Nuclear stellar discs in early-type galaxies — II. Photometric properties

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\textbf{ABSTRACT}

Hubble Space Telescope images of two early-type galaxies harboring both nuclear and outer stellar discs are studied in detail. By means of a photometric decomposition, the images of NGC 4342 and NGC 4570 are analyzed and the photometric properties of the nuclear discs investigated. We find a continuity of properties in the parameter space defined by the central surface brightness $\mu_0$ and the scalelength $R_d$ of discs in spirals, S0s and embedded discs in ellipticals, in the sense that the nuclear discs extend the observed disc properties even further towards smaller scalelengths and brighter central surface brightnesses. When including the nuclear discs, disc properties span more than four orders of magnitude in both scalelength and central surface brightness. The nuclear discs studied here are the smallest and brightest stellar discs known, and as such, they are as extreme in their photometric properties as Malin I, when compared to typical galactic discs that obey Freeman’s law. We discuss a possible formation scenario in which the double-disc structure observed in these galaxies has been shaped by now dissolved bars. Based on the fact that the black holes known to exist in some of these galaxies have masses comparable to those of the nuclear discs, we explore a possible link between the black holes and the nuclear discs.

\textbf{Key words:} galaxies: disk – galaxies: elliptical and lenticular, cD – galaxies: photometry – galaxies: individual: NGC 4342, NGC 4570

1 \textbf{INTRODUCTION}

The dichotomy amongst early-type galaxies inferred some years ago from ground-based observations (Bender 1988; Bender et al. 1989; Nieto et al. 1991) has recently been confirmed and strengthened with high spatial resolution images obtained with the Hubble Space Telescope (HST). These images show that early-type galaxies can be divided in two classes according to the shape of the surface brightness profiles in the central regions: the bright pressured supported boxy systems show central luminosity profiles which can be well fit by a double power-law (they show a clear break); the low luminosity discy galaxies have brightness profiles that lack a clear break and keep rising steeply down to the smallest scales accessible by the HST (e.g., Ferrarese et al. 1994; Lauer et al. 1995; Gebhardt et al. 1996). Lauer et al. (1995) refer to the bright ellipticals with a clear inner break-radius as “core galaxies” and to the low luminosity ellipticals with single power-law luminosity profiles as “power-law” galaxies. They were termed Type I and Type II respectively by Jaffe et al. (1994).

The high resolution HST images revealed the presence of small nuclear stellar discs in a number of power-law early-type galaxies (van den Bosch et al. 1994; Lauer et al. 1995; van den Bosch, Jaffe & van der Marel 1998). These galaxies are in general composite systems, consisting of a bulge and a large or intermediate kpc-scale disc. A well known example is the Sombrero galaxy, in which besides the outer kpc-scale disc, a bright nuclear disc had already been discovered from ground-based observations (Burkhead 1986, 1991; Kormendy 1988; Emsellem et al. 1996). Most of the galaxies that harbor a nuclear disc are either S0s or discy ellipticals. The latter harbor fully-embedded kpc-scale stellar discs (Carter 1987; Bender 1990; Nieto et al. 1991; Rix & White 1990, 1992; Scorza & Bender 1990, 1995), which are smaller and brighter than discs in S0s and spirals (Scorza & Bender 1995, 1996), but significantly larger than the nuclear pc-scale discs discussed here. Recently Seifert & Scorza (1996) examined in detail the images of 15 S0 galaxies and found, in a significant fraction of them, evidence for discs with inner cut-offs, signatures of inner discs and rings, and kinematic features connected to the double-disc structure. Although the resolution of these images is not sufficient to unambiguously reveal pc-scale nuclear discs, the double disc structure nevertheless seems to be a common property of early-type galaxies with kpc-scale discs rather than a mere rarity. After all, the double disc structure is only detectable if the galaxy is oriented sufficiently close to edge-on (Rix & White 1990).

In order to find constraints on the origin of these com-
plex disc-structures, it is important to study in detail the photometric properties of the various disc components once they have been separated from the bulge via photometric decomposition. In this paper we focus on the inner photometric structure of two power-law early-type galaxies in the Virgo cluster that harbor both an outer and a nuclear disc: NGC 4342 and NGC 4570. We separate the nuclear discs from the inner regions of the bulges in order to study their photometric properties and the transition region towards the outer discs. In particular, we investigate the location of these nuclear discs in the parameter space defined by the central surface brightness $\mu_0$ and the scalelength $R_d$ of galactic discs. The relations between bulge and disc properties are also investigated in order to look for constraints on possible formation processes.

