prominent in S0s than in spirals. The suggestion is that if spirals really are the progenitors of S0s, then there must exist a mechanism that allows bar evolution to continue after gas depletion. One possible mechanism, tied to the skewness of early-type galaxy bars, is a potential-density phase shift that can evolve the purely stellar distibution, allowing continued bulge-building that will help to weaken any bar remaining after gas depletion. The earlier findings of the high frequency of lenses in S0s fits to the scenario in which bar evolution continues after depletion.

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Table 1. The NIRS0S Sample of 183 Galaxies[a]

Galaxy	T	Q_g	σ	Galaxy	T	Q_g	σ	Galaxy	T	Q_g	σ
1	2	3	4	1	2	3	4	1	2	3	4
N0205[b]	−5.0	.....	.....	N3384	−3.0	0.055	0.019	N4772	1.0	0.061	0.001
N0404[b]	−3.0	.....	.....	N3412	−2.0	0.081	0.013	N4880	−1.0	0.115	0.016
N0439[h]	−3.3	.....	.....	N3414[c]	−2.0	0.084	0.042	N4914	−4.0	0.064	0.004
N0474	−2.0	0.054	0.016	N3489	−1.0	0.068	0.008	N4976	−5.0	0.045	0.003
N0507	−2.0	0.052	0.008	N3516	−2.0	0.066	0.009	N4984	−1.0	0.340	0.006
N0524	−1.0	0.019	0.004	N3607	−2.0	0.088	0.000	N5026	−.2	0.222	0.062
N0584	−5.0	0.098	0.025	N3619	−1.0	0.024	0.006	N5078[i]	1.0	.....	.....
N0718	1.0	0.121	0.009	N3626	−1.0	0.106	0.000	N5087	−3.0	0.171	0.000
N0890	−3.0	0.088	0.001	N3665	−2.0	0.078	0.013	N5101	0.0	0.237	0.016
N0936	−1.0	0.204	0.045	N3706[h]	−3.0	.....	.....	N5121	1.0	0.025	0.003
N1022	1.0	0.145	0.009	N3718[g]	1.0	0.315	0.059	N5128[b]	−2.0	.....	.....
N1079	0.0	0.228	0.039	N3729	1.0	0.216	0.003	N5206[j]	−2.5	0.150	0.010
N1161	−2.0	0.127	0.009	N3892	−1.0	0.190	0.008	N5266	−3.0	0.074	0.001
N1201	−2.0	0.101	0.017	N3900	−1.0	0.081	0.021	N5273	−2.0	0.036	0.012
N1291	0.0	0.102	0.009	N3941	−2.0	0.113	0.010	N5353[d]	−2.0	0.246	0.002
N1302	0.0	0.092	0.006	N3945	−1.0	0.094	0.009	N5354[d]	−2.0	.....	.....
N1316	−2.0	0.076	0.002	N3998	−2.0	0.037	0.008	N5377	1.0	0.244	0.069
N1317	1.0	0.082	0.002	N4073[h]	−3.8	.....	.....	N5365	−3.0	0.105	0.009
N1326	−1.0	0.139	0.009	N4105[d]	−5.0	0.092	0.002	N5419	−4.7	0.052	0.015

Table 1—Continued

Galaxy	T	Q_g	σ	Galaxy	T	Q_g	σ	Galaxy	T	Q_g	σ
1	2	3	4	1	2	3	4	1	2	3	4
N1344	−5.0	0.081	0.011	N4106[d]	−1.0	.....	.....	N5448[i]	1.0	.....	.....
N1350	1.8	0.210	0.050	N4138	−1.0	0.047	0.002	N5473	−3.0	0.082	0.007
N1371	1.0	0.115	0.015	N4143	−2.0	0.075	0.006	N5485	−2.0	0.043	0.002
N1380	−2.0	0.158	0.003	N4150	−2.0	0.053	0.003	N5493[c]	−2.0	0.291	0.005
N1387	−3.0	0.067	0.003	N4203	−3.0	0.040	0.002	N5631	−2.0	0.051	0.005
N1389	−3.3	0.080	0.018	N4245	0.0	0.188	0.015	N5701	0.0	0.217	0.001
N1400	−3.0	0.034	0.001	N4262	−3.0	0.071	0.024	N5728	1.0	0.343	0.003
N1411	−3.0	0.022	0.006	N4267	−3.0	0.045	0.003	N5846[h]	−5.0	.....	.....
N1512	1.0	0.158	0.006	N4281[h]	−1.0	.....	.....	N5898	−5.0	0.023	0.001
N1533	−3.0	0.105	0.008	N4293[i]	0.0	.....	.....	N6340	0.0	0.029	0.001
N1537	−2.5	0.146	0.063	N4314	1.0	0.445	0.010	N6438[f]	−2.0	.....	.....
N1543	−2.0	0.125	0.017	N4339	−5.0	0.030	0.005	N6482	−5.0	0.064	0.002
N1546[b]	−1.3	.....	.....	N4340	−1.0	0.224	0.032	N6684	−2.0	0.109	0.001
N1553	−2.0	0.102	0.000	N4350[c]	−2.0	.....	.....	N6703	−2.5	0.022	0.001
N1574	−2.7	0.065	0.006	N4369	1.0	0.491	0.005	N6861[i]	−3.0	0.155	0.016
N1617	1.0	0.100	0.028	N4371	−1.0	0.246	0.002	N6958	−3.8	0.023	0.006
N1808[b]	1.0	.....	.....	N4373[d]	−2.9	1.057	0.037	N7029	−5.0	0.083	0.000
N1947[b]	−3.0	.....	.....	N4378	1.0	0.053	0.000	N7049	−2.0	0.084	0.000
N2196	1.0	0.065	0.023	N4382[k]	−1.0	.....	.....	N7079	−2.0	0.084	0.008

