

Review Article

Overview of the Near-IR S0 Galaxy Survey (NIRS0S)

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An overview of the results of the near-IR S0 galaxy survey (NIRS0S) is presented. NIRS0S is a magnitude- ($m_B \leq 12.5$ mag) and inclination- ($<65^\circ$) limited sample of ~ 200 nearby galaxies, mainly S0s, but include also Sa and E galaxies. It uses deep K_s -band images, typically reaching a surface brightness of 23.5 mag arcsec $^{-2}$. Detailed visual and photometric classifications were made, for the first time coding also the lenses in a systematic manner. As a comparison sample, a similar sized spiral galaxy sample with similar image quality was used. Based on our analysis, the Hubble sequence was revisited: following the early idea by van den Bergh we suggested that the S0s are spread throughout the Hubble sequence in parallel tuning forks as spirals (S0a, S0b, S0c, etc.). This is evidenced by our improved bulge-to-total (B/T) flux ratios in the S0s, reaching small values typical to late-type spirals. The properties of bulges and disks in S0s were found to be similar to those in spirals and, also, the masses and scale parameters of the bulges and disks to be coupled. It was estimated that the spiral bulges brighter than -20 mag in K -band are massive enough to be converted into the bulges of S0s merely by star formation. Bars were found to be fairly robust both in S0s and spirals, but, in spite of that, bars might evolve significantly within the Hubble sequence.

1. Introduction

We review the main results of the near-IR S0 galaxy survey (NIRS0S) obtained so far. NIRS0S is a magnitude- ($m_B \leq 12.5$ mag) and inclination- (less than 65°) limited sample of ~ 200 nearby galaxies, mainly S0s, but include also Sa spirals and 25 late-type ellipticals. Late-type ellipticals were included for not to miss any potentially misclassified S0s. The observations were done in the K_s -band, carried out using 3-4-meter-sized ground-based telescopes with subarcsecond pixel resolution. The images are deep, typically reaching a surface brightnesses of 23.5 mag arcsec $^{-2}$ in azimuthally averaged profiles (~ 2 mag deeper than the 2MASS images), thus allowing the detection of the faint outer disks in S0s. Our main emphasis was to address possible secular evolutionary processes in galaxies by comparing the photometric properties of S0s and spirals, based on similarly selected samples, with similar image quality.

In the early classification by Hubble [1], the S0s were an enigmatic group of galaxies between the ellipticals and early-type spirals, and, since then, they have appeared to be important in any galaxy evolutionary model. S0s are suggested to evolve from spirals, either by internal secular processes in isolation or by gas stripping mechanisms, followed by quiescent star formation [2]: in cluster environment by ram pressure stripping [3] or by galaxy harassment [4] and in galaxy groups by tidal encounters (e.g., [5]). Alternatively, S0s have been suggested to form by galaxy mergers in a similar manner as elliptical galaxies [6, 7] or have accreted most of their mass in minor mergers [8, 9].

Originally, the stripping scenario was adopted because S0s were found to appear mainly in galaxy clusters [10] and also because they were kinematically more related to spirals than to ellipticals [11]. However, the large bulge fractions found by Simien and de Vaucouleurs [12] in S0s has worked as a counterargument to this scenario, because spiral galaxies do not have sufficient amount of interstellar gas to build such

large bulges [13]. Some S0s are also found to have chemically and kinematically decoupled cores [14], which are generally interpreted in terms of sinking of small gas poor satellites into the main galaxies. Likewise, the merger approach has problems, at least if interpreted as the dominant mechanism for producing the S0s. For example, modern semianalytical merger models (e.g., [9]) successfully produce the large bulge masses by Simien and de Vaucouleurs [12], but fail to recover the observed trend in α/Fe elements with stellar velocity dispersion [15, 16]. They have also difficulties to explain the observed tight luminosity-size relation for the S0s [17].

The morphological division between E and S0 galaxies was obscured by the detection of boxy and disky ellipticals by Bender ([18]; see also [19]). It was also found that both the galaxy luminosity and the degree of rotational support (σ/V_{max}) correlate with the isophotal shape of the elliptical galaxies [20]. Among other things, these findings led King. [21] and Djorgovski [22] to announce that the Hubble sequence is breaking down and should be replaced by a more physical approach, based on measured physical parameters, related to galaxy kinematics. Recently it was suggested by Cappellari et al. [23] that such a parameter could be λ_{Re} , a proxy for the specific angular momentum in galaxies. Based on λ_{Re} they showed that most S0s and also even 2/3 of the elliptical galaxies in the nearby Universe are rotationally supported. It was also shown by Emsellem et al. [24] that this kinematic parameter has no clear correlation with the boxy/disky isophotal shapes. These findings are suggested to put into a new light many of the previous results, including the morphological classification of the early-type galaxies [23]. NIRS0S has a large overlap with the sample by Cappellari et al. [23] (used in [24]), thus allowing to compare the kinematic classification with the new morphological classification of S0s made by Laurikainen et al. [25].

In the following an overview of the main results of NIRS0S is given, discussed in conjunction of some recent studies of S0s (more complete references can be found in the original papers). As a comparison sample, the Ohio State University Bright Spiral Galaxy Survey (OSUBSGS; [26]) has been used, for which galaxies we have carried out similar analysis as for NIRS0S. Our main analysis methods include detailed visual and photometric classification of galaxies, 2D multicomponent structural decompositions, Fourier's analysis for calculating the properties of bars, and isophotal analysis. In this paper we also analyze a subsample of NIRS0S, which has kinematic information given by Emsellem et al. [24]. A picture is outlined supporting the view that S0s in general are evolved from spiral progenitors. They are suggested to be spread throughout the Hubble sequence forming S0a, S0b, S0c types, in a similar manner as spirals. Our scenario, originally outlined in Laurikainen et al. [27], is similar to that suggested recently by Kormendy and Bender [28].

2. NIRS0S Atlas

NIRS0S Atlas [25] presents the flux calibrated images, shown in a logarithmic scale. Also shown are the dimensions of

the identified structures, as well as the radial profiles of the isophotal analysis results (ellipticity, position angle, and the parameter b_4 , which measures the isophote's deviations from perfect ellipticity). An example of the layout of the atlas images is shown in Figure 1.

2.1. Morphological Classification and How It Compares with Kinematic Classification. The classification is based on de Vaucouleurs' revised Hubble-Sandage system ([29]; see also [30, 31]), which includes the stage ($S0^-$, $S0^o$, $S0^+$, Sa), family (SA, SAB, SB), variety (r, rs, s), outer ring or pseudo ring (R, R'), possible spindle shape, and the presence of peculiarity. The ring classification follows Buta and Crocker [32] and Buta [33]. What is new in our classification is that lenses (nuclear, inner, outer) are, for the first time, systematically coded for a significant sample of S0s. A new lens type "barlens" is also introduced: it is a lens-like structure embedded in a bar, with a fairly sharply declining outer surface brightness profile—this component has been often erroneously mixed with the bulge. Barlenses are shorter than the main bars and are typically identified inside strong bars. Due to the subarcsecond pixel resolution, it was also possible to classify the central structures like nuclear bars, rings, and lenses in a systematic manner.

Beside the above discussed visual classification, we also made a photometric classification where faint structures are identified even if they were not directly visible in the images. Faint structures, overshadowed by bulges, were detected after subtracting the bulge model in the decomposition and/or by making unsharp masking. Lenses were detected by inspecting the surface brightness profiles, in which they generally appear as nearly exponential subsections, however, with more shallow profiles than the main disk component. Photometric classification turned out to be critical for separating S0s from the elliptical galaxies at the E/S0 interface.

NIRS0S has 66 galaxies in common with the 3D Atlas, which is a volume-limited sample of 260 early-type galaxies, with the kinematic λ_{Re} parameter available [24]. λ_{Re} is a proxy for the specific angular momentum in galaxies and can be used as a measure for the rate of the kinematic support, thus dividing the galaxies to fast and slow rotators. It is measured within one effective radius of galaxy brightness, thus covering well the bulge region. Of the 66 galaxies in common, 9 were ellipticals and 56 were S0-S0/a galaxies in the Third Reference Catalog of Bright Galaxies ([29], RC3). However, in our classification only 2 out of the 9 galaxies were truly ellipticals. Kinematically, one of the two ellipticals is a slow rotator, whereas the other is a fast rotator showing an inner disk. The complete NIRS0S has 26 galaxies classified as ellipticals in RC3, of which only 3 remained ellipticals in our photometric classification. This comparison shows that generally the Hubble stage based on the morphological and kinematic classification is consistent with each other (notice that NIRS0S does not include highly inclined galaxies). However, based on λ_{Re} not all galaxies with prominent outer disks are fast rotators. Slow rotators include NGC 4552, NGC 5846, NGC 5631, and NGC 6703, in which the S0 nature is confirmed by the detection of a lens (NGC 5846 even