Secular evolution, driven by (now dissolved) bars, has been invoked to explain the formation of nuclear discs, truncated outer discs, and rings in early-type galaxies (Bagget, Bagget & Anderson 1996; Emsellem et al. 1996; van den Bosch & Emsellem 1998). Small nuclear bars have been proposed as efficient mechanisms to transport pre-enriched gas into the centers of galaxies (Friedli & Martinet 1993; Wada & Habe 1995). The fact that S0 galaxies exhibit high line-strength values at their centers (Fisher, Frank & Illingworth 1996) and that there is evidence for the existence of embedded bars in early-type galaxies (e.g., Busarello et al. 1996, Scorza et al. 1998) supports this secular-evolution picture. However, the available data is at present insufficient to make any conclusive statements about the formation of nuclear stellar discs. We will speculate on other possible formation scenarios in the discussion section of this paper.

This paper is organized as follows. Section 2 discusses the HST data of NGC 4342 and NGC 4570. In Section 3 we use this data to decompose the galaxies into their bulge and disc components and we discuss the uniqueness and limitations of the decompositions. In Section 4 we present the results of the photometric decomposition and discuss the properties of the separate components. In Section 5 we show the location of the nuclear discs in the $\mu_0-R_d$ diagram, and compare them to discs in spirals, S0s and embedded-discs in ellipticals. Finally, in Section 6, we discuss our results and speculate on possible formation scenarios for these multiple disc structures.

2 THE HST IMAGES

2.1 The data

The nuclear stellar discs in NGC 4342 and NGC 4570 were discovered from Wide Field and Planetary Camera 1 (WFPC1) HST images (van den Bosch et al. 1994). In addition, the same study revealed a nuclear stellar disc in the E/S0 NGC 4623. The quality of these data suffers from the spherical aberration of the HST primary mirror.

In a follow-up program, van den Bosch, Jaffe & van der Marel (1998, hereafter BJM98) obtained $U$, $V$ and $I$ band images of NGC 4342 and NGC 4570 with the Wide Field and Planetary Camera 2 (WFPC2) and the now refurbished HST. The spatial resolution of these images is set by the HST Point Spread Function (PSF), which has a FWHM of $\sim 0.1''$, and by the size of the CCD pixels ($0.0455'' \times 0.0455''$). Details on the images and their reduction can be found in BJM98. Because of the better quality of these data we use the WFPC2 V-band images of NGC 4342 and NGC 4570 for our photometric decomposition. Unfortunately, no WFPC2 images are available for NGC 4623. Because of the poorer quality of the WFPC1 data we do not include NGC 4623 in our sample here.

2.2 Deconvolution

Because of the small sizes of the nuclear discs, and the steep central luminosity profiles of the galaxies, the PSF can have strong effects on the outcome of the photometric decomposition. Even though the HST PSF has improved significantly with the 1993 refurbishment mission, the PSF has still relatively broad wings with several percent of the light being scattered more than 1'' away. It is therefore essential to deconvolve the images in order to be able to derive the proper nuclear disc parameters.

BJM98 have presented models of the deconvolved surface brightness of NGC 4342 and NGC 4570. These models were constructed with the Multi Gaussian Expansion method developed by Emsellem, Monnet & Bacon (1994), and describe the observed (convolved) surface brightness distribution as a sum of flattened Gaussians. Upon describing the PSF as a sum of Gaussians as well, one can recover the intrinsic (deconvolved) surface brightness distribution, also described by a sum of flattened Gaussians. In the present work, we use these models to determine the parameters of the nuclear discs in these two galaxies. The parameters of the MGE models and the fit of the models to the observed surface brightness are presented in BJM98. The MGE deconvolved surface brightness is in excellent agreement with the results from Lucy deconvolution (cf. BJM98).

3 PHOTOMETRIC DECOMPOSITION

3.1 The method

We apply the method described by Scorza & Bender (1995) to derive the parameters of the nuclear discs. This method is particularly well suited for a photometric decomposition of a system with a disc that does not strongly dominate the projected surface brightness. The method is based on the assumption that the bulge component has perfectly elliptical isophotes. No assumptions are made regarding the flattening or the luminosity profile of the bulge. Infinitesimally thin exponential disc models are subtracted iteratively from the galaxy frames, until the remaining bulge shows perfectly elliptical isophotes. The disc model is described by a central surface brightness $\mu_0$, a scalelength $R_d$, and an inclination angle $i$. In both galaxies discussed here the nuclear discs could be accurately fitted with an exponential profile.

Before and after subtraction of the disc models an isophotal analysis of the galaxy image is carried out using the method described in Bender & Möllenhoff (1987). In addition to the surface brightness, ellipticity, and position angle of each isophote, the method determines the higher-order Fourier coefficients that describe deviations of the isophote from an elliptical shape. The most well-known of these is the fourth cosine coefficient $a_4$, which describes whether the isophote is discy ($a_4 > 0$) or boxy ($a_4 < 0$). This $a_4$ parameter has proven to be a very good indicator for the existence
of embedded discs (Scorza & Bender 1995). The best fitting disc parameters are determined by finding the disc model which, after subtraction from the galaxy image, yields the smallest rms values of the $a_4$ Fourier coefficients over the radial interval where the disc is expected to be visible against the background of the bulge light.