Table 1—Continued

Galaxy 1	T 2	Q_g 3	σ 4	Galaxy 1	T 2	Q_g 3	σ 4	Galaxy 1	T 2	Q_g 3	σ 4
N2217	−1.0	0.110	0.002	N4406[l]	−5.0	.....	.....	N7098	1.0	0.160	0.004
N2273	0.5	0.196	0.008	N4424[i]	1.0	.....	.....	N7192	−4.3	0.010	0.004
N2292[d]	−2.0	.....	.....	N4429[i]	−1.0	0.283	0.002	N7213	1.0	0.010	0.000
N2293[d]	−1.0	.....	.....	N4435[c]	−2.0	0.130	0.001	N7371	0.0	0.075	0.005
N2300	−2.0	0.056	0.012	N4457	0.0	0.108	0.008	N7377	−1.0	0.052	0.007
N2380	−1.7	0.023	0.005	N4459	−1.0	0.027	0.003	N7457	−3.0	0.050	0.022
N2655	0.0	0.089	0.004	N4474[c]	−2.0	0.094	0.013	N7585	−1.0	0.070	0.010
N2681	0.0	0.058	0.001	N4477	−2.0	0.100	0.025	N7727	1.0	0.075	0.015
N2685[g]	−1.0	0.249	0.003	N4503	−3.0	0.061	0.015	N7743	−1.0	0.109	0.019
N2768[i]	−5.0	0.072	0.008	N4531	−0.5	0.119	0.001	N7796	−3.8	0.053	0.001
N2781	−1.0	0.065	0.006	N4552	−5.0	0.137	0.039	I1392	−3.0	0.120	0.021
N2782	1.0	0.109	0.067	N4578	−2.0	0.063	0.000	I4214	1.5	0.158	0.008
N2787	−1.0	0.172	0.044	N4596	−1.0	0.281	0.047	I4329	−3.0	0.031	0.007
N2859	−1.0	0.102	0.004	N4608	−2.0	0.263	0.010	I4889	−5.0	0.121	0.024
N2911	−2.0	0.079	0.002	N4612	−2.0	0.086	0.000	I4991	−2.0	0.063	0.004
N2950	−2.0	0.103	0.069	N4638[c]	−3.0	0.251	0.020	I5240	1.0	0.192	0.016
N3100	−2.0	0.064	0.031	N4643	0.0	0.332	0.005	I5250 [b]	−2.0	.....	.....
N3166	0.0	0.216	0.004	N4649[d]	−5.0	0.354	0.015	I5250A[b]	−2.0	.....	.....
N3169	1.0	0.082	0.009	N4665	0.0	0.257	0.016	I5267	0.0	0.026	0.001

Table 1—Continued

Galaxy	T	Q_g	σ	Galaxy	T	Q_g	σ	Galaxy	T	Q_g	σ
1	2	3	4	1	2	3	4	1	2	3	4
N3226[d]	−5.0	0.098	0.001	N4691[e]	0.0	.....	.....	I5328	−5.0	0.063	0.003
N3227[d]	1.0	0.185	0.013	N4694	−2.0	0.141	0.007	E137−010	−2.7	0.056	0.009
N3245	−2.0	0.062	0.002	N4696	−4.0	0.041	0.003	E137−034[b]	0.0	.....	.....
N3358	0.0	0.088	0.008	N4754	−3.0	0.199	0.028	E208−021[h]	−3.0	.....	.....

[a]Col. 1: galaxy name; col. 2: RC3 numerical stage index; col. 3: bar strength; col 4: error estimate for bar strength. The sample is selected according to mean total blue magnitude $< B_T > \leq 12.5$, logarithmic isophotal blue light axis ratio $logR_{25} \leq 0.35$, and RC3 numerical stage index T<2 (earlier than Sab).