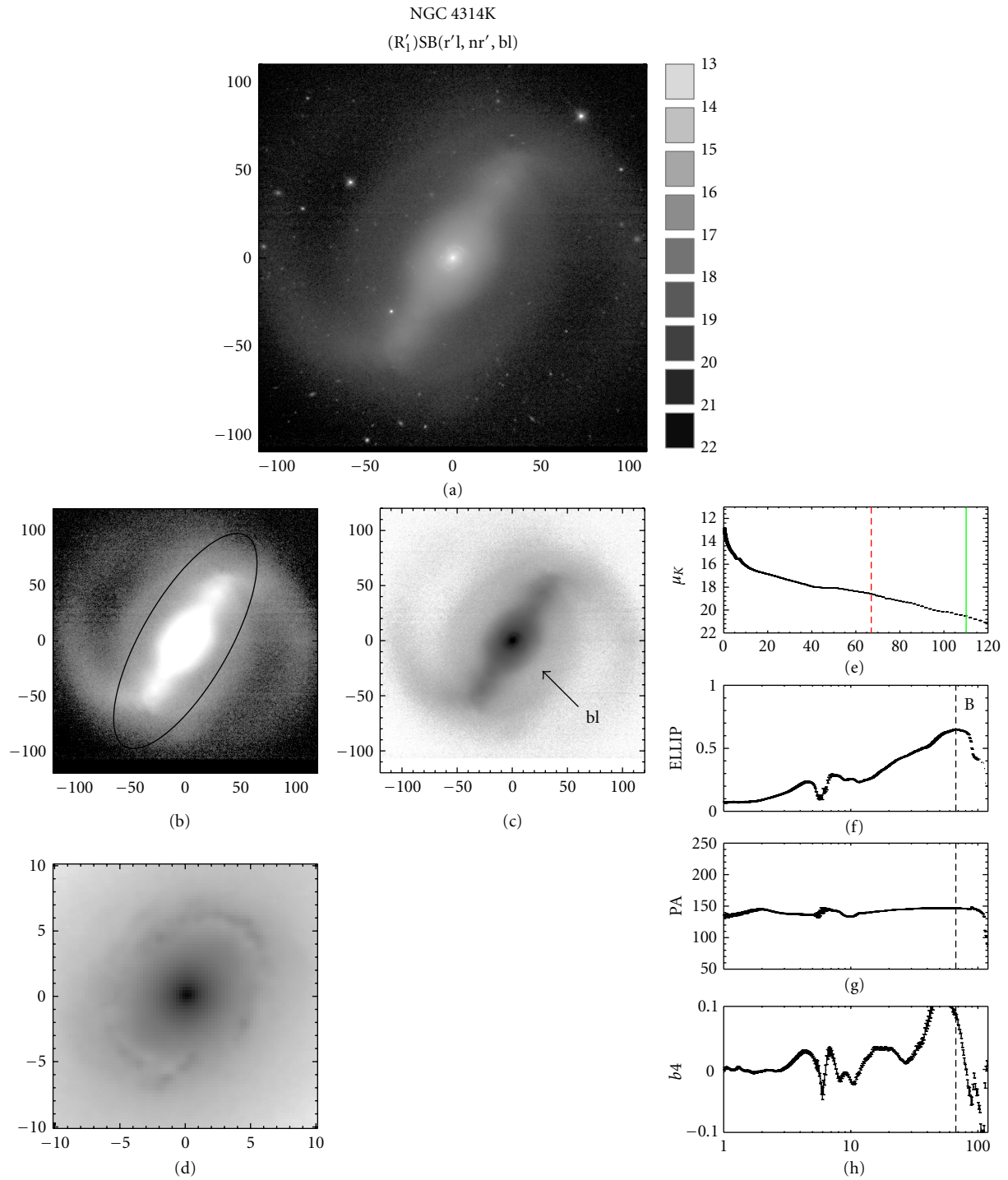


FIGURE 1: An example of the atlas image [25]. The upper subfigure shows the whole galaxy using the full magnitude range, for which the scale is indicated in the right. The scales in x - and y -axes are in arcseconds. The small subfigures show the same image, but selecting the radial and magnitude scales in a different manner: the two upper subfigures use the full radial scale, whereas in the lower one only the central region of the galaxy is shown. The morphological classification is from the Atlas paper. The graphics show the radial profiles of the surface brightness (a), 2MASS r_K20 ellipse (b) denotes 2MAS K20 isophote, position angle (c), and parameter b_4 (d) indicating deviations from perfect ellipticity. The logarithmic radial scale is in arcseconds. In these plots the vertical dashed lines indicate the bar radius, and the full line is the radius where the surface brightness is 20 mag arcseconds⁻². Originally the figure appeared in Laurikainen et al. [25].

has multiple lenses). Slow rotators comprise also NGC 4406 and NGC 4472, which have exponential outer profiles, used as evidence of a disk in our photometric classification. In conclusion, this means that λ_{Re} alone cannot be used to distinguish the Hubble stage among the S0s and the elliptical galaxies.

3. Properties of Bars

3.1. Morphology of Bars in S0s. Bars are the main characteristic common in S0s and spirals. They can be regular elongated structures (NGC 4608), have condensations at the two ends of the bar (ansae; e.g., NGC 2983), or show X-shaped structure in the inner part of the bar (e.g., IC 5240) (Figure 2). Beside ansae, NGC 2983 and NGC 4608 have also barlenses. Both structures are illustrated in Figure 2 by subtracting the underlying bar + bulge model from the image of NGC 2983: the residual image shows a nearly spherical barlens and two blots (ansae) that form part of the bar.

It was shown by Laurikainen et al. [34] that ansae in bars are characteristic to S0s, appearing less frequently in spiral galaxies (40% and 12%, resp.). This was shown simultaneously also by Martinez-Valpuesta et al. [35], who additionally suggested that strong bars (B) have ansae more frequently than weak bars (AB). Both studies used a subsample of NIRS0S and in [35] also the de Vaucouleurs' atlas by Buta et al. [30]. By repeating the statistics for the complete NIRS0S sample in this study using the classifications of the NIRS0S Atlas, we find ansae in 30% of the S0s, which are still clearly higher than those in spirals. However, now the fraction of ansae is the same for strong (B) and weak (AB) bars. In Laurikainen et al. [36], the large fraction of ansae bars among the S0s was discussed as evidence of bar evolution in the Hubble sequence.

In NIRS0S Atlas X-shaped bars appear in 9 galaxies, which is 8% of all barred galaxies [25]. This is important, because all the galaxies in NIRS0S have inclinations less than 65° , although the X-shaped bars are generally discussed in the context of nearly edge-on galaxies, suggested to be formed by vertical thickening due to buckling effects [37, 38]. It was shown by Athanassoula and Beaton [39] that the vertical thickening might still be recognized at inclinations of 77.5° , whereas our study shows that the X-shaped bar morphology can be visible even in almost face-on galaxies. A nice example of such a bar appears in IC 5240 (Figure 2), which has an inclination of 49° (taken from [25]). Evidently, bar buckling alone, leading to a vertical thickening of a bar, is not sufficient to explain such bar morphologies.

Multiple bars appear in $\sim 20\%$ of the S0s [36], which is a similar number as found previously also for spirals [40, 41]. It is worth noticing that S0/a galaxies have a larger number of multiple bars [36]. A prototypical case where two bars appear nearly perpendicular to each other is shown in Figure 3, in which both the nuclear and the main bar are surrounded by lenses. Some galaxies, like NGC 2681, have even three bars.

3.2. Fourier Properties of Bars: S0s Versus Spirals. The properties of bars in S0s (using a subsample of NIRS0S) and

spirals (using OSUBSGS) have been studied by Laurikainen et al. [34] using a Fourier method. For the complete NIRS0S, they will be presented in a forthcoming paper. Tangential forces induced by the nonaxisymmetric structures, mainly bars, were measured using a bar torque approach [42], applying the polar method by Salo et al. ([43, 44]; see also [45]). In this method the surface brightness at each radius is decomposed into azimuthal Fourier's components. Using the even Fourier components (typically up to $m = 10$), the gravitational potential in the equatorial plane of the galaxy is obtained by FFT over azimuth, combined with direct summation over radial and vertical coordinates. An important advantage of the polar method is the suppression of spurious force maxima which may arise in the direct 3D Cartesian FFT integration in the noisy outer disks. The calculated Fourier amplitude profiles also provide another useful tool for characterizing bars (see below).

As a measure of bar strength, we use $Q_g = \max(F_T/\langle F_R \rangle)$, the maximum of tangential force amplitude relative to the mean axisymmetric radial force, evaluated at the region of the bar. The mass-to-light ratio (M/L) is assumed to be constant, and the vertical scale height of the disk (and bar) is estimated from the exponential scale length, using a Hubble-type-dependent mean ratio. Also, the different 3D density distribution of the bulge is corrected, based on bulge models obtained from decompositions. The effect of including dark halo force field was also investigated, but its influence on Q_g appeared to be insignificant at the bar region [46, 47]. These calculations also give a proxy for the bar length, r_{Q_g} , which is the radius where the maximum tangential force Q_g occurs. Bar lengths were estimated also from the phases of the A_2 Fourier amplitude by assuming that it is maintained nearly constant in the bar region (a correlation between this bar length and r_{Q_g} was shown by [48]). The maximum of $m = 2$ Fourier's amplitude, A_2 , was used as an estimate of the relative brightness of the bar. These properties are shown in Figure 5 in Laurikainen et al. [34] as a function of the Hubble type: bars grow in length and in relative brightness (A_2) towards the early-type galaxies, but for Q_g the trend is opposite. Notice that although the bar ellipticity (shown in the same figure) correlates with Q_g [49], it has no systematic correlation with the Hubble type. In Laurikainen et al. [48], the tendency of weakening bar strengths (Q_g) towards the early-type galaxies was explained by a dilution effect due to the more massive bulges in the early-type galaxies (e.g., the average Q_g parameter may decrease even if the average A_2 amplitude increases, since the bulge contribution to radial force becomes more important toward earlier types). There exist a correlation also between Q_g and A_2 , but for the above reason the correlations are different for the early- and late-type galaxies (see Figure 8 in [48]). The obtained tendency for bar lengths was originally shown by B. Elmegreen and D. Elmegreen [50].