The field-of-view of the HST images used here is unfortunately too small to allow a proper analysis of the outer disc parameters. In the case of NGC 4342, however, the extent of the galaxy expressed in solid angle on the sky is sufficiently small such that the outer disc of this galaxy is almost completely registered on the HST image. Since the outer disc in NGC 4942 dominates the projected surface brightness at large radii, it does not predominantly show up in the higher-order Fourier coefficients, but mainly cause a strong increase in the ellipticity of the outer isophotes. For this reason, we cannot decompose the outer disc from the bulge by using the method described above. However, in order to study the transition region and change of properties between the inner and outer discs, we use another iterative method to determine the outer disc parameters of NGC 4342. This method is described in detail in Scorza et al. (1998), where it is applied to decompose several disc-dominated early-type galaxies. The procedure is as follows: after subtraction of an initial outer disc model, the bulge profile in the intermediate region, where the bulge dominates the projected surface brightness, is fit by a $r^{1/4}$-law profile and extrapolated out to radii where the disc dominates. From this bulge profile, an $r^{1/4}$-bulge model is constructed and subtracted from the galaxy image; the residual disc is then used as input disc for a further iteration. In this way, a reliable decomposition is achieved.

3.2 Reliability and uniqueness of the decomposition

As shown by Rix & White (1990), several combinations of disc-to-bulge ratios and inclination angles can produce similar $a_4$ profiles. Therefore, in order to obtain unique disc solutions from the $a_4$ coefficient, it is necessary to constrain the inclination angle of the disc. In the method of Scorza & Bender (1995) this is done via the $a_6$ Fourier coefficient. Indeed it has been found that only one combination of central surface brightness $\mu_0$, scalelength $R_d$, and inclination $i$ of the disc models leads to simultaneously vanishing $a_4$ and $a_6$ coefficients and therefore to a unique disc solution (see tests in Scorza & Bender 1990).

It is important to realize that the parameters of the discs determined from the decomposition methods outlined above are based on the assumption that the discs are infinitesimally thin. Realistic discs have a finite thickness, and taking this thickness into account is especially important when constructing dynamical models for these systems. In the Appendix we discuss how to convert the infinitesimally thin discs to a set of more realistic, thick disc models. We also discuss the degeneracy between the inclination angle and the thickness of galactic discs. Thus, whereas the assumption of zero-thickness yields well defined unique disc parameters, relaxing the assumption that discs are infinitesimally thin, results in some amount of non-uniqueness regarding the inclination angle. As long as the galaxy is seen sufficiently close to edge-on, this non-uniqueness is small and unimportant.

**Figure 1.** Ellipticity, $a_4$ and $a_6$ Fourier coefficient profiles of NGC 4342. The left panels show the profiles of the original image (crosses) and the MGE-model (open circles). Middle panels: same profiles of the deconvolved MGE-model before (open circles) and after (crosses) subtraction of the nuclear and outer discs. Right panels: MGE-model prior to deconvolution before (open circles) and after (crosses) subtraction of the convolved nuclear and outer disc models.

**Figure 2.** Same as Figure 1, but now for NGC 4570. Note that for this galaxy, no outer disc parameters could be determined (see text).

Recently, in studying the deprojection of axisymmetric bodies, Gerhard & Binney (1996) found that the $D/B$ ratios derived from decomposition procedures are in principal ill-determined from the photometry alone unless the disc is bright and seen near to edge-on. This is due to the fact that there are different intrinsic density distributions that project to the same surface brightness (Rybicki 1986). In the present study we concentrate on close to edge-on, prominent bright nuclear discs, such that the non-uniqueness of the deprojected light distribution is only small and the disc-to-bulge ratio well constrained (cf. Romanowsky & Kochanek 1997; van den Bosch 1997).

4 RESULTS

4.1 The nuclear disc parameters

The results of the photometric decompositions of NGC 4342 and NGC 4570 are shown in Figures 1 and 2, respectively. Upper panels show the ellipticity, middle panels show
$a_4/a \times 100$, and lower panels show $a_0/a \times 100$. The left panels of Figures 1 and 2 show the isophotal parameters of the original HST images (crosses) and the MGE-models (open circles) prior to deconvolution. These parameters agree very well with each other, indicating the accuracy of the fit of the MGE-models to the data. A discrepancy in the $a_4$ coefficient at the outside of the MGE-model of NGC 4342 is visible in Figure 1. This discrepancy is due to a small isophote twist in the outer region of this galaxy, not taken into account by the MGE-model (see BJM98), and does not significantly influence the parameters determined for the outer disc. The middle panels of Figures 1 and 2 show the deconvolved MGE-models before (open circles) and after (crosses) subtraction of the best fitting disc models. As can be seen, after disc subtraction the central regions of the bulges become elliptical (near to zero $a_4$ and $a_6$ Fourier coefficients) and of moderate flattening as the ellipticity drops down to small values. For NGC 4342 both the outer and the nuclear discs are subtracted, whereas for NGC 4570 this is limited to the nuclear disc only.