[b]no observations obtained in program

[c]edge-on galaxy

[d]member of a close pair

[e]no clear nucleus

[f]strongly interacting

[g]peculiar or otherwise disturbed

[h]luminosity distribution well-fitted by a single Sersic function

[i]inclination too high for reliable deprojection

[j]dwarf

[k]peculiar, nonbarred, edge-on, and warped?

[l]no bar; flattened bulge

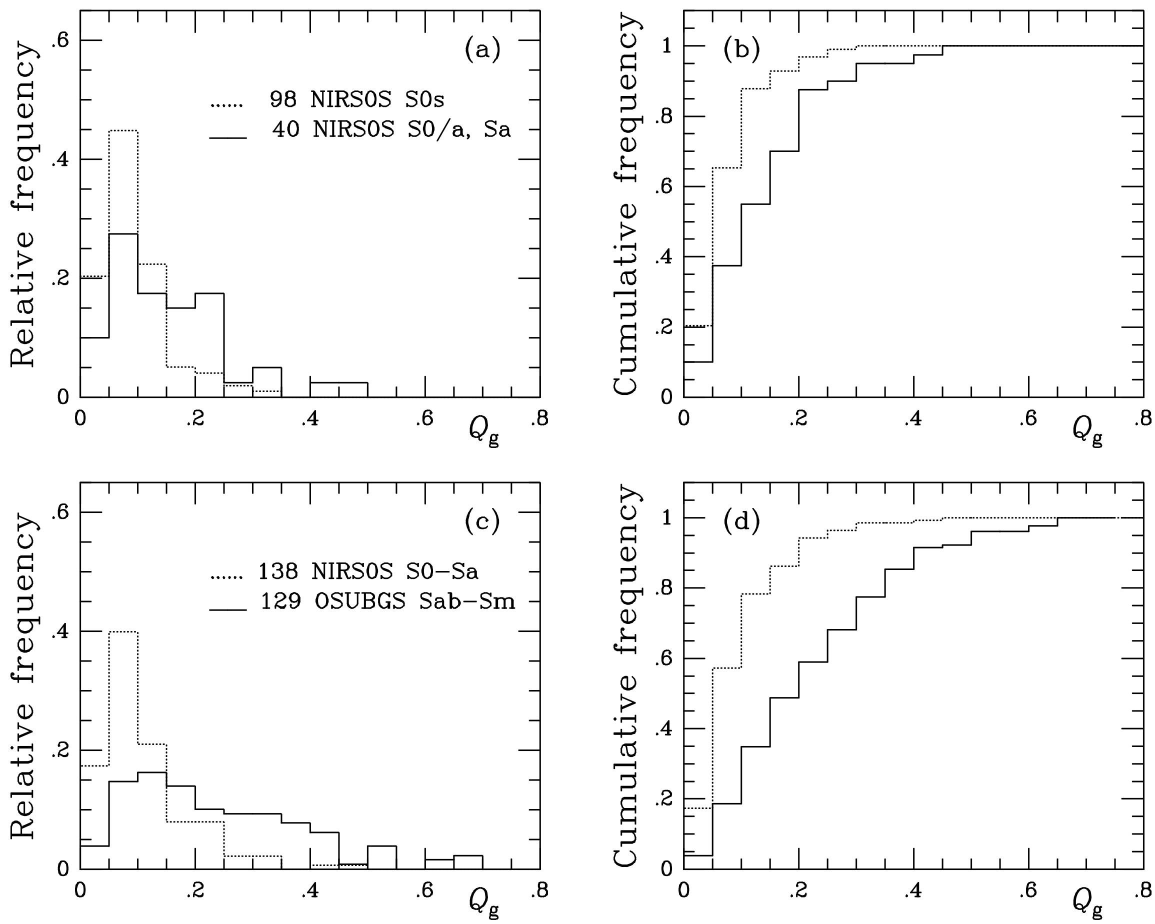

Fig. 1.— (a,b) Histograms of the distribution of bar strengths in S0s as compared early-type spirals (S0/a,Sa); (c,d) the same for the early-type galaxy NIRS0S sample and a subset of OSUBSGS spirals.