For a subsample of 26 barred galaxies in NIRS0S, the radial A_2 profiles were fitted by single (SG) and double (DG) Gaussian functions by Buta et al. [51]. It appeared that 65% of the bars in S0-S0/a galaxies have single Gaussian profiles, whereas 35% are best fitted by two Gaussian functions. Typical examples of such profiles are shown in Figure 4. The

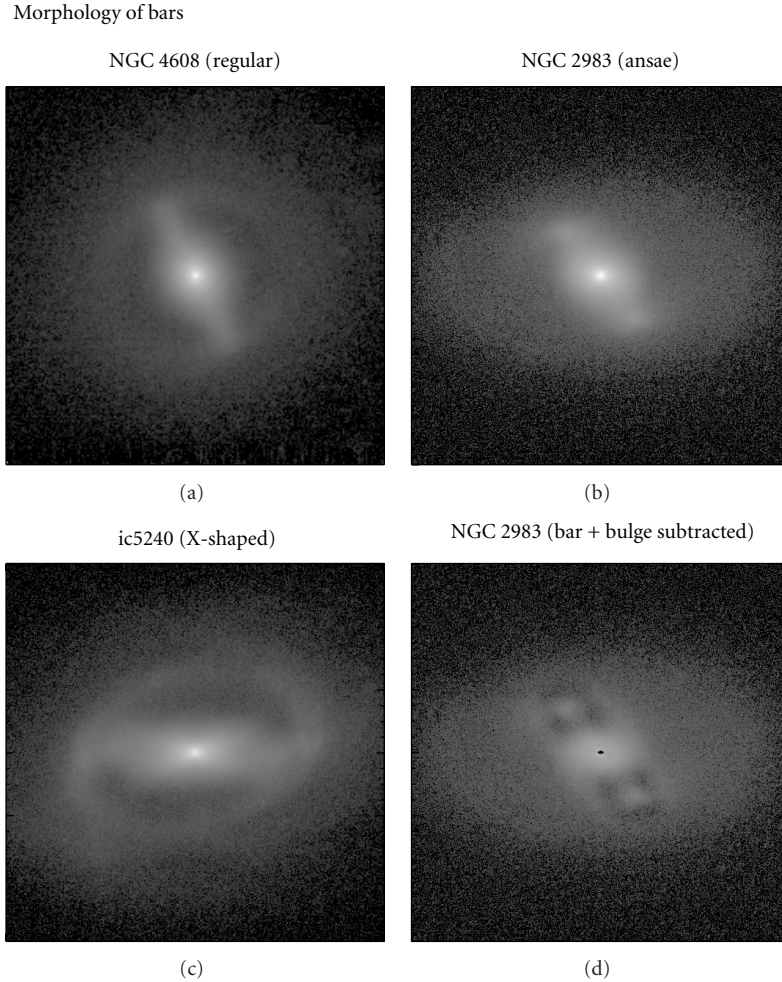


FIGURE 2: This figure is compiled of two figures that originally appeared in Laurikainen et al. [22]. The images are flux calibrated and are shown in a logarithmic scale, covering the full magnitude range of the images. The original images are shown, except in d) where the bar and bulge models from the decomposition are subtracted from the original image of NGC 2983. These images highlight the main bar morphological types in S0 galaxies.

galaxies with DG bars typically have also significant higher Fourier modes in the bar region ($m = 4, 6, 8$), in addition to $m = 2$ [34]. It was discussed by Buta et al. that the DG profiles are similar to those predicted by the simulation models (e.g., [52]) in which the bar transfers a large amount of angular momentum to the halo. An attempt to associate the DG profiles to specific morphological structures was made by Laurikainen et al. [34] who suggested that the fat or double-peaked Gaussian amplitude profiles are due to two bar components, a long and narrow bar, and a shorter component in the inner parts of the bar (or an inner oval). DG bars were found to be more prominent, not only in terms of Q_g but also in A_2 and bar length [34]. In Laurikainen et al. [25], these inner bar components were associated mainly with barlenses (though some of them can be ovals), which are found to appear in 30% of barred S0-S0/a galaxies in NIRS0S. A good example is NGC 4314 (Figure 1), in which the barlens is the fat elongated structure inside the bar. Erwin et al. [53] have discussed two S0s, in which a superposition of

a classical and a pseudo bulge was suggested. These galaxies are NGC 2787 and NGC 3945, which form part of NIRS0S. In both galaxies the component, interpreted as a pseudo-bulge by Erwin et al., is called as a fat inner bar component in [34] and more recently defined as a barlens by us [25].

3.3. Do S0s Have the Bar Strengths Expected for Systems Not Accreting Any Gas? The above question was recently made by Buta et al. [56] with the main emphasis to test the hypothesis by Bournaud and Combes [55], in which multiple-bar episodes are expected in the Hubble time. In this scenario, bars form and evolve in galaxies when they have gas, and the evolution stops when the gas is used in star formation. These stars are then transferred into the bulge, for example, by bars or spiral arms in the central regions of the galaxies. When the central mass concentration formed by star formation becomes very high, the bar will be destroyed. Therefore, if bar strength varies over time, the relative frequency of galaxies in each Q_g bin tells us the

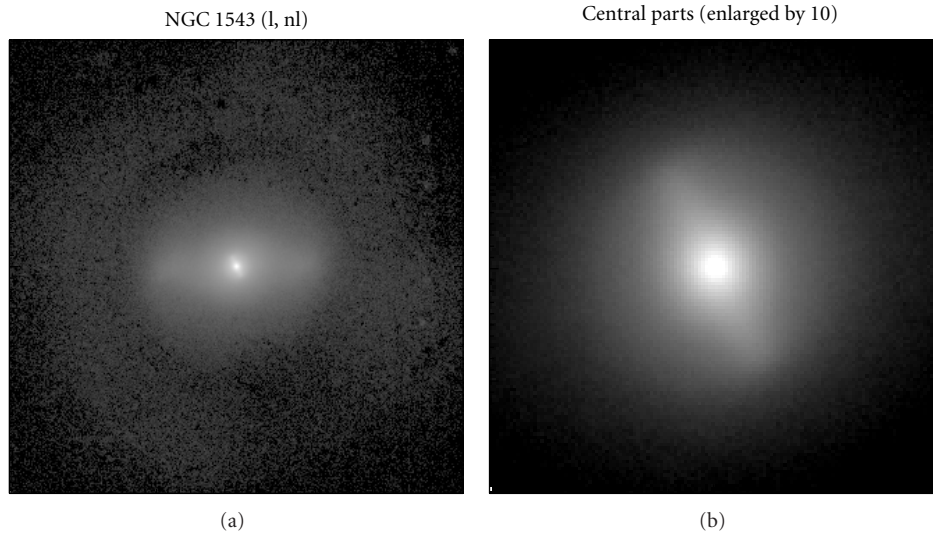


FIGURE 3: Two subfigures from Figure 15 in Laurikainen et al. [25] are shown. In (a) the whole galaxy is shown using the full magnitude range of the image. In this image the outer lens and the inner lens surrounding the main bar are clearly visible. In (b) only the central regions of the galaxy is shown (enlarged by a factor of 10), demonstrating the morphology of the nuclear bar and the nuclear lens extending to the radius of the nuclear bar.

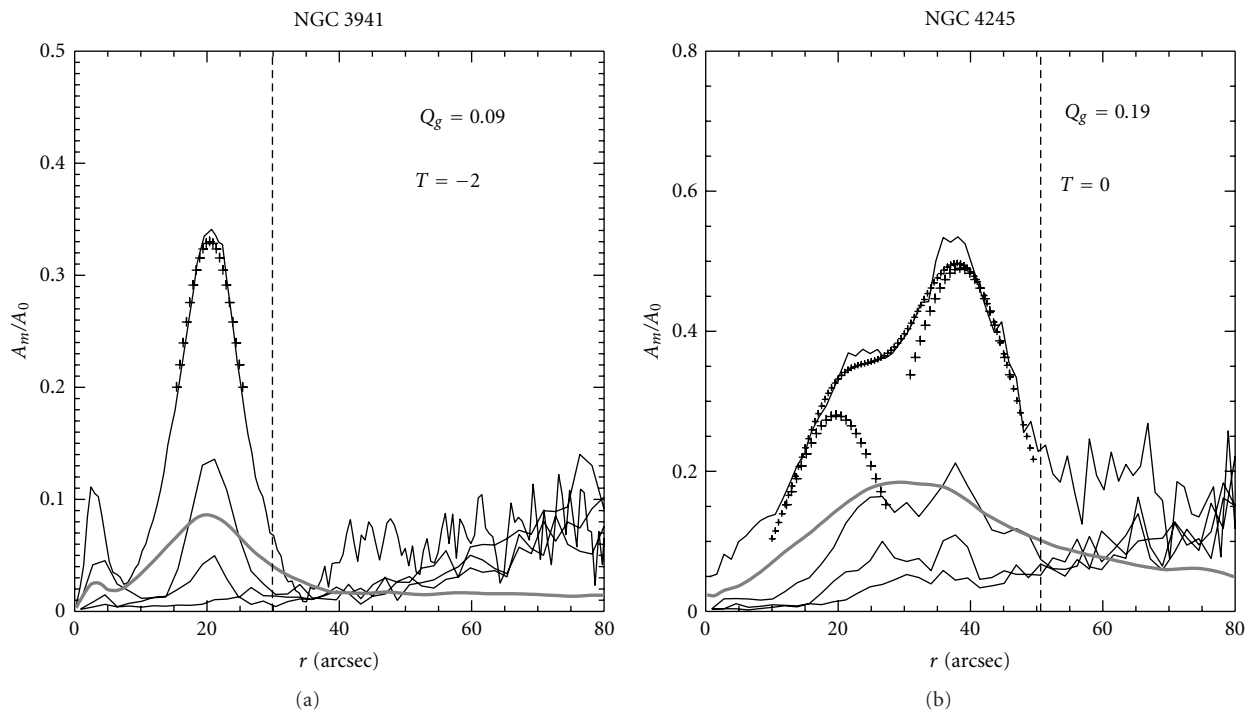


FIGURE 4: Radial profiles of the Fourier amplitudes of density: (a) shows a simple bar, whereas (b) shows a two-component bar: both lower and higher Fourier modes are significant in these two components. The thin lines show the $m = 2, 4, 6, 8$ Fourier's amplitudes, normalized to $m = 0$. The thick grey line shows the force ratio $QT(r) = |FT(r, \phi)| \max / (|FR(r, \phi)|)$ (Q_g indicates the maximum of QT), and the vertical line indicates the length of the bar. The crosses show individual Gaussian fits to the $m = 2$ Fourier's amplitude profile. The single-peaked bar represents a thin classical bar. The double-peaked amplitude profile is associated to a bar having a shorter and vertically thicker inner part and a longer and vertically thinner outer part. This figure is a modified version of Figure 8 in Laurikainen et al. [34].