Once the best-fitting disc model is found, we convolve it with the same PSF that we used for the deconvolution of the MGE-model, and subtract this convolved disc model from the MGE-model prior to deconvolution. In the absence of deconvolution artifacts, this should yield a similar vanishing of the $a_4$ and $a_6$ Fourier coefficients and a similar ellipticity of the central part of the bulge as the results from the deconvolved photometry. This procedure allows us to cross-check the disc parameters derived. The results of this analysis are shown in the right panels of Figures 1 and 2 were we have plotted the isophotal parameters of the MGE-model prior to deconvolution (same as in left panels) before (open circles) and after (crosses) subtraction of the convolved disc model. As can be seen, the results in the middle and right panels are in excellent agreement, indicating that there are no deconvolution artifacts.

In both galaxies the nuclear discs could be accurately fitted with an exponential profile. Table 1 lists the nuclear disc parameters: the projected central surface brightness of the nuclear disc $\mu_0$, the central surface brightness of the disc corrected to face-on $\mu_0^f$ via

$$\mu_0^f = \mu_0 - 2.5 \log(\cos i),$$

the scalelengths $R_d$ converted to parsecs via the radial velocities of the RC3 catalogue (de Vaucouleurs et al. 1991) and assuming $H_0 = 100 \text{ km s}^{-1} \text{Mpc}^{-1}$; the inclination angle $i$ (assuming the disc is infinitesimally thin), and the total luminosity $L_{\text{disc}}$ in $L_\odot$. Nuclear discs are indicated by ‘N’, outer discs by ‘O’.

### 4.2 Discussion on individual objects

#### NGC 4342

This galaxy is classified as E7 and S0 in the RSA and RC2 catalogues, respectively. The rotation curve of this galaxy reveals the nuclear disc as a kinematically distinct component (BJM98). No strong color gradients are found, especially inside $\sim 2''$, so that no population difference between bulge and nuclear disc is apparent (see BJM98). The nucleus of NGC 4342 harbors a massive black hole (BH) of $\sim 1.4 \times 10^8 M_\odot$ (Cretton & van den Bosch 1998). The dynamical modeling of these authors also yields an I-band mass-to-light ratio of 13.2. Both these numbers have been converted to the distance of NGC 4342 of 7.14 Mpc adopted in this paper. Together with the observed central $(V-I)$-color of $\sim 1.3$, and the total V-band luminosity of the nuclear disc listed in Table 1, this yields a total mass of the nuclear disc of $\sim 1.7 \times 10^9 M_\odot$ (using $(V-I)_0 = 0.81$), comparable to the mass of the BH. Figure 3 shows the surface brightness profile along the major axis of this galaxy (full line), its outer disc (long-short dashed line), nuclear disc (short dashed line) and bulge (dashed-dotted line). The subtraction of the outer disc from the MGE-model of NGC 4342 yields an almost perfectly elliptical bulge (see $a_4$ profile at large radii in the middle panel of Figure 1).

#### NGC 4570

NGC 4570 is classified as S0/E7 and S0 in the RSA and RC2 catalogues respectively. Like NGC 4342, its nuclear disc is visible as a distinct component in the rotation curve. BJM98 report a significant color gradient in this galaxy and an unusually large $H\beta$ line-strength in the nucleus, suggestive of recent star-formation. Van den Bosch & Emsellem (1998) found strong evidence for secular evolution driven by a nuclear bar in NGC 4570. They report two edge-on rings between the nuclear and outer discs, whose locations are consistent with the Inner Lindblad and Ultra Harmonic Resonances of a tumbling triaxial potential. Because of the small HST field, it was not possible to investigate the outer disc of this galaxy. Figure 4 shows the surface brightness profile along the major axis of NGC 4570 (full line) and of its nuclear disc (dashed-line). Due to the small contribution of the nuclear disc to the central luminosity, the bulge+outer-disc profile in this region (dotted-dashed line) is hardly distinguishable from the galaxy profile.

