

HUBBLE SPACE TELESCOPE PHOTOMETRY OF THE CENTRAL REGIONS OF VIRGO CLUSTER ELLIPTICAL GALAXIES. III. BRIGHTNESS PROFILES

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ABSTRACT

We have used the Planetary Camera on the *Hubble Space Telescope* to study the morphology and surface brightness parameters of a luminosity-limited sample of fourteen elliptical galaxies in the Virgo cluster. The total apparent blue magnitudes of the galaxies range between 9.4 and 13.4. In this paper, the core brightness profiles are presented, while the overall morphology and the isophotal shapes are discussed in two companion papers [Jaffe *et al.* AJ, 108, 1567 (1994); van den Bosch *et al.* AJ, 108, 1579 (1994)]. We show that, in spite of the spherical aberration affecting the *HST* primary mirror, deconvolution techniques allow recovery of the brightness profile up to 0.2 arcsec from the center of the galaxies. We find that none of the galaxies has an isothermal core. On the basis of their morphological and photometrical properties, the galaxies can be divided in two physically distinct groups, referred to as Type I and Type II. All of the Type I galaxies are classified as E1 to E3 in the *Revised Shapley Ames Catalog* (Sandage & Tammann 1981), while Type II galaxies are classified as E5 to E7. The characteristics of Type II galaxies are explained by the presence of disks component on both the 1 arcsec and the 10 arcsec scales, while Type I galaxies correspond to the classical disk-free ellipticals.

1. INTRODUCTION

In this paper we describe a study of the brightness profiles in the nuclear regions of a statistically complete sample of bright elliptical galaxies in the Virgo cluster, derived from *Hubble Space Telescope* images. The sample and reduction techniques are described in Paper I (Jaffe *et al.* 1994), and the images are presented there. In Paper II (van den Bosch *et al.* 1994) we studied the isophote *shapes* in the central region; here we will concentrate on brightness profiles along the major and minor axes.

Previous theoretical and observational studies have shown that, with sufficient resolution, these profiles may indicate the presence of a central black hole, or indicate whether a galaxy has undergone collisions. For example, Young (1980) showed that a black hole accreting in the nucleus of an isothermal elliptical galaxy will produce a nuclear cusp in the brightness profile: the more massive the black hole, the more

pronounced the cusp. In the well studied case of NGC 4486 (=M87) (Young *et al.* 1978; Sargent *et al.* 1978; Lauer *et al.* 1992) the brightness profile shows departure from isothermality in the inner 2 arcsec, and has been interpreted as due to a massive black hole a few times $10^9 M_\odot$. On the other hand, Kormendy (1984) simulated the merging of two elliptical galaxies and found that, under some conditions, the brightness profile of the resulting galaxy presents a "core within the core" structure. As a specific example, Kormendy shows that the brightness profile of NGC 5813 deviates from that expected for an isothermal sphere in the inner 1 arcsec, probably because of the occurrence of a merging process. Thus, two completely different phenomena, the accretion of a black hole and the merging of two galaxies, modify the brightness profile in the inner few arcsec, but have little or no influence beyond the core of the galaxy. Even though kinematic information is needed in order to distinguish between different scenarios, the study of the brightness profile

is the first step in pinning down different models of galaxy formation and evolution.

A great deal of effort has been spent in the past few years (Lauer 1985a, b; Kormendy 1985; Nieto 1992; Møller *et al.* 1993; Crane *et al.* 1993) to determine what fraction of elliptical galaxies possesses nuclear substructures. Unfortunately, ground-based studies of nuclear structures are severely impaired by atmospheric seeing (Schweizer 1979; de Vaucouleurs & Capaccioli 1979; Capaccioli & de Vaucouleurs 1983; Djorgovski 1983; Lauer 1985a,b; Franx *et al.* 1989a,b). Peletier *et al.* (1990) estimated that seeing effects extend to radii 5 to 10 times the seeing FWHM. Given the fact that core radii for most galaxies are in the range between 1 and 4 arcsec at the distance of the Virgo cluster, great care is necessary in interpreting the brightness profile even if the observed core radius is much larger than the seeing. Studies by Lauer (1985a,b), Kormendy (1985), and Møller *et al.* (1993) conclude that for all galaxies where the core is resolved the brightness profile is not isothermal, and shows evidence of substructure in the nuclear region. However, the majority of galaxies have unresolved cores, and no conclusion can be drawn.