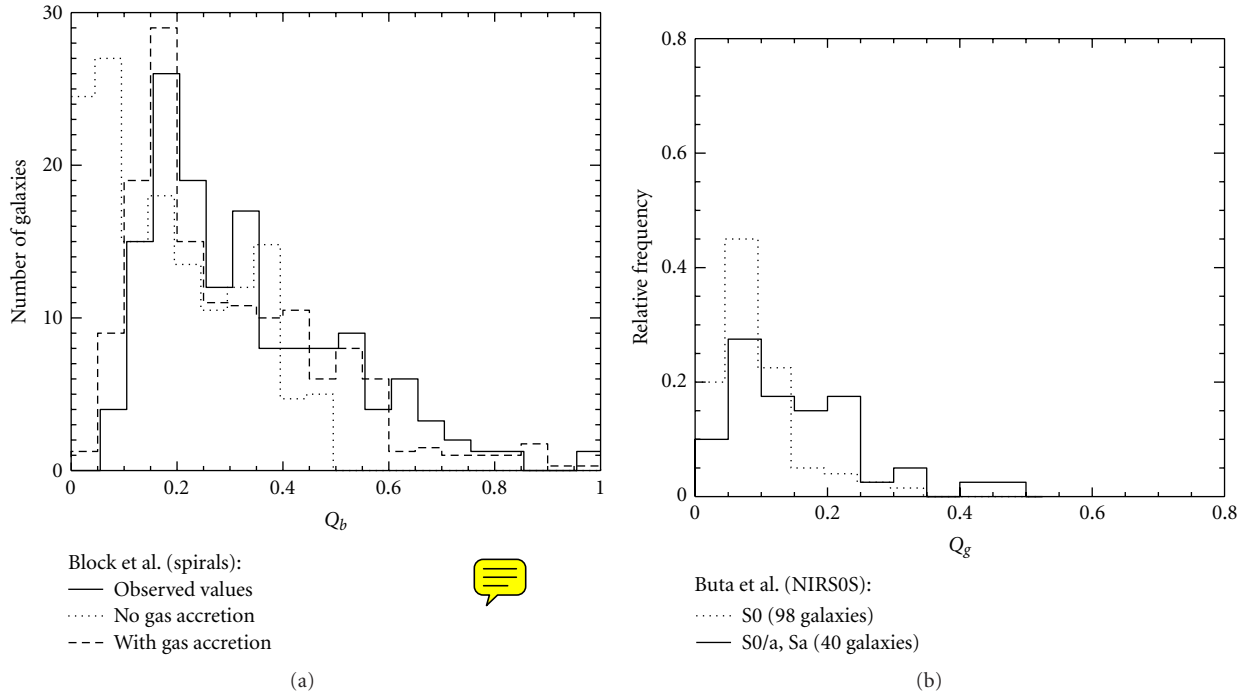


FIGURE 5: (a) the observed Q_g distribution for spirals in the OSUBSGS (cover the Hubble types up to $T = 9$), taken from Block et al. [54], compared with the simulation models by Bournaud and Combes [55]. The solid line shows the observed values from Block et al., the dotted line is the model with no gas accretion, and the dashed line shows the model that doubles the total galaxy mass in 10^{10} years. (b) the observed Q_g distributions for the S0s and early-type spirals in NIRS0S, taken from Buta et al. [56]. Notice that Q_b in Block et al. [54] in (a) has the same meaning as Q_g in Buta et al. [56] in (b).

relative amount of time a galaxy spends in a certain bar state (strong, weak, nonbarred). For spirals this was first tested by Block et al. [54]. They suggested that galaxies might have doubled their mass in 10^{10} years (see Figure 5(a)), evidenced by the extended tail towards strong bars and the lack of weak bars, whose features are predicted in the strong gas accretion models by Bournaud and Combes [55].

This test was later repeated by Buta et al. [57] for the same galaxy sample, but using the refined bar torque method described in the previous section (we also discussed why the obtained Q_g distribution was different from that by Block et al. [54]). In Buta et al. [47], the bar and spiral fluxes were additionally separated from each other. Although the correction affected Q_g in a few individual cases having very strong spiral arms, it barely affected the Q_g distribution. The refined Q_g distribution [47, 57] has a large number of weak bars lacking from that obtained by Block et al. Likewise, it has a slightly smaller number of very strong bars. In fact, the obtained Q_g distribution (see Figure 8a in [47]) largely resembles the nonaccretion model by Bournaud and Combes shown in Figure 5(a), thus supporting the view that bars in spirals are fairly robust. In Buta et al. [56], the Q_g distribution for NIRS0S was calculated. Most importantly, a clear difference was found between S0s and early-type spirals (see Figure 5(b)). This was suggested to support the view according to which S0s have not accreted gas for a long time, evidenced by the lack of the extended tail and the existence of a large number of weak bars. As discussed above

(see Section 3.2), the smaller number of strong bars among the S0s can be due to a dilution effect caused by the more massive bulges and thicker disks in S0s. However, it was also discussed by Buta et al. [56] that this cannot produce all of the difference in Q_g between the S0s and early-type spirals: although spirals have a larger number of strong bars than S0s, still there are no galaxies having $Q_g > 0.5$. The conclusion in this study was that, if S0s are stripped spirals, the weaker bars in S0s could indicate that bar evolution continues to proceed even after gas depletion in galaxies.

4. Lenses

Lenses appear as flat-disk components with rather sharp outer edges [58]. However, not all lenses are directly visible in the images. In the NIRS0S Atlas [25], lenses were generally detected as exponential subsections in the surface brightness profiles. NGC 524 (Figure 6) shows all the main lens types, nuclear (nl), inner (I), and outer lenses (L). When the outer lens is very prominent compared to the underlying disk, as in NGC 1533, it manifests as a broad bump in the surface brightness profile, in this case having also some characteristics of a ring (RL).

For clarity the examples shown of the different lens types are for nonbarred galaxies. However, lenses appear both in barred (61%) and nonbarred (38%) S0s, based on the classification in the NIRS0S Atlas [25]. In Laurikainen et al. [36], even a larger fraction of lenses was found, but it

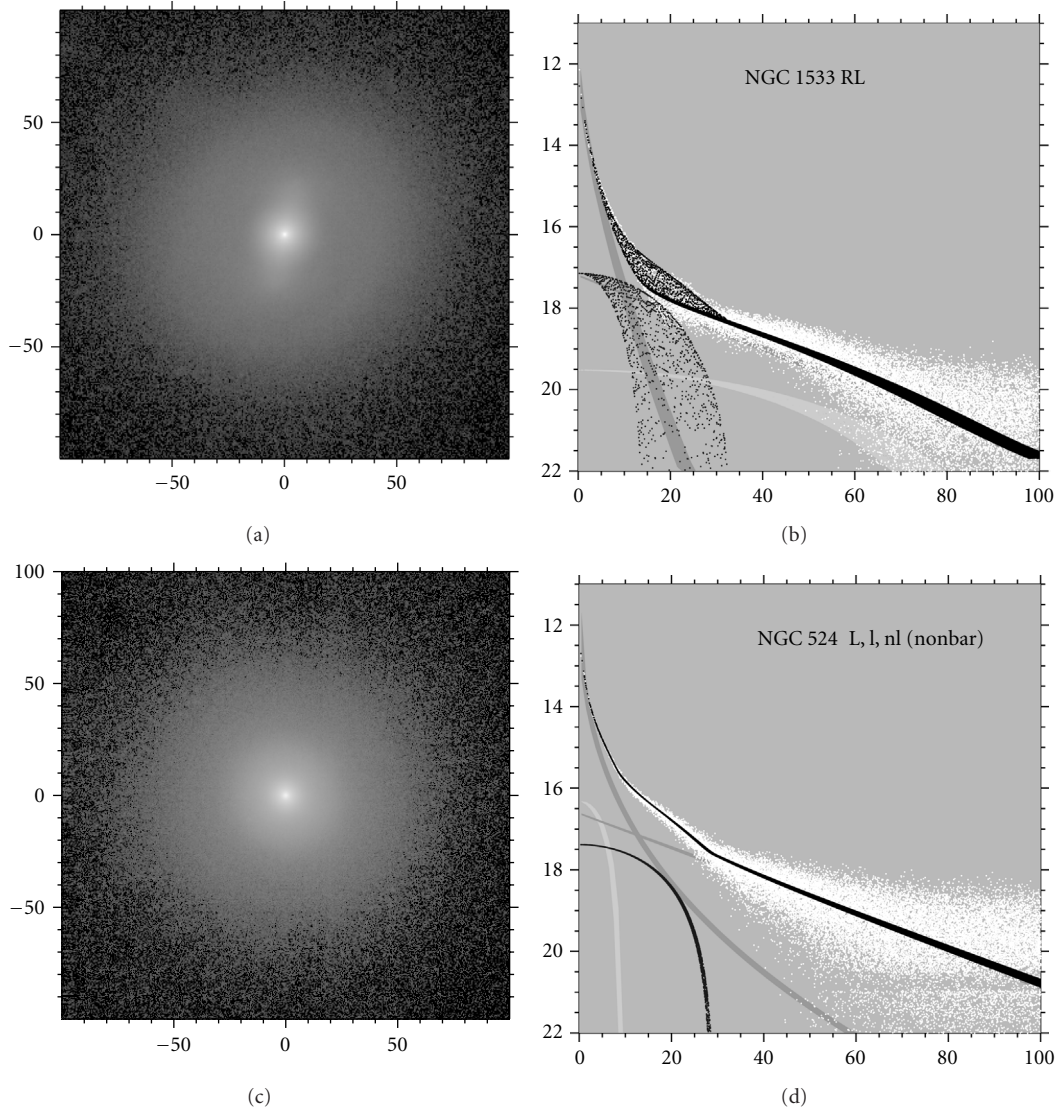


FIGURE 6: Examples of nonbarred lens galaxies. (a, c) show the images, whereas (b, d) show the 2-dimensional surface brightness profiles, in which overplotted are the fitted functions to the structural decompositions, as well as the total model. White dots are for the image pixel values, and the black lines/dots are for the total model. Models for the bulges are shown by dark grey lines and the models for the lenses by light grey and black dots in the inner regions. For example, in NGC 524 the two curved inner components are the nuclear lens (nl) and lens (l), and the outer exponential function fits the outer lens (L). This figure was originally published by Laurikainen et al. [25].