### 4.3 Nuclear and outer disc: two discs or one?

Are the nuclear and outer discs really two separate structures, or are they merely the manifestation of a single disc that has a double-exponential surface brightness profile? Since NGC 4342 is the only case for which we could determine the disc parameters of both the outer and the nuclear disc, we focus here on this galaxy only. As can be seen from Table 1, the outer and nuclear discs in NGC 4342 seem to indicate a different inclination angle: the nuclear disc yields $i = 83^\circ$, whereas from the outer disc we derive $i = 78^\circ$. We

| NGC   | $\mu_0$ | $\mu_0^f$ | $R_d$ | $i$  | $L_{\text{disc}}$ | N/O |
|-------|---------|-----------|-------|------|------------------|-----|
| 4342  | 13.14   | 15.43     | 7.3   | 83.0 | $8.1 \times 10^6$ | N   |
| 4342  | 17.39   | 19.10     | 430.0 | 78.0 | $9.7 \times 10^8$ | O   |
| 4570  | 14.85   | 17.06     | 23.5  | 82.5 | $1.9 \times 10^7$ | N   |

| Column (1) lists the NGC number of the galaxy. Column (2) gives the projected central surface brightness of the nuclear disc in magn arcsec$^{-2}$. The face-on corrected value for this, derived using equation (1), is listed in column (3). Column (4) gives the scalelength in pc, column (5) the inclination angle (assuming the disc is infinitesimally thin), and column (6) the total luminosity of the nuclear discs in $L_\odot$. The last column indicates either a nuclear disc ‘N’ or an outer disc ‘O’. |
recall that the applied decomposition technique allows a determination of the inclination angle with a precision of ∼ 2° (see Scorza & Bender 1990). Since we consider it unlikely that both discs are seen under different inclination angles (as this would imply an unstable situation), this indicates that the two discs have different thicknesses (see Appendix). If we assume that NGC 4342 is seen edge-on, we find that the outer disc is almost a factor three thicker than the nuclear disc. This, strongly suggests that the nuclear and outer discs are actually two distinct discs rather than a single double-exponential disc. The difference in thicknesses suggests different amounts of energy dissipation during their respective formations.

As discussed in Section 1, a general feature of multi-disc systems seems to be the presence of an inner cut-off in the outer disc. The presence, or absence of an inner cut-off is of particular interest, since it may provide clues to the formation of the double-disc structure (see Section 6). As can be seen from Figure 3 it is unfortunately impossible to discriminate between the presence or absence of an inner cut-off based on our photometry: the contribution from the outer disc to the projected surface brightness is completely negligible in the inner 1 to 2 arcsec, where the bulge and nuclear disc dominate the light. We have thus determined the outer disc parameters of NGC 4342 assuming no inner cut-off, but keep in mind that our current data can not distinguish whether the outer disc of NGC 4342 harbors an inner cut-off radius, or whether it continues all the way to the center.

### 4.4 The bulge parameters

Photometry with the HST has revealed that the central luminosity profiles of early-type galaxies are cusped, and that the galaxies can be classified in two classes according to the cusp steepness (see discussion in Section 1). Here we investigate the luminosity profiles of the bulges in the systems with a nuclear disc. Lauer et al. (1995) introduced the so-called “Nuker”-law profiles, which provide a good fit to the observed central luminosity profiles of early-type galaxies. The Nuker law is given by

\[
I(r) = I_b \left( \frac{r}{r_b} \right)^{\gamma} \left[ 1 + \left( \frac{r}{r_b} \right)^\beta \right]^{-\gamma / \beta}.
\]  

Note that for $r \ll r_b$, $I \propto r^{-\gamma}$, while for $r \gg r_b$, $I \propto r^{-\beta}$. The parameter $\alpha$ controls the sharpness of the transition from cusp to outer power-law at the break-radius $r_b$.

After subtraction of the nuclear discs from the images, we determine the luminosity profiles of the bulges along the minor axes, by fitting isophotes to the disc-subtracted images. This axis is least affected by any uncertainty in either the nuclear or the outer disc parameters. We fit equation (2) to the bulge luminosity profiles using the Levenberg-Marquardt method to determine the best fitting parameters $(I_b, r_b, \alpha, \beta, \gamma)$.

Figure 5 shows the minor axis luminosity profiles of the bulges (open circles), along with our best fitting Nuker-laws (solid lines). The lower panels show the residuals. As can be seen, the fits are very good, yielding residuals less than 0.1 magnitudes throughout. The best fitting parameters are listed in Table 2. Both bulges have very steep cusps ($\gamma \sim 0.7 - 0.8$) and harbor a clear break (i.e., large difference between $\beta$ and $\gamma$).