Only a few studies of the cores of elliptical galaxies based on higher resolution *HST* data have been published previously, and none were based on a complete sample. Stiavelli *et al.* (1993) found a nonisothermal core for the galaxy NGC 1399, which they interpret as due to a nuclear black hole a few times $10^9 M_\odot$. Lauer *et al.* (1992) present *HST* PC images of NGC 4486, and conclude that the brightness profile is consistent with a few times $10^9 M_\odot$ nuclear black hole. Crane *et al.* (1993) obtained *HST* Faint Object Camera data for 10 galaxies, of which five are ellipticals, and concluded that none of the cores is isothermal.

The outline of the present study is as follows: in Sec. 2 we describe the data extraction, in Sec. 3 we present the data and discuss the results, in Sec. 4 we draw conclusions. Detailed theoretical modeling of the brightness profiles presented in this paper will be discussed in a subsequent work (Ferrarese *et al.* 1994).

2. DATA REDUCTION AND MODELING

2.1 Data Reduction

The reduction procedure applied to the images, including deconvolution, has been discussed in Paper I. Paper II describes simulations to determine the limits of the deconvolution techniques with respect to the reliability of the resulting isophotal shapes. In the next section we describe additional simulations that test the reliability of the deconvolved brightness profiles. This modeling shows that the accuracy of the derived profiles is not significantly affected by small variations in the PSF, caused, for example, by jitter in the *HST* pointing, nor by variations in the true surface brightness parameters of the galaxy being studied.

The brightness profiles have been determined by fitting the isophotes using an iterative method described in Paper II, except that rebinning was only applied at large radii where an insufficient slope of the profile precluded a good solution. Details of the algorithm can be found in Jedrzejewski (1987).

In several galaxies dust prevented a straightforward determination of the brightness profiles. In the case of NGC 4342 and NGC 4472 it was possible to mask the regions affected by dust and at the same time have enough unaffected points along the isophotes for a solution to be found; the same was not possible for NGC 4261, NGC 4374, NGC 4476, and NGC 4550, where we thus lack reliable information on the true brightness profile in the regions containing dust. In these regions the brightness profiles (uncorrected for obscuration) have been found simply by integrating along ellipses whose ellipticity, center and major axis position angle have been set equal to the average values found in the dust free areas. Finally, at distances 6 to 8 arcsec from the center of the galaxy, the slope of the brightness profile is not high enough to allow the solutions to converge (cf. Paper II). In order to extend the analysis to larger radii, the images have been rebinned by averaging over 4×4 pixels. As a result of the rebinning, the surface brightness gradient per pixel becomes larger, and the isophotal parameters can be found up to 17 to 26 arcsec from the center, depending on the particular galaxy. At these radii ground-based observations are not typically affected by seeing conditions, and can be used to complement the *HST* data.

2.2 Testing Deconvolution Procedures Using Model Galaxies

The spherical aberration affecting the *HST* primary mirror can seriously alter the brightness profile of elliptical galaxies in the central region. Excellent results in recovering the original *HST* performance have been obtained by means of deconvolution techniques, improved and updated during the past two years in order to suit *HST* data (Hanisch 1993). In Paper II we have described the effects of spherical aberration on the ellipticity, position angle, and isophotal shapes of elliptical galaxies and we concluded that deconvolution techniques are able to recover the original surface brightness parameters at distances larger than 0.5 arcsec from the center of the galaxy. In this paper, we will focus on the surface brightness profiles. Our aim is to determine how the aberrated *HST* PSF modifies the brightness profile, test whether the performances of deconvolution techniques depend on the intrinsic shape of the galaxy (for example on the ellipticity), and determine if the results of deconvolution are sensitive to small variations of the PSF.