was based on a subsample of NIRS0S. In barred galaxies nuclear (nl) and inner (l) lenses typically end up to the radius of the nuclear and the main bar, respectively, relating them to resonances of the rotating bar (see NGC 1543 in Figure 3). However, not all lenses are related to resonances. For example, series of lenses in some nonbarred S0s appear, like in NGC 1411, which cannot be immediately understood in the framework of the resonance theory. Lenses can also be relics of significant star formation in the spiral arms as suggested in the NIRS0S Atlas [25]. Originally the idea is from Bosma [59], who also confined the lens formation to the epoch of galaxy formation. Lenses are also suggested to form by disk instability, in a similar manner as bars [60]. It was further suggested by Kormendy [58] that bars may

gradually dissolve into lenses. In fact there are many results in NIRS0S which are consistent with this scenario: (a) lenses in barred S0s often end at the bar radius, (b) S0s were found to have a smaller bar fraction, and a larger fraction of lenses than spirals [36]. Also, (c) dissolution of bars would explain the large number of lenses in nonbarred S0s in a natural manner. Using the ellipticity of a bar, a smaller bar fraction in S0s, compared to that in spirals, was found also by Aguerri et al. [61]. Most probably lenses have multiple origins, and in order to better understand their nature detailed analysis of their dimensions and physical properties needs to be performed. A forthcoming NIRS0S paper will focus on that.

It is worth noticing that multiple lenses appear even in 25% of the S0s in the NIRS0S Atlas, including barred and

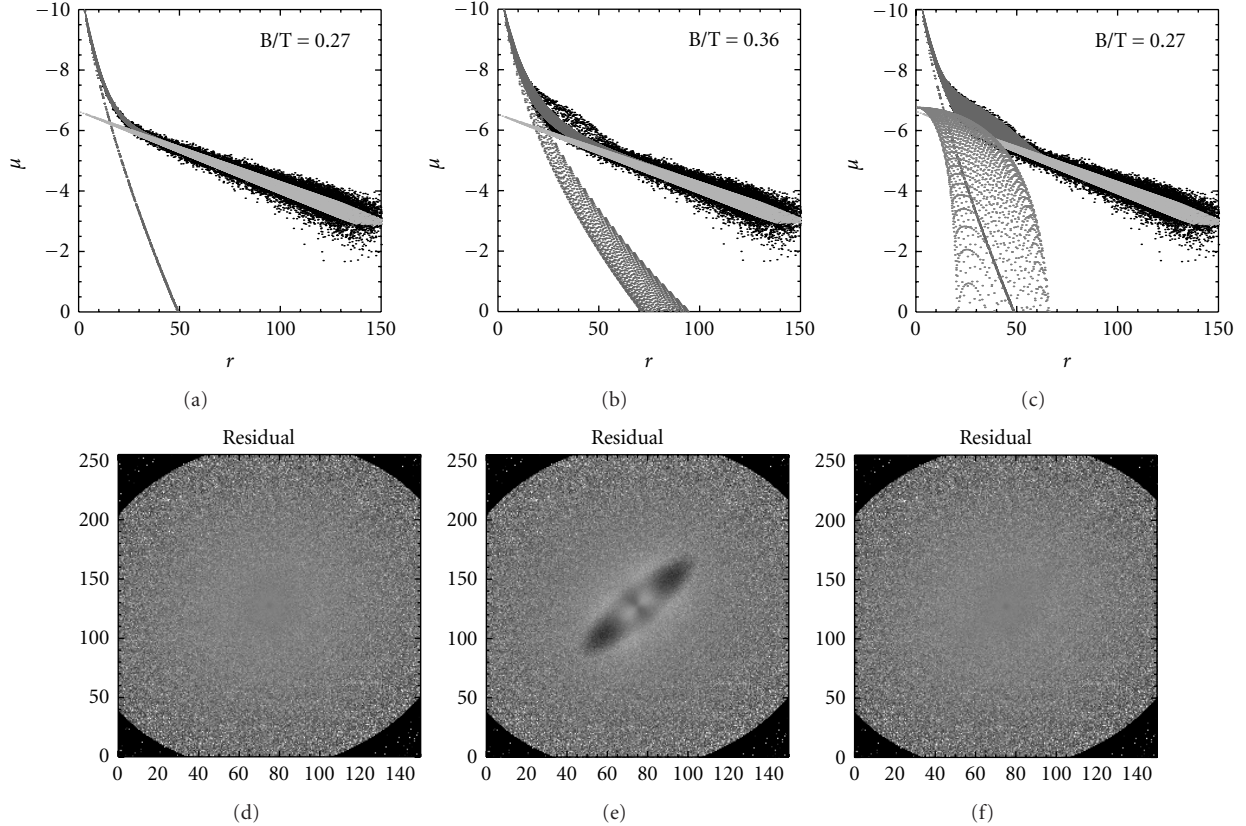


FIGURE 7: (a, b, c) surface brightness profiles of synthetic images in which noise is added to mimic a real image. In (a) the image has only a bulge and a disk, whereas in (b) and (c) a small bar is added on top of the disk. Black dots show the pixel values of the synthetic images, and the other symbols show the functions fitted to the 2-dimensional images, as explained in the text. (d, e, f) the residual images for the above decompositions are shown. They are obtained by subtracting the total decomposition model from the original synthetic image. The figure is a modified version of Figure 2 in Laurikainen et al. [62].

nonbarred galaxies [25], which needs to be understood in the formation and evolution of galaxies. For example, if a large fraction of the mass in the S0s was accreted by minor mergers, it needs to be understood how the multiple lenses can survive through such processes.

5. 2D Multicomponent Decompositions for NIRS0S

5.1. The Multicomponent Approach. A 2D multicomponent code, BDBAR (written by Salo, and described in [48, 62]), was used for decomposing the light distributions of the K_s -band images into bulges, disks, bars, ovals, and lenses. This multicomponent approach turned out to be important, not only for barred galaxies but also for galaxies with prominent lenses. Using artificial images, this was tested by Laurikainen et al. [63]. Figure 7(a) shows the surface brightness profile of a synthetic image with a bulge and a disk, with random noise added, whereas Figures 7(b) and 7(c) show the same image after adding a small bar on top of that. However, in case a) a simple bulge-disk fit gives the correct $B/T = 0.27$. Making a simple bulge-disk decomposition for the barred synthetic image (in the middle) overestimates $B/T (= 0.36)$,

due to erroneous assignment of the bar flux to the bulge, whereas the bulge-disk-bar decomposition (right) recovers the correct B/T value ($B/T = 0.27$). The residual image also shows a bar in the simple bulge-disk model, but not in the bulge-disk-bar decomposition.

A test for the observed NIRS0S images was made by Laurikainen et al. [62], collected in Table 1, where 1D (using azimuthally averaged profiles) and 2D decompositions are also compared. It appears that simple bulge-disk decompositions give a similar mean B/T ratio, independent of whether 1D or 2D fitting is used, whereas the three-component approach gives significantly lower B/T . The value $\langle B/T_K \rangle = 0.55$ in the bulge-disk decomposition is very similar to $\langle B/T_B \rangle = 0.57$ as obtained by Simien and de Vaucouleurs [12]. We also estimated that the different wavelengths used does not cause this difference. Adding even more components (= “final” model in the Table), like nuclear bars, further lowers the B/T , but the change is not as dramatic as between the 2- and 3-component models. The Sérsic index is also smaller in the bulge-disk-bar decompositions, but even in the simplest models the mean value is not as large as 4, as often produced by merger simulations.

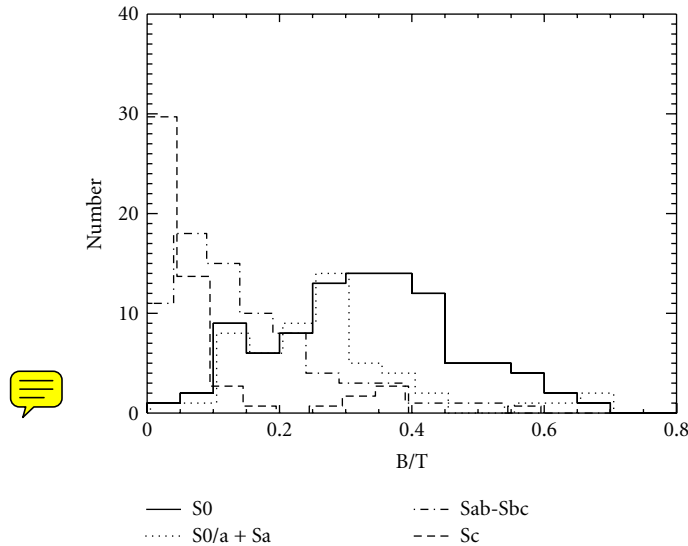


FIGURE 8: Histogram of the B/T flux ratios in K_s -band, corrected for galactic and internal dust extinction. The corrections are different for the bulge and the disk. The histograms for the S0s (full line), and the S0/a galaxies (dotted line) are based on the NIRS0S sample. For spirals the lines for Sab-Sbc (full white line) and later than Sc (dashed white line) are drawn using the OSUBSGS sample. This figure was originally published by Laurikainen et al. [27].