There has been some discussion in recent literature as to the origin of the light that produces the steep cusp in these galaxies. It was suggested by Jaffe et al. (1994) to be due to the nuclear disc seen close to edge-on. Faber et al. (1997) investigated a much larger sample of early-type galaxies imaged by HST, and concluded that it is the spheroidal component which has an intrinsic steep cusp. The analysis performed here clearly reveals that indeed the bulges in NGC 4342 and NGC 4570 are steeply cusped, and that the contribution to the central light by the nuclear disc is only small compared to that of the bulge’s cusp.
Table 2. Bulge parameters

| NGC | $I_b$ | $r_b$ | $r_b/R_d$ | $\alpha$ | $\beta$ | $\gamma$ |
|-----|-------|-------|-----------|----------|--------|----------|
| 4342 | 18.28 | 2.28  | 8.14      | 1.03     | 3.56   | 0.73     |
| 4570 | 19.41 | 7.34  | 26.21     | 1.57     | 3.88   | 0.77     |

Parameters of the Nuker-law (eq. [2]) that best fit the minor axis bulge luminosity profiles of NGC 4342 and NGC 4570. Column (1) lists the NGC number of the galaxy. Column (2) gives the surface brightness $I_b$ in magn arcsec$^{-2}$ at the break radius $r_b$, which is listed, in arcsec, in column (3). Column (4) gives the ratio of the break radius of the bulge over the scalelength of the nuclear disc $R_d$. Columns (5), (6), and (7) list the parameters $\alpha$, $\beta$, and $\gamma$.

5 THE $\mu_0$–$R_d$ DIAGRAM

When Freeman (1970) studied the photometry of 36 spiral galaxies, he found the amazing result that the central surface brightness of 28 galaxies of this sample fell within the range of $\mu_0(B) = 21.65 \pm 0.3$ magn. arcsec$^{-2}$. Ever since, there has been a considerable debate on the validity of this so-called Freeman law. Some showed that the effect might be real (e.g., van der Kruit 1987), while others argued that it is due to selection effects (e.g., Disney 1976) and/or extinction (Valentijn 1990). The discovery of low surface brightness (LSB) galaxies in a number of surveys (e.g., Schombert & Bothun 1988; Impey, Bothun & Malin 1988; Schombert et al. 1992; McGaugh & Bothun 1994; de Blok, van der Hulst & Bothun 1995) as well as recent near-infrared photometry studies of large samples of ‘normal’ or so-called high surface brightness (HSB) galaxies (e.g., de Jong & van der Kruit 1994) have clearly revealed a large range in central surface brightness amongst disc galaxies, contrary to Freeman’s law. An extreme example is Malin I (Impey et al. 1988; Impey & Bothun 1989), which is the largest (LSB) spiral galaxy known to date and has a central surface brightness of $\mu_0(B) = 26.5$ magn. arcsec$^{-2}$, almost 5 magnitudes fainter than Freeman’s value. When plotting the central surface brightnesses $\mu_0$, versus the scalelengths $R_d$ of the discs, the LSB extend the region occupied by HSB discs but do not fill in the entire range between normal spirals and Malin 1 (Sprayberry et al. 1995). Thus, among spirals galaxies there seems to be a clear upper limit to the surface brightness of the discs, but no clear limit at the faint end of the $\mu_0$ distribution.

If the parameters of the embedded discs in discy-ellipticals are included in the $\mu_0(V)$–$R_d$ parameter space (Scorza & Bender 1995), it is found that these discs extend the region occupied by spiral and S0 discs towards higher $\mu_0$ and shorter scalelengths $R_d$. The nuclear discs studied here reach even higher central surface brightnesses and have much smaller scalelengths. In Figure 6 we plot the central surface brightness (in V-band) as a function of the logarithm of the scalelength of a vast variety of discs, ranging from the extraordinary large disc of Malin I (solid triangle, data taken from Bothun et al. 1987), to the nuclear discs studied in this paper (asterisks). We include the parameters of the nuclear disc in NGC 3115 (open triangle) as derived by Kormendy
et al. (1996a) with the same method as used here. In addition, we plot the parameters of discs in S0s and embedded discs in discy ellipticals (solid circles, data taken from Scorza & Bender 1995, and Scorza et al. 1998), and of a combined sample of HSB and LSB spiral discs (open circles, data taken from Kent 1985; de Jong 1996; Sprayberry et al. 1995; de Blok, van der Hulst & Bothun 1995; McGaugh & Bothun 1994). For comparison, we have also plotted the Freeman value. Figure 6 presents the results for discs that span almost 4 orders of magnitude in both scalelength and central surface brightness. Clearly, the nuclear discs are as extreme in their photometric properties as Malin I, when compared to typical ‘normal’ HSB spiral discs that obey Freeman’s law.

It is important to note here that the main parameter that changes along the sequence of discs depicted in the diagram of Figure 6 is the disc-to-bulge ratio \( D/B \). Spirals and S0s typically have \( D/B \gtrsim 1 \), discy ellipticals have \( D/B \sim 0.1 \), and the nuclear disc systems studied here have \( D/B \sim 0.01 \). The importance of this parameter with regard to disc stability and the position of the different discs in the \( \mu_0(V)-R_d \) diagram is discussed in van den Bosch (1998).