We constructed a set of model elliptical galaxies, spanning a wide range of brightness profiles, ellipticity, position angle of the major axis, and isophotal shape. In order to study the effects of the aberrated *HST* PSF, each model was convolved with a PSF appropriate for chip 6 of the PC, where all the galaxies have been centered, and filter F555W. Poisson noise and read out noise were added to the convolved, or aberrated, image. The models have a signal-to-noise ratio per pixel between 20 and 30 at the galaxy center after convolution with the *HST* PSF; this represents the typical signal-to-noise ratio in the real data. Finally, the aberrated image was deconvolved using the Richardson–Lucy (RL) algorithm. The RL iterations converge to the maximum likelihood solution for Poisson statistics, and are therefore well

suited for deconvolving *HST* PC data. In addition, the RL deconvolved data is forced to be positive and the deconvolved image has good photometric linearity (White 1993). The PSFs used for convolution and deconvolution were created using the TinyTim software (Krist 1992), as described in Paper I.

It is reasonable to assume that the results of deconvolution may depend on the intrinsic surface brightness profile of the galaxy: a brightness profile which flattens towards the galaxy center is expected to be less affected by convolution than a very steep brightness profile, and, as a consequence, deconvolution is expected to give better results for a flatter profile rather than for a steeper one. We have considered four different forms for the brightness profile, three with one component only, and one with two separate components, covering a wide range in shape and steepness in the crucial (as far as convolution and deconvolution are concerned) inner 5 arcsec. The four profiles are given by: a de Vaucouleurs law

$$\Sigma(r) = \Sigma_0 \times 10^{-3.33[(r/r_0)^{1/4} - 1]}, \quad (1)$$

where r is along the major axis of the galaxy, $\Sigma_0 = 5$ PC counts and $r_0 = 13$ arcsec; a Hubble law

$$\Sigma(r) = \frac{\Sigma_0}{(1 + r/r_0)^2}, \quad (2)$$

with $\Sigma_0 = 2000$ counts and $r_0 = 4.3$ arcsec; an exponential profile

$$\Sigma(r) = \Sigma_0 \times e^{-r/r_0}, \quad (3)$$

with $\Sigma_0 = 1500$ counts and $r_0 = 13$ arcsec; an exponential profile plus a central Gaussian component:

$$\Sigma(r) = \Sigma_0^1 \times e^{-r/r_0} + \Sigma_0^2 \times e^{-(r^2/2\sigma^2)}, \quad (4)$$

with $\Sigma_0^1 = 1500$ counts, $r_0 = 13$ arcsec, $\Sigma_0^2 = 500$ counts, $\sigma = 1.6$ arcsec.

The brightness profiles described by formulas (1) to (4) are sketched as solid lines in the upper panels of Fig. 1 for a model elliptical galaxy with constant major axis position angle and mild ellipticity ($\epsilon' = 0.2$). In the same figure, the dashed lines represent the same, but now aberrated, brightness profiles, derived by convolving the model images with an *HST* PSF and adding noise. As can be seen, substantial differences are present in the inner 2 arcsec, the aberrated profile being lower and flatter than the original one. As in the case of images blurred by atmospheric seeing, light is removed from the innermost part of a galaxy and pushed to intermediate radii, while the surface brightness at large radii remains undisturbed. In contrast with the seeing PSF, however, the *HST* PSF is stable, accurately known, and contains spatial information up to a very high frequency, 10 cycles arcsec⁻¹. This allows the successful use of deconvolution techniques which are inapplicable in the case of seeing convolved images. The process of convolving model galaxies with an *HST* PSF has been carried out using several *HST* PSFs, differing one from the other for the position on the chip, the spectral shape, or the amount of jitter. The results show that the aberrated image does not change significantly due to variation of the PSF.