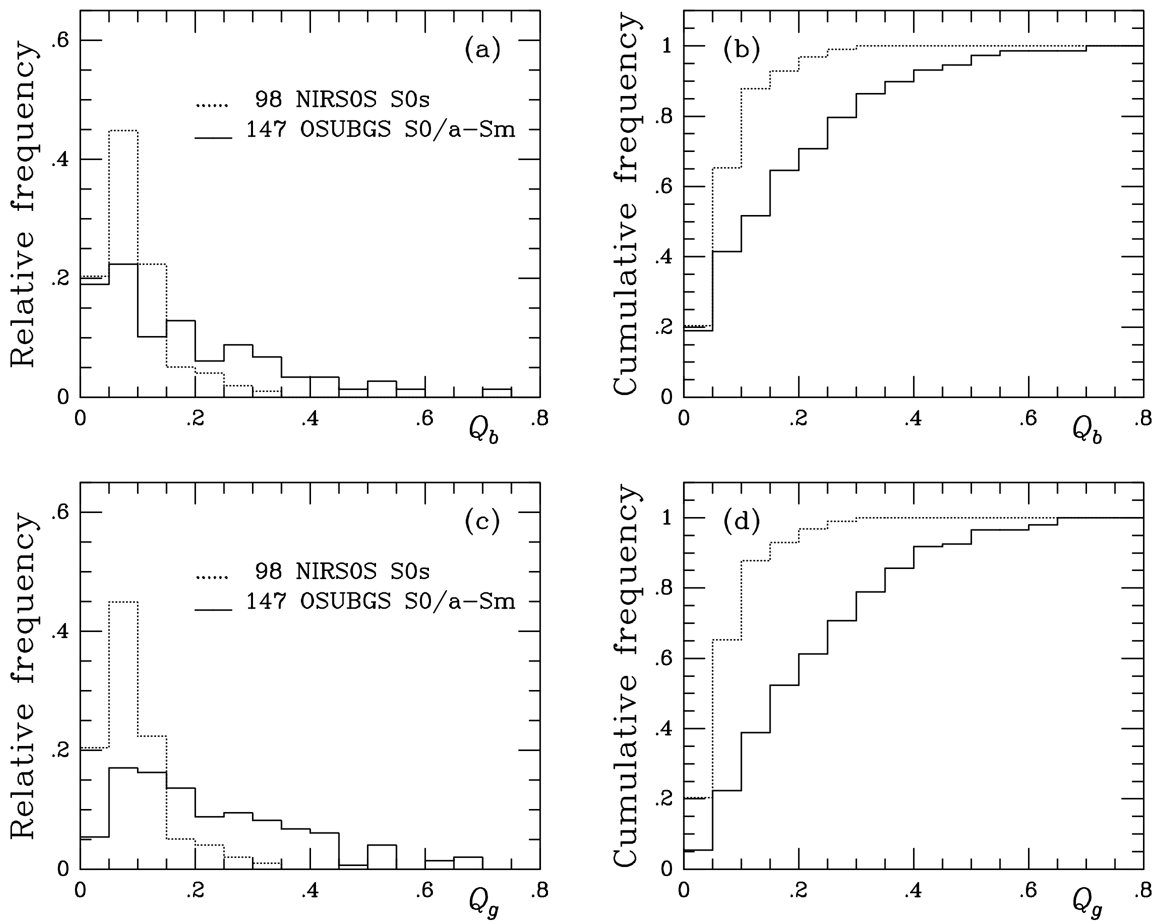

Fig. 2.— Histograms of the distribution of bar strengths in S0s as compared to OSUBSGS spirals, a sample dominated by intermediate to late-type spirals. Note that the distinction between Q_b and Q_g is relevant only to the OSUBSGS sample. For the S0s, we have set $Q_b = Q_g$.

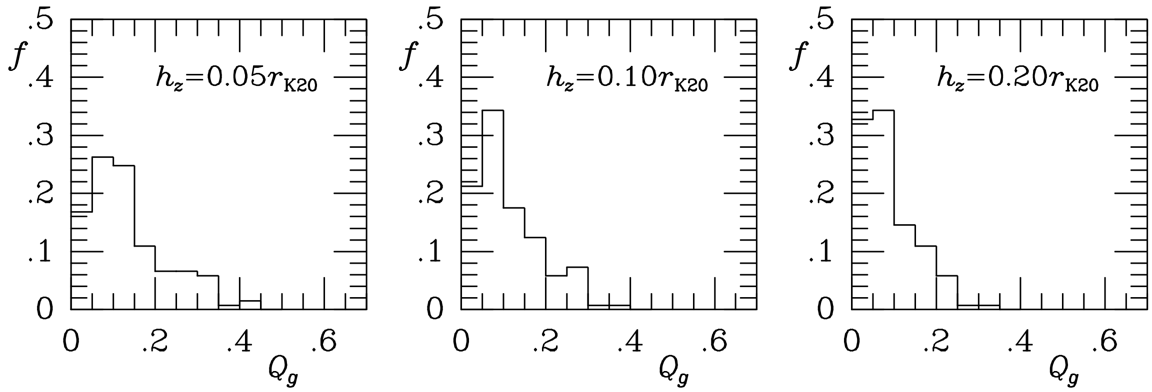

Fig. 3.— Histograms of the distribution of bar strengths in 137 NIRS0S galaxies for three different values of the assumed vertical scaleheight.