6 CONCLUSIONS

We have studied the photometric structure of two power-law early-type galaxies with nuclear stellar discs. Special attention has been paid to the nuclear disc components, which were separated from the central part of the bulges by means of a photometric decomposition method. We find a continuity of photometric properties in the parameter space defined by the central surface brightness \( \mu_0 \) and the scalelength \( R_d \) of discs in LSB, HSB spirals, S0s and embedded discs in ellipticals, in the sense that the nuclear discs extend the observed disc properties even further towards smaller scalelengths and brighter central surface brightnesses. The \( \mu_0-R_d \) diagram includes now discs that cover four orders of magnitude in both scalelength and central surface brightness. The nuclear discs studied here are the smallest and brightest stellar discs known, and as such, they are as extreme in their properties as Malin I, when compared to typical galactic discs that obey Freeman’s law. The small scalelengths of these discs \( (R_d < 25 \text{ pc}) \) and their relatively large masses \( (\sim 10^9 \text{ M}_\odot) \) suggest strong dissipational processes in the central regions of their host galaxies.

Nuker-law fits to the surface brightness profiles of the bulge components of NGC 4342 and NGC 4570 along the minor axis reveal that the bulges have very steep cusps. We thus confirm the conclusion of Faber et al. (1997) that the central surface brightness in these galaxies is dominated by that of the bulges and not by the nuclear discs. The latter only contribute significantly to the projected surface brightness in a limited radial interval between \( \sim 0.3'' \) and \( \sim 1.0'' \).

In recent years it has become apparent that many disc galaxies have double-disc structures. This discovery has prompted the question as to the origin of this multi-component disc structure. One possible formation mechanism is related to bars. In particular, it has been argued that the inner-truncated discs could be linked with the presence of a tumbling bar potential (Baggett, Baggett & Anderson 1996). In fact, in one of the galaxies studied here, NGC 4570, there is strong evidence that the multi-disc structure has indeed been shaped by secular evolution induced by a small bar (van den Bosch & Emsellem 1998). A similar conclusion was reached by Emsellem et al. (1996) for the case of the Sombrero galaxy, which is the prototypical galaxy with a double disc structure. Thus, secular evolution driven by a nuclear bar could be the process responsible for the formation of nuclear disc components in power-law early-type galaxies. One of the promising features of this scenario is that it provides a natural explanation for the double disc structure observed in most, if not all, cases where nuclear stellar discs have been discovered: the outer disc became bar unstable, and the nuclear disc formed out of (pre-enriched) gas transported inwards by this bar structure. In this scenario, one expects an inner cut-off of the outer discs at radii similar to the semi-major axis of the nuclear bar. The significant difference between the inclination angle inferred from the different disc components, suggests that the nuclear and outer discs are two distinct discs, rather than merely the manifestation of a single disc with a double-exponential surface brightness profile. Whether or not the outer discs harbor an inner cut-off can unfortunately not be addressed by the current data.

Although the bar-hypothesis outlined above seems promising, we can currently not rule out alternative formation scenarios for the nuclear discs. One of these alternatives may be related to the formation of central BHs. A significant fraction of the galaxies with nuclear stellar discs have been shown to harbor massive BHs (e.g., NGC 3115, Kormendy et al. 1996a; NGC 4342, Cretton & van den Bosch 1998;}

![Figure 6](image_url)
NGC 4594, Kormendy et al. 1996b). It has to be noted however that this may be an observational bias since the presence of a nuclear disc helps in the detection of a BH (see e.g., van den Bosch & de Zeeuw 1996; Ford et al. 1997). The mass of the nuclear disc in NGC 4342 is similar to that of its BH (see Section 4.2). The same holds for NGC 4594, for which we have estimated a nuclear disc mass of $1.9 \times 10^9 M_\odot$, based on the disc parameters of Emsellem et al. (1996) and $(M/L)_V \approx 4$ (Kormendy 1988). The BH mass in this galaxy is $1.0 \times 10^9 M_\odot$ (Kormendy et al. 1996b). For NGC 3115, the nuclear disc mass of $2.3 \times 10^8 M_\odot$ is approximately a factor four smaller than the BH mass of $1.0 \times 10^9 M_\odot$ determined by Kormendy et al. (1996a). Note that again we have converted all masses to a distance scale with $H_0 = 100$ km s$^{-1}$Mpc$^{-1}$. Loeb & Rasio (1994) simulated the collapse of primordial gas clouds at a scale $\lesssim 1$ kpc. Although the major fraction of the gas fragments to form a spheroidal component, typically $\sim 5$ percent of the initial mass settles to form a smooth nuclear gaseous disc. This disc requires a seed BH of mass $\gtrsim 10^6 M_\odot$ in order to be stable. If this seed BH is indeed present (see Loeb & Rasio 1994) and references therein for formation scenarios for such seed BH), it can subsequently grow by steady accretion from this nuclear disc to reach a typical quasar BH mass $\sim 10^8 M_\odot$. Although this scenario gives account primarily of the formation of quasar BHs, it could provide a possible link between the nuclear stellar discs that we observe today and BHs. The fact that the observed BHs and nuclear discs have masses that are remarkably similar at least implies that the nuclear discs in these galaxies could have been massive enough in the past to be an accretion source for the BHs. Nuclear discs could thus be the remnants of the primordial gas discs that fed the (seed) BH.