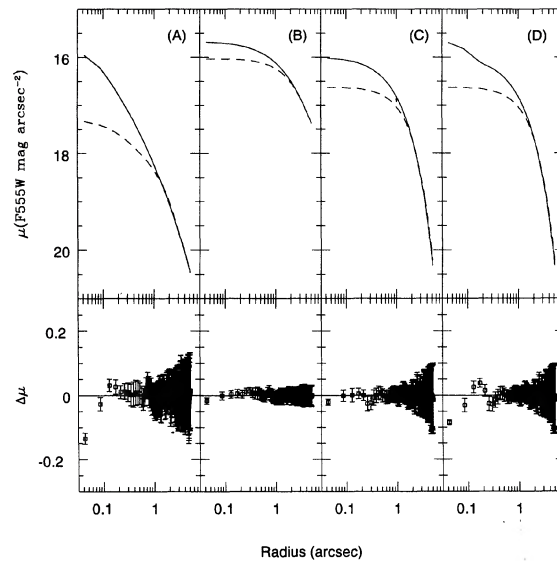


FIG. 1. The solid lines in the upper panels show the brightness profiles corresponding to (a) a de Vaucouleurs law (formula 1 in the text), (b) a Hubble law (formula 2), (c) an exponential law (formula 3), (d) and exponential law plus a central Gaussian component (formula 4). The dashed lines show the same brightness profiles as seen by the aberrated *HST* PC. Major deviations are present in the inner 2 arcsec as due to the spherical aberration affecting the *HST* primary mirror. The lower panels show the residual between the deconvolved brightness profile obtained from the aberrated images (dashed lines) by means of deconvolution techniques and the expected brightness profiles (solid lines in the upper panels). The original brightness profile is recovered up to 0.2 arcsec from the center. Even in the inner 0.2 arcsec, deviations between deconvolved and original surface brightnesses are no larger than 0.15 mag arcsec⁻².

At this stage, the RL algorithm was employed in order to recover the original brightness profile. We first determined if and how differences in steepness and curvature of the brightness profile influence the results of deconvolution. In the lower panels of Fig. 1 we show the difference between the original brightness profile shown in the upper panel as solid line and the deconvolved brightness profile obtained from the aberrated images after 100 RL iterations. The PSF used for the deconvolution was the same as the one used for the initial convolution. The original brightness profile is reproduced by RL deconvolution with accuracy higher than 0.05 mag arcsec⁻² at radii larger than 0.2 arcsec and accuracy higher than 0.15 mag arcsec⁻² at smaller radii.

We have also determined whether the accuracy of the deconvolution techniques depends on other surface brightness parameters, such as ellipticity, position angle, and departures of the isophotes from pure ellipses. For example, the ellipticity of an elongated galaxy will decrease towards the center as a consequence of the convolution with the aberrated *HST* PSF, and since the brightness profile is found by integrating along isophotes, larger deviations are expected in the brightness profile of deconvolved galaxies when the ellipticity is higher. Figure 2(a) shows the difference between the original brightness profile and the deconvolved brightness profile (after 100 RL iterations) in the case of an elliptical galaxy with a de Vaucouleurs profile (formula 1), constant major axis position angle and high ellipticity $\epsilon = 0.6$. As in Fig. 1, we

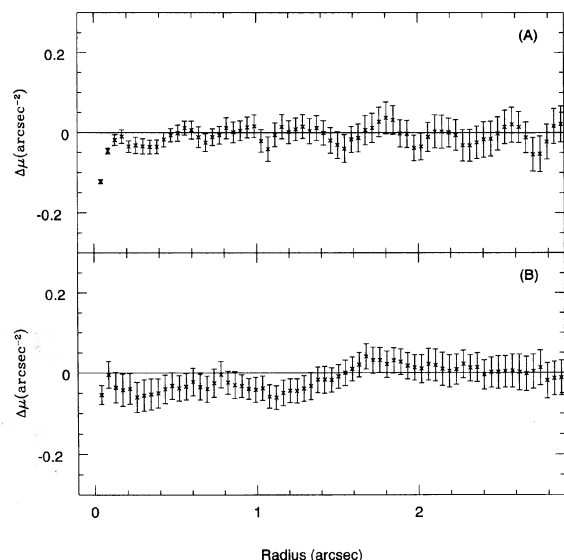


FIG. 2. (a): Residuals between the deconvolved and expected brightness profile for a highly elongated galaxy (E6) with an intrinsic de Vaucouleurs brightness profile (formula 1). Deconvolution performs only slightly worse for galaxies with high ellipticity, in all cases, the brightness profile is correctly recovered up to 0.2 arcsec from the center. Inside this radius deviations are not higher than 0.15 mag arcsec⁻². (b): Residuals between the deconvolved brightness profiles for an E2 galaxy obtained with PC PSFs differing for the amount of jitter and the spectral shape of the point source. Small variation of the PSF have very little effects on the results of deconvolution.

find that, at most, deviations up to 0.15 mag arcsec⁻² are present in the inner 0.2 arcsec. Slightly smaller deviations are observed for rounder galaxies.

In the same way, we found that the results of deconvolution are not affected by variations of the major axis position angle (models were built with position angle varying up to 90 degrees in a 4 arcsec range) or by deviations of the isophotes from pure ellipses (models were built with the fourth cosine Fourier coefficient as high as 0.05 in absolute value; see Paper II for a detailed discussion of the Fourier coefficients).