TABLE 1: Mean B/T ratio and Sérsic n parameter of the bulge as estimated using the 1D and 2D decompositions, applied for the K_s -band images. This table was originally published in Laurikainen et al. [62].

Method	$\langle B/T \rangle$	$\langle n_{\text{bulge}} \rangle$
2D (final)	0.25 ± 0.03	2.1 ± 0.1
2D (bulge/disk/bar)	0.30 ± 0.03	2.1 ± 0.1
2D (bulge/disk)	0.55 ± 0.06	2.6 ± 0.1
1D	0.48 ± 0.04	2.7 ± 0.4

5.2. Low B/T Values Obtained Both for S0s and Spirals.

The 2D multicomponent decompositions for the complete NIRS0S sample are discussed by Laurikainen et al. [27], where they are also compared with a similar sized sample of OSUBSGS spirals, using the same decomposition approach (see [34, 48]). Internal dust correction was applied to all galaxies, in a similar manner as in Graham and Worley [64]. For spirals these results are in good agreement with the bulge-disk decompositions made for nonbarred galaxies [65, 66] and with other multicomponent decompositions [67–69]. It is encouraging that Weinzirl et al. [67], applying bulge-disk-bar decompositions, obtained very similar low B/T ratios as obtained previously by Laurikainen et al. [34, 48] for the same sample of spirals. In both studies M/L ratio was assumed to be radially constant. Graham and Worley [64] also obtained fairly low B/T values, but their study uses heterogeneous data from the literature, including simple and multicomponent decompositions. (The 2-component decompositions are thoroughly discussed in the recent review by Graham, to appear in the next edition of “Planets, Stars, and Stellar Systems,” Vol. 6, 2011.)

The dust-corrected B/T histograms for the morphological type bins are shown in Figure 8: though finding an overlap in B/T among the Hubble types is not new, this figure clearly demonstrates how B/T in S0s extends to the region of the late-type spirals, thus covering the full B/T range to near zero values. To our knowledge, this is the first observational evidence in support of the scenario suggested by van den Bergh [70], according to which the S0s might form a sequence of S0a, S0b, and S0c galaxies in a similar manner as spirals.

5.3. Low B/T in Conjunction with Semianalytic Models

(e.g., Khochfar et al. [9]). Formation of early-type galaxies (ETC) has been recently modeled by Khochfar et al. [9] by semianalytical models (SAMs), taking into account the new 3D Atlas kinematic observations by Emsellem et al. [24], defining the fast and slow rotators. In their models B/T is a critical boundary condition to define the ETCs. The range $0.5 < B/T < 0.9$ is used for 80% of the fast rotators, and 20% of them have $B/T < 0.5$, for which galaxies also the gas fraction was used as a selection criterion. The galaxies with low B/T are similar to late-type spirals, called “red spirals”, except that they have barely no gas and, therefore, have no spiral arms. In their models the majority of fast rotators have accreted their bulge mass in minor mergers, whereas the “red spirals” were formed by starvation in more dense galaxy environments.

The above models seem to explain well the distribution of λ_{Re} , a proxy of specific baryonic angular momentum content in galaxies. The difference between fast and slow rotators is largely based on the stellar disc fractions in galaxies. This is consistent with our morphological analysis of NIRS0S in which, beside S0s, also most of the galaxies classified as late-type ellipticals in RC3 show disk structures. However,

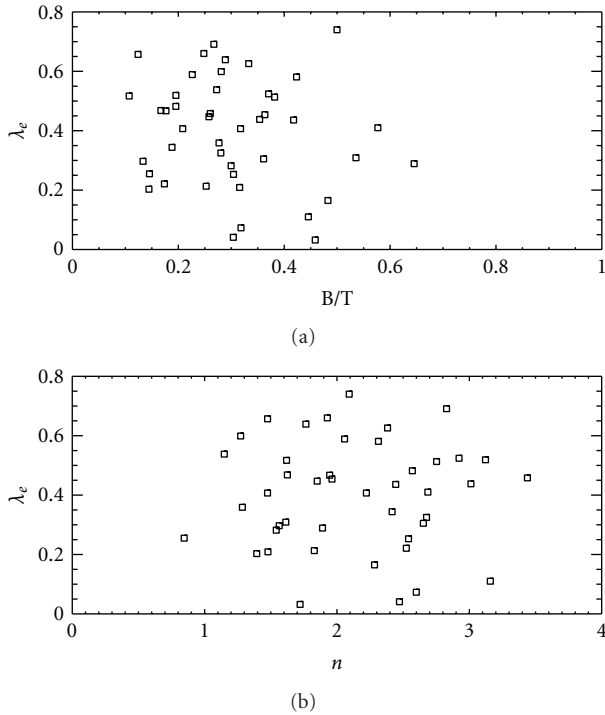


FIGURE 9: The kinematic parameter λ_R versus B/T (a) and versus Sérsic n (b). Parameter λ_{Re} , taken from Emsellem et al. [24], can be used as a discriminator between oblate and triaxial nature of the galaxies, within the apertures used in the measurements. In this plot λ_R obtained within one effective radius of the galaxy is used. The n parameters and the dust-corrected B/T values are taken from Laurikainen et al. [27].

in many S0s also small central components appear in the regions covered by the kinematic observations. This complicates the fast/slow interpretation, because nuclear bars, lenses and rings might have different velocity dispersions. The richness of the central structures in S0s might partly explain why B/T does not correlate with λ_{Re} , which is shown in Figure 9 (above); for example, galaxies with larger B/T do not have smaller λ_{Re} . Also, there is no correlation between λ_{Re} and the Sérsic index n , as shown in Figure 9 (below); for example, galaxies with disk-like pseudo bulges (with small n) do not have a tendency to be more rotationally supported.

Good news in the models by Khochfar et al. [9] is also that they predict a fairly large range of B/T s for the fast rotators. However, the used B/T range of 0.5–0.9 is almost completely outside the range obtained by the multicomponent decompositions for the S0s (see Figure 8). In the literature possible mechanisms have been discussed which might lower the B/T in SAMS: (a) increasing the energy injected by supernovae [71] or (b) taking into account mass loss from already existing stars, which can lower B/T by a factor of 2–3 [72]. However, these explanations have been criticized by Scannapieco et al. [73]. The first because during the mass loss the bulge density is also reduced, and the density of the disk increases only in the central parts of the disk. And the second, because the suggested efficiency of SN feedback is too high compared to the cosmological

models, for example, by Guo et al. [74]. In the current models by Khochfar et al., lower B/T values for fast rotators are obtained by significantly decreasing the frequency of minor mergers, but that might not be consistent with the observed merger frequency in the Universe.

5.4. Low B/T in Conjunction with Tidal Models (e.g., Bekki and Couch [75]). In the stripping models the B/T problem has generally been the opposite: it has been difficult to make such massive bulges as observed in galaxies. In Bekki and Couch [75] the problem was solved by assuming that the tidal effects increase the efficiency of star formation and might also add some fresh material into the galaxies during the encounter process. Here we discuss how well the B/T ratios obtained in NIRS0S are compatible with these models.

Compared to Khochfar et al. [9], in Bekki and Couch [75] a lower B/T range of 0.3–0.5 was used for the S0s. This is well within the range of the measured B/T values in Figure 8, but still lacking the lower B/T tail. In the simulations by Bekki and Couch, B/T is measured kinematically from the simulations by linking each simulated star either to a bulge or a disk. Based on the comparison by Scannapieco et al. [73], such kinematic decompositions give significantly higher B/T values than the decomposition of the flux distribution in galaxies, done in a similar manner as in observations. A similar conclusion was made also by Laurikainen and Salo [76]. Taking this into account the B/T range in the models by Bekki and Couch might be even more closer with the observed B/T range.

6. Properties of Bulges and Disks, Based on the Decompositions

6.1. Properties of Bulges and Disks: S0s Versus Spirals. The photometric properties of bulges and disks were compared between S0s and spirals by Laurikainen et al. [27], without including any kinematic information. The parameters were corrected for the internal dust in galaxies. The final sample, with reliable decompositions made, consists of 340 galaxies. Naively, strong correlations between the parameters of the bulge and the disk are expected if the disks were formed first and the bulges emerged from the disc by secular evolution. On the other hand, in hierarchical clustering, followed by galaxy mergers, the properties of bulges were established already during the last major merger event [77] and presumably changed very little after that. Also, if the formative processes of bulges in S0s were similar to those of the elliptical galaxies, a continuity in the properties of bulges and ellipticals is expected.