The above mentioned formation scenarios constitute an important frame of work for future observations. At the present, the small number of objects with high resolution photometry and spectroscopy does not allow to draw definitive conclusions.

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APPENDIX: CONVERSION TO THICK DISC MODELS

The decomposition method described in Section 3.1 yields the disc parameters under the assumption that the discs are infinitesimally thin. This is however not very physical and can result in some mathematical difficulties when constructing dynamical disc models. In this Appendix we show how to convert the infinitesimally thin exponential discs to a set of thick discs that have an identical surface brightness distribution as the thin exponentials, and in the mean time are differentiable in all directions, and therefore ideally suited for dynamical modeling.

The luminosity density of an infinitesimally thin exponential disc in the equatorial plane ($z = 0$) is

$$\Sigma^*(R) = \Sigma^*_0 \exp(-R/R_d^*),$$ (A.1)

When projected on the sky under an inclination angle $i_0$, one obtains the surface brightness distribution

$$S^*(x, y) = \frac{\Sigma^*_0}{\cos i_0} \exp(-m^*/R_d^*),$$ (A.2)

where $m^* = \sqrt{x^2 + y^2 / \cos^2 i_0}$, and $(x, y)$ are coordinates in the plane of the sky.

Van den Bosch & de Zeeuw (1996) have discussed the so-called exponential spheroid discs. These are not infinitesimally thin, and also project to an exponential surface brightness distribution. The luminosity density of the exponential spheroid is

$$\nu(R, z) = \frac{\Sigma_0}{\pi R_d} K_0(m R_d),$$ (A.3)

where $m = \sqrt{R^2 + z^2 / q_d^2}$ and $K_0$ is the modified Bessel function. In the following we refer to $q_d$ as the thickness of the disc. The total luminosity of the exponential spheroid disc is

$$L_{\text{disc}} = 2\pi q_d \Sigma_0 R_d^2.$$ (A.4)

A simple, single quadrature equation for the potential of the exponential spheroid is given in van den Bosch & de Zeeuw (1996). For an inclination angle $i$ the projected surface brightness is given by

$$S_i(x, y) = \frac{q_d}{q_d^*} \Sigma_0 \exp(-m'/R_d).$$ (A.5)

Here $m' = \sqrt{x^2 + y^2 / q_d^2}$ and $q_d$ is the projected flattening of the disc, which is related to the intrinsic flattening $q_d$ and the inclination angle $i$ through

$$q_d^2 = \cos^2 i + q_d^2 \sin^2 i.$$ (A.6)

It is straightforward to show that when $R_d = R_d^*$,

$$i = \arcsin\left(\frac{\sin i_0}{\sqrt{1 - q_d^2}}\right).$$ (A.7)

Figure A.1 The degeneracy between disc flattening $q_d$ and inclination angle $i$. All exponential spheroids (eq. [A.3]) with parameters $(q_d, i)$ on one of these lines project to exactly identical surface brightness, and can therefore not be distinguished from photometry alone.

and

$$\Sigma_0 = \frac{\Sigma^*_0}{q_d},$$ (A.8)

the full 2D surface brightness of the exponential spheroid disc is exactly equal to that of the infinitesimally exponential disc. Therefore, one can use the assumption of infinite thinness for the disc, derive its parameters (\(\Sigma_0^*, R_d^*, i_0\)) from the disc/bulge decomposition, and subsequently rescale these parameters to a set of thick discs with $i_0 \leq i \leq 0^\circ$ and $0 \leq q_d \leq \cos i_0$.

This also means that there is a strong degeneracy between inclination angle $i$ and disc flattening $q_d$. This degeneracy is plotted in Figure A.1, for different values of $i_0$ (i.e., the inclination angle corresponding to the infinitesimally thin disc). All discs with parameters $(q_d, i)$ that fall on a curve in Figure A.1 project to exactly identical surface brightness. Therefore, there is no possibility to uniquely determine both $q_d$ and $i_0$ from the surface photometry alone.