Finally, we have studied the effects of small variations in the PSF on the results of deconvolution. The detailed PSF shape depends on the position on the chip, on the spectral shape of the point source, on jitter due to the *HST* pointing, and on the time of observation. We have therefore used different PSFs for deconvolution; Figure 2(b) shows the difference between the deconvolved brightness profiles of a model galaxy (de Vaucouleurs profile, $\epsilon=0.2$) deconvolved using two PSFs, differing for the position of the PSF on the chip. The case presented in the figure is quite extreme, since the two PSFs used have been modeled for positions far apart one from the other and close to the edge of the chip, where asymmetries in the PSF shape are larger. Our models show that if the PSF used for deconvolution is modeled for the position corresponding to the center of the galaxy, the deconvolved brightness profile deviates from the original by less than 0.05 mag arcsec⁻², and these deviations are limited in the inner 0.2 arcsec. In addition, we found that deconvolution is not

sensitive to changes in the PSF shape due to jitter or to the spectral shape of the point source, which can give errors of, at most, 0.05 mag arcsec⁻² in the inner 0.2 arcsec.

3. RESULTS AND DISCUSSION

The *HST* surface brightness profiles of the fourteen galaxies in the sample are plotted in Fig. 3 as a function of both the major and minor axis of the galaxies (values of the ellipticity are reported in Paper II). The upper curves in Fig. 3 represent the major axis profiles, while the lower curves represent the minor axis profiles, displaced down by one magnitude for clarity. A tabulated version of the brightness profiles can be found in the Astronomical Journal CD-ROM distribution.

3.1 Comparison with Ground Based Data

We have compared the surface brightness presented here with published *B* and *R* ground-based photometry (Liller 1966; Peletier *et al.* 1990; Michard 1985; Caon *et al.* 1990, 1993; Vigroux *et al.* 1988; Jedrzejewski 1987; Barbon *et al.* 1984; Lauer 1985b; Watanabe 1982). In Fig. 4 we plot the difference between the *HST* surface brightness along the major axis and the ground based surface brightness for two representative galaxies, NGC 4168 and NGC 4478 (similar results are obtained for all other galaxies). Since the data by Michard (1985) and Caon *et al.* (1990), used for the comparison, was obtained in the *B* band, it has been necessary to apply a constant color correction in order to match the results in the outer region ($r=8-10$ arcsec). The color correction turns out to be $B-V \approx 1.0$ mag arcsec⁻², consistent with the value generally accepted in the literature (for example, Franx *et al.* 1989b). Note that, as discussed by Franx *et al.* (1989b), Peletier *et al.* (1990), and Møller *et al.* (1993) differential color corrections in the core are very small and can be neglected for our purposes. As can be seen from Fig. 4, *HST* and ground-based observations disagree inside ≈ 2 arcsec, in the sense that the cores appear brighter when observed with *HST*. As discussed in Sec. 2, this is due to seeing smearing affecting the ground-based observations.

3.2 Are Cores Isothermal?

None of the core brightness profiles is isothermal. For some of the galaxies (NGC 4168, NGC 4365, NGC 4472, and NGC 4473) the brightness profile flattens out towards the center, as expected for an isothermal law with core radius larger than a few tens of arcsec, but cannot be described by an isothermal over the entire range of radii observed here. As an example, the brightness profile of NGC 4472 is plotted in Fig. 5. The solid curve is the best fitting isothermal: the isothermal does not accurately reproduce the profile even in the innermost region.

In several cases (e.g., NGC 4478, NGC 4570, NGC 4623) the brightness profile can be roughly described by a power law with index between -0.8 and -1.5 over the range of radii presented here (cf. Sec. 3.4). It is worth pointing out that an isothermal brightness profile can be approximated by a power law with index -1.0 at radii large compared to the