It was found that the bulges of S0s are different from the elliptical galaxies and, similar to the bulges in spirals, manifested in the r_{eff} (bulge) versus M_{bulge} diagram (Figure 10): bulges both for the S0s and spirals appear below the line for the elliptical galaxies, indicated by the dashed line; (the dashed line is not for the Coma cluster ellipticals, as erroneously claimed in Laurikainen et al. [27].) It was shown by Graham and Worley ([64], their Figure 11) that this line nicely follows the observed distribution of the ellipticals (see

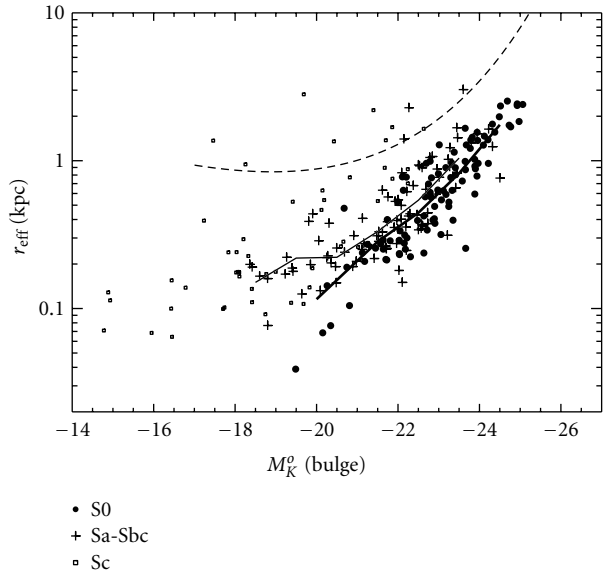


FIGURE 10: The effective radius of the bulge (r_{eff}) plotted against the absolute brightness of the bulge (M_K^0 (bulge)). Shown separately are S0s (filled symbols), Sa-Sbc spirals (crosses), and Sc and later types (squares). The dashed line shows the location of the elliptical galaxies, taken from Graham and Worley [64]. The continuous lines show the mean values of the data points in one magnitude bins: the thick line is for the S0s and the thin line for the Sab-Sbc spirals. This figure is part of Figure 8(a) in Laurikainen et al. [27].

[78]), covering a large magnitude range and appearing in various types of environments. For spirals the discontinuity of bulges and ellipticals was shown also by Gadotti [79]. The fact that the bulges of S0s are not similar to the elliptical galaxies is manifested also in the Kormendy relation and in the photometric plane where only the brightest bulges of S0s follow the location of the Coma cluster ellipticals (see Figures 2 and 3 in [27]).

The r_{eff} (bulge) versus M_{bulge} in Figure 10 extends to the regime of very small bulges, corresponding to the effective radii of the dwarf early-type galaxies, dEs. In Figure 10 the dEs would appear in the flat part of the dashed line (see [78]). However, it is worth noticing that the small bulges in S0s have several magnitudes higher surface brightnesses than dEs and, therefore, do not fit to the scenario in which dEs were formed from Sc-type spirals by losing their disks in galaxy harassment in dense cluster potentials. This is consistent with the recent study by Kormendy and Bender [28], who suggested that the red and dead dwarf galaxies are rather transferred from later-type Scd-Im galaxies.

Not only bulges but also the disks in S0s are similar to those in spirals. It was shown, by Laurikainen et al. [27], that both for the S0s and spirals the scale length of the disk (h_R) varies between 1 and 10 kpc and the central surface brightness (μ_0) between 16 and 20 magnitudes. Also, μ_0 has no correlation with the mass of the disk (M_{disk}). It was concluded that μ_0 does not follow the Freeman law [80] pertaining a constant central surface brightness (see Figure 9 in [27]). The similarity in the disc sizes between S0s and

spirals is consistent with the tidal models by Bekki and Couch [75] for the origin of S0s. They stated that “it is unlikely that S0s have systematically larger disk masses in comparison with spirals.”

For the S0s the photometric properties of bulges and disks in NIRS0S are found to be coupled, in a similar manner as for spirals [27]. This is manifested in correlations between their scale parameters, h_R versus r_{eff} (bulge), and their masses, M_{bulge} versus M_{disk} , as shown in Figure 11. Also, for the bulges having $M_{\text{bulge}} = -20$ mag in the K_s -band, the difference in M_{disk} between the early- (S0, S0/a, Sa) and late-type (Sab and later) galaxies is nearly one magnitude. Based on the stellar population models by Bedregal et al. [81], this difference could be explained by quiescent star formation if star formation of the disc in spiral galaxies was truncated 1–6 Gyr ago.

These results are consistent with the picture in which the discs were formed first and the bulges emerged from the disc material afterwards, without invoking any merger events, which might destroy the observed correlations between the bulges and disks. However, our results do not unambiguously rule out the other scenarios. For example, in minor mergers the satellite galaxies increase the bulge mass in one hand, and at the same time the disks’ stars are spilled to a larger radius, which might also lead to a correlation between the scale parameters of the bulge and the disk.

6.2. Properties of Bulges in the Hubble Sequence. Figure 12 shows the mean total galaxy brightnesses in the K_s -band and the parameters of the bulge in the Hubble sequence [27]. The bulge parameters are compared with those by Graham and Worley [64]. Notice that the comparison is meaningful only when $T = 0-5$ where enough common galaxies appear in both studies.

The following things can be noticed: (1) in the near-IR, tracing the old stellar population of galaxies, the S0s in NIRS0S are not less luminous than the spirals in OSUBSGS (both samples are magnitude-limited, selected in a similar manner). A similar result in the near-IR was obtained also by Burnstein et al. [82]. This is a puzzle if S0s were formed from spirals Sc or earlier, simply by losing their gas in the stripping mechanisms, followed by quenching of star formation. The luminosities of S0s could be explained if they have gained more mass after the S0 characteristics were settled down, for example, by accreting a significant number of satellite galaxies during their lifetime. However, that is not supported by our analysis of the Q_g distribution of bars in S0s, at least if the accreting satellites were gas rich. A more likely solution to this puzzle is that at higher redshifts some fraction of the progenitors of S0s were more luminous than the local spirals. This is evidenced by Geach et al. [83] showing that LIRGS at $z = 0.5$ could account for the star formation needed to explain the bright end of the S0 galaxy luminosity function (see the discussion in [27]). (2) r_{eff}/h_R decreases slightly from S0s towards spirals. This parameter is smaller than that obtained in the previous studies, mainly because we use multicomponent decompositions which presumes the erroneous additions of bars to the bulges. For all the

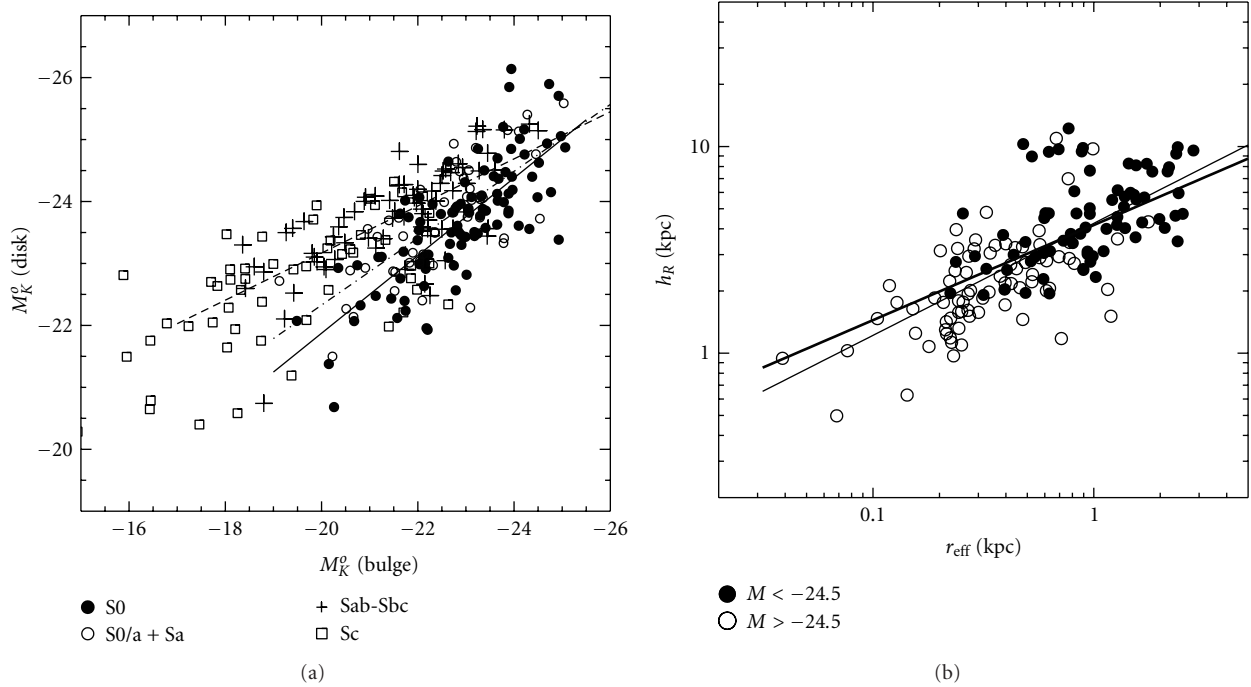


FIGURE 11: (a) the absolute brightness of the disk (M_K^o (disk)) is plotted against the absolute brightness of the bulge (M_K^o (bulge)). (a) S0s (red filled circles), S0/a+Sa (open circles), Sab-Sbc (crosses), and Sc and later types (squares). Solid, dash-dotted, and dashed lines show linear fits for the S0s, S0/a+Sa, and Sab-Sbc galaxies, respectively. All the correlations are statistically significant. (b) h_R (disk) versus r_{eff} (bulge) for the galaxies in NIRS0S, divided to two galaxy brightness bins in K_s -band. This figure is compiled from two figures originally published by Laurikainen et al. [27, 36].

Hubble types, the observed mean r_{eff}/h_R is smaller than that predicted by the current merger models (e.g., [84]). (3) The Sérsic index n is very similar for S0, S0/a, and Sa galaxies and slightly decreases towards the later types. Such small values of the Sérsic index ($n \leq 2$) are not predicted in the current merger models (e.g., [85, 86]). (4) B/T was already discussed in Section 5. Figure 12 additionally shows that the mean B/T is very similar for S0, S0/a, and Sa galaxies and only after that decreases towards the later types. It was also shown by Laurikainen et al. [34] that B/T is lower for barred than nonbarred galaxies and also lower for galaxies having flat-top DG bars compared to the more simple SG bars.