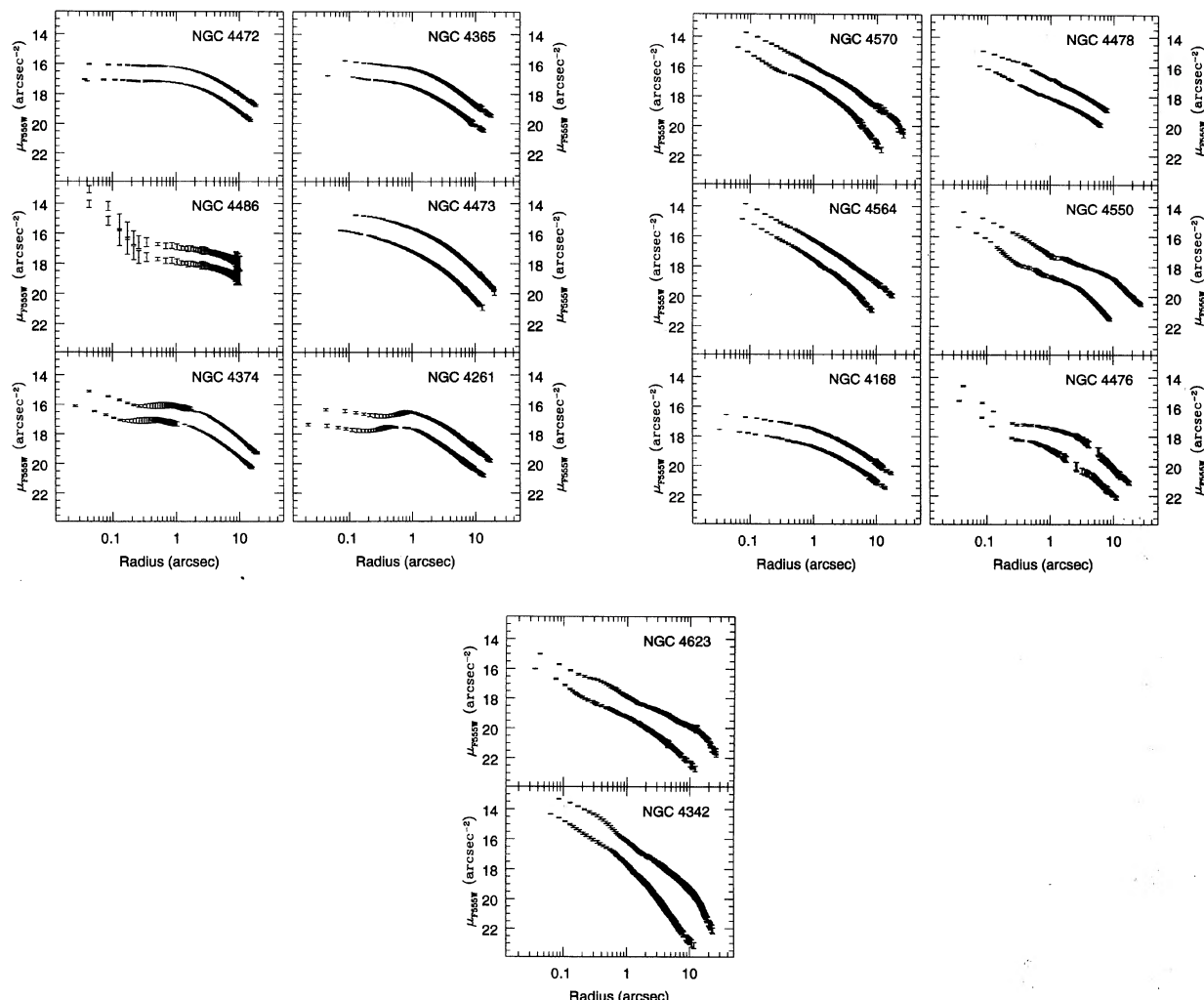


FIG. 3. The brightness profiles for all the galaxies in the sample derived from the Richardson–Lucy deconvolved PC images by finding the average surface brightness along the isophotes. The upper curves show the brightness profile along the major axis of the galaxy, while the lower curves show the brightness profile along the minor axis of the galaxy. The lower curves have been displaced down by one magnitude for clarity.

core radius (Binney & Tremaine 1987); for example an isothermal galaxy with a core radius smaller than 0.01 arcsec would give rise to a power law profile with index -1.0 outside 0.2 arcsec. However, an isothermal with a small core radius does not provide a very good fit for any of the galaxies with a “power law-like” profile.

3.3 Galaxies with Multiple Kinematic Components

NGC 4550, NGC 4365, and NGC 4472 show kinematic evidence for the presence of multiple components; we wish to establish whether there are corresponding peculiarities in the brightness profile. NGC 4550 is known to have two counter-rotating stellar disks (Rubin *et al.* 1992; Rix *et al.* 1992). The *HST* brightness profile of NGC 4550 presents a discontinuity around 1.3 arcsec (see Fig. 3). However, NGC 4550 is heavily contaminated by dust in the inner 6 arcsec, hence the irregularities in the brightness profile are more probably due to spatially variable dust obscuration rather than to the separate components. Surma (1993) found kinematic

evidence for a decoupled core inside 5 arcsec in NGC 4365. The major axis brightness profile of NGC 4365 seems to flatten towards the center, but then slightly steepens again inside 0.5 arcsec. No dust has been detected in this galaxy, hence this change in slope might be linked to the kinematically decoupled core, even if no indication for a separate component is seen from the analysis of the isophotal shapes (Paper II). Finally, NGC 4472 is known to have a kinematically decoupled core (Davies & Birkinshaw 1988; Franx *et al.* 1989a); however, neither the brightness profile nor the isophotal analysis (Paper II) reveal any sign of a separate component in the inner ~ 7 arcsec, where the kinematical decoupling is observed.

3.4 General Galaxy Morphology

The fourteen galaxies in our sample can be grouped in two broad classes according to the shape of the brightness profiles (Fig. 3). Some of the galaxies, to which we will refer as “Type I” in the following discussion, show a resolved

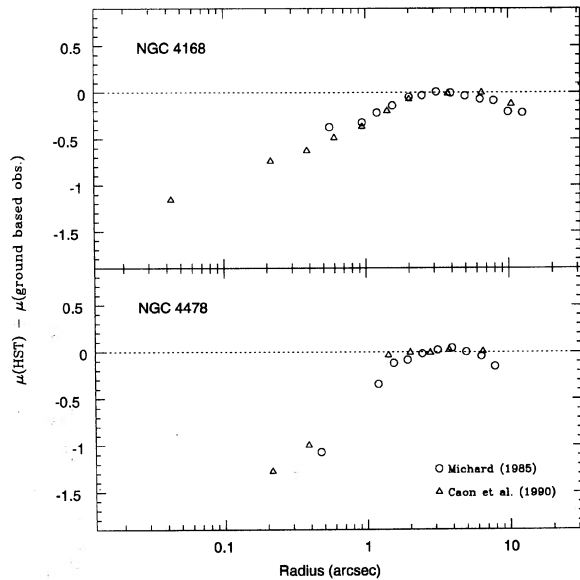


FIG. 4. Comparison between the surface brightness as measured with *HST* and ground-based facilities for two typical galaxies in the sample, NGC 4168 and NGC 4478. The discrepancies seen in the inner 2 arcsec, are due to underestimation of the surface brightness by the ground-based observations, due to seeing smearing.

core, with the brightness profile flattening towards the center: NGC 4472, NGC 4365, NGC 4473, and NGC 4168. In contrast, NGC 4342, NGC 4564, NGC 4570, NGC 4623, NGC 4550, and NGC 4478 do not have a resolved core: the brightness profile roughly follows a power law, and remains steep all the way up to the very center. We will refer to this second class of galaxies as “Type II.” The remaining four galaxies are difficult to place in one or the other category: NGC 4486

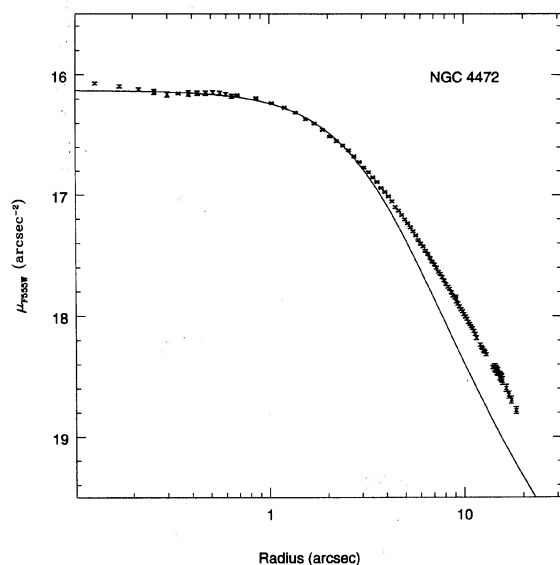


FIG. 5. The crosses and the error bars represent the *HST* measurement of the surface brightness for NGC 4472, the brightest galaxy in the sample. The solid curve is the best fitting isothermal.