Overall, the above properties of bulges are not well compatible with the current merger models.

7. The Outlined Picture

7.1. S0s Transformed from Spirals: The Hubble Sequence Revisited. The Hubble sequence is revisited, following the early suggestion by Spitzer and Baade [87] and van den Bergh [70]; namely, the S0s are suggested to be spread throughout the Hubble sequence in parallel tuning forks as spirals (S0a, S0b, S0c, etc.) [25, 27]. Originally this scenario was arisen by van den Bergh because he found that the entire S0 class was offset towards fainter optical magnitudes from the luminosity distribution of Sa galaxies. He then assumed that there must exist anemic S0s whose surface brightness distributions are similar to the faint surface brightness levels

of Sb and Sc galaxies. However, at that time no such galaxies were found. Our NIRS0S/OSUBSGS analysis has shown that, indeed, the disks in S0s have a similar range of central surface brightnesses and scale lengths of the disk as the disks of Sa-Sc type spirals. And in particular, our multicomponent decomposition approach has shown that the bulges in many S0s have B/T ratios as small as typically found in Sc-type spirals [27]. A similar view to the Hubble sequence was taken recently also by Cappellari et al. [23], based on new kinematic observations, showing that bulges in S0s are fast rotating oblate systems. During the refereeing process of this work, a paper by Kormendy and Bender [28] appeared in *astro-ph*, in which a similar view was also suggested.

Our results are consistent with the idea according to which S0s are mainly former spirals transformed into S0s by losing their gas in some stripping mechanisms. The following results of our NIRS0S/OSUBSGS analysis are consistent with this picture: (a) S0s cover the full observed B/T range of spirals. (b) The photometric properties of bulges and disks appeared to be similar in S0s and spirals. And most importantly, the bulges in S0s have no continuity with the elliptical galaxies in the r_{eff} (bulge) versus M_{bulge} diagram. (c) The relative masses and scale parameters of the bulges and disks in S0s are coupled, in a similar manner as in spirals, which hint to a common origin of the bulges and disks in these galaxies. What needs to be explained in this scenario is why the S0s in NIRS0S are not less luminous than their assumed spiral progenitors.

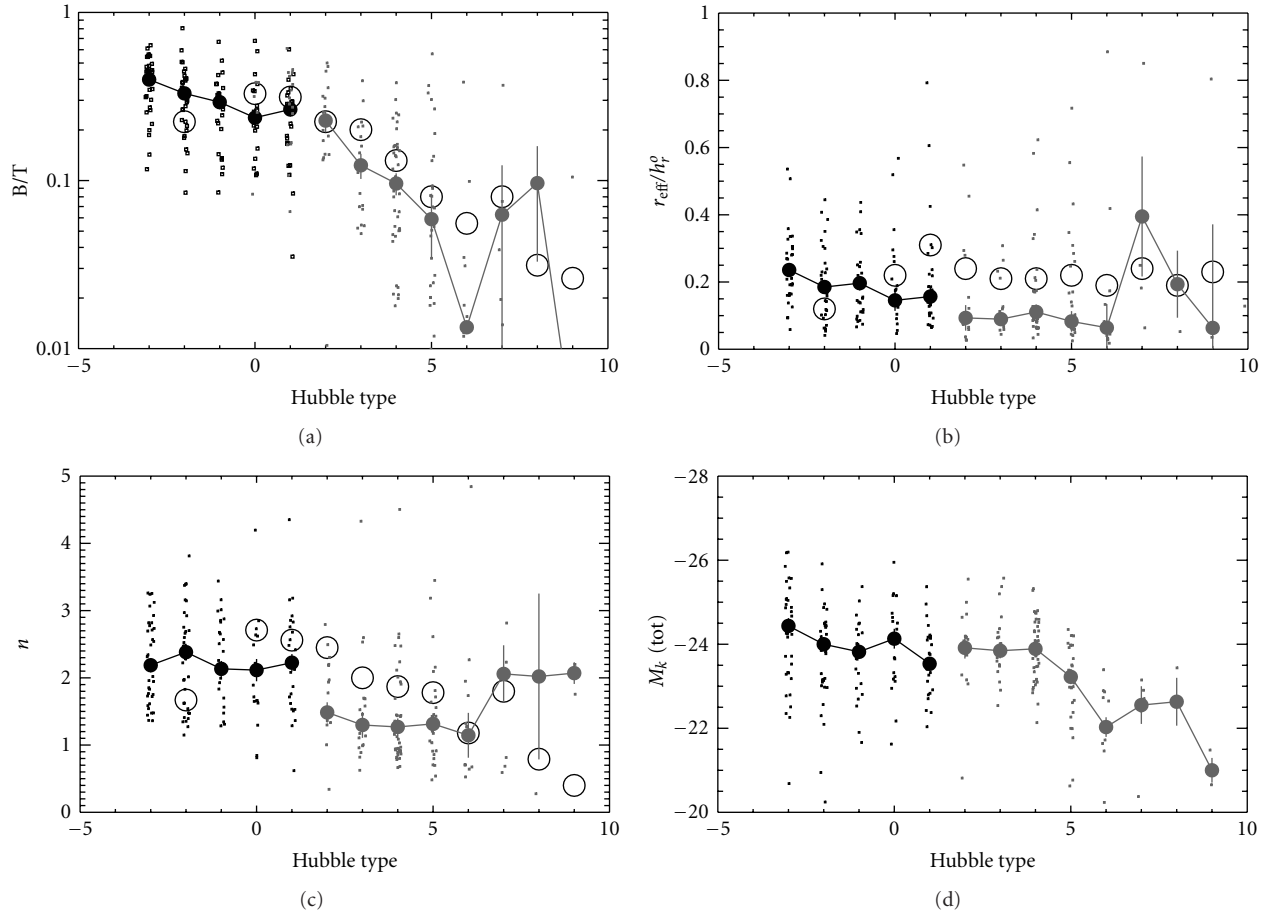


FIGURE 12: As a function of the Hubble type are shown (a) the dust corrected B/T , (b) the Sérsic index n , (c) the ratio of the effective radius of the bulge (r_{eff}) divided by the scale length of the disk (h_d^2), and (d) the total absolute galaxy magnitude corrected for galactic extinction (M_k^{tot}). The *small symbols* show the measurements for the individual galaxies (with a small random horizontal offset), *filled circles* show the median values in each Hubble-type bin, and *large open circles* are the median values from Graham and Worley ([64]; their value for S0s refers to types -3 , -2 , -1 and is here drawn at $T = -2$). The error bars are taken to be the sample standard deviations in each bin divided by square root of the number of galaxies in each bin. Dark symbols are for the galaxies in NIRS0S and light symbols for the galaxies in OSUBSGS. In a slightly different form, the same figure was originally published by Laurikainen et al. [27].

7.2. Solution for the Bulge Problem in the Stripping Scenario?

In the stripping scenario, a problem of larger bulges in S0s, compared to bulges in spirals, was discussed. It was concluded, based on the stellar population models by Bedregal et al. [81], that spirals with bulges brighter than -20 magnitudes in the K -band are massive enough to be converted into bulges of S0s, simply by slow internal galaxy evolution. However, that cannot explain why S0s are not dimmer than the spirals, as expected if they lost some of their gas in the stripping process. This implies that some other mechanism is also needed to complete the mass accretion in the bulges of S0s. Possible alternatives are that the progenitors of S0s were more gas rich than the present day spirals, which would explain also the similar total galaxy brightnesses in most S0s, compared to the galaxy brightnesses in spirals, in the near-IR. Or some mechanism other than gas accretion is taking place. One suggested mechanism is the so-called potential-density phase shift mechanism suggested by Zhang [88], allowing stellar mass

transfer even after the gas depletion has stopped. Or, as suggested by Bekki and Couch [75], tidal effects in galaxy groups can increase star formation efficiency in the central regions. Minor mergers can also accrete material to the main galaxies, but that process needs to be mild enough for not to increase the Sérsic index over the fairly low observed values, at least in the current models. Also, if our conclusion of the Q_g distribution for the S0s is correct, the accreting satellites need to be fairly gas poor.

7.3. Bars and Lenses: Evidence of Secular Evolution?

A test was made for the simulation models by Bournaud and Combes [55], in which bars are expected to have multiple episodes during the Hubble time. Based on the observed bar strength (Q_g) distribution, we concluded that the S0s have not accreted gas for a long time. Spirals show a larger number of strong bars, but the observed Q_g distribution even for them resembles the nonaccretion models. This implies that most probably bars are fairly robust in all Hubble types,

without experiencing multiple bar episodes in the Hubble time. However, in spite of that, bars may evolve significantly over time, as manifested in the morphology of the old stellar population of bars in the near-IR. Namely, bars in S0s have ansae morphology and double-peaked Fourier's density profiles much more frequently than bars in spiral galaxies. According to the dynamical models, such features can be associated to evolved strong bars. Bars may also dissolve into lenses, as first suggested by Kormendy [58], which is consistent with the observed lower bar fraction and a larger fraction of lenses among the S0s. However, based on the morphology of lenses, not all lenses can be dissolved former bars.

A new lens type, barlens, was introduced, appearing in strong bars, most probably forming part of the bar itself. We assume that it might be related to the redistribution of matter in galaxies. Also, X-shaped bars in nearly face-on galaxies were detected, which cannot be simply vertically thickened bars by buckling effects and, therefore, needs to be explained in the framework of the theoretical models. Multiple lenses were detected even in 25% of the S0s, including barred and nonbarred galaxies, which are not yet well understood in the current paradigm of galaxy formation and evolution. We anticipate that secular evolution might play an important role in the formative processes of lenses.

Acknowledgment

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