because of the presence of the nonthermal nucleus; NGC 4261, NGC 4374, and NGC 4476 because dust prevents a determination of the underlying brightness profiles at small or intermediate radii. The brightness profile of NGC 4486 has been extensively studied in the literature, both from ground-based (Young *et al.* 1978; Zavatti *et al.* 1984; Baguolo & Chambers 1987; Lauer 1985a; Kormendy 1985) and *HST* data (Lauer *et al.* 1992). The profile is fairly flat up to 0.3 arcsec from the center, but it steepens very rapidly inside, due to the presence of the unresolved nucleus. From our image of this galaxy, it is not possible to find a solution for the isophotes by letting ellipticity, major angle position angle, and isophotal center be free parameters, partly because of the low signal-to-noise ratio of the data, and partly because of the very low ellipticity of the galaxy. The brightness profile shown in Fig. 3 has been derived by integrating along isophotal paths with fixed ellipticity ($\epsilon=0.0$) and center. Therefore, ellipticity, major axis position angle, and Fourier coefficients are not available for this galaxy. As a consequence, we will exclude NGC 4486 when discussing correlations including isophotal shape parameters.

A look at Fig. 3 also reveals that while there are no noticeable differences in the brightness profiles along major and minor axis for Type I galaxies (resolved cores), significant differences are present for Type II galaxies. Therefore, we choose the differences between major and minor axis profiles, and the profile shapes to initially quantify the Type I/II classification. We will then investigate to what extent the isophotal parameters, such as central surface brightness, ellipticity, deviations of the isophotes from pure ellipses, and total magnitude, correlate with this classification.

We quantify the difference between the major and minor axis profiles by defining the parameter $\Delta\mu$ as the minimum rms difference between the two profiles, obtained by rescaling the minor axis by a constant factor, depending on the mean ellipticity of the galaxy. The values of $\Delta\mu$ are reported in Table 1. After rescaling the minor axis, significant differences between the major and minor axis profiles are present only for Type II galaxies, as shown by the high value of $\Delta\mu$ (≈ 0.1 for Type II compared with $\Delta\mu \approx 0.02$ for Type I).

In addition, we quantify the shape of the profile by fitting the major and minor axis profiles with a suitable parameterized function. For the galaxies with a resolved core, or Type I, a very good fit is given by the blend of two power laws, one describing the profile at large radii (typically $r > 7-10$ arcsec), the other at small radii ($r < 1$ arcsec). We have therefore chosen the following function:

$$I = \sqrt{2} I_c \times \left\{ \left(\frac{r}{r_c} \right)^{2\beta_1} \times \left[1 + \left(\frac{r}{r_c} \right)^{2(\beta_2 - \beta_1)} \right] \right\}^{-1/2}, \quad (5)$$

where I is the surface brightness expressed in $\text{erg cm}^{-2} \text{s}^{-2} \text{\AA}^{-1} \text{arcsec}^{-2}$ and the power law indices β_1 and β_2 are both defined to be positive (i.e., the luminosity increases towards the center).

The core radius r_c is defined as the radius at which the inner and outer power laws meet; β_2 and β_1 are the profile slopes at $r > r_c$ and $r < r_c$, respectively; and I_c is the surface brightness at the core radius. The extra factors of 2 and 1/2 in the exponents are introduced to force a sharper transition

TABLE 1. Surface brightness and morphological problems.

NGC (1)	B_T (2)	ϵ (3)	$d\epsilon/dr \times 10^3$ (4)	$B4 \times 100$ (5)	$\Delta\mu$ (6)	β_1^M (7)	β_2^M (8)	β^M (9)	β^n (10)	r_c (11)	μ_0 (12)	Type (13)
4472	9.37	0.122 ± 0.003	8 ± 2	-0.23 ± 0.02	0.02	0.09	1.17	—	—	2.64 ± 0.04	16.11 ± 0.03	I
4486	9.59	—	—	—	0.01	0.21	1.30	—	—	7.81 ± 0.24	16.31 ± 0.43	I
4374	10.09	0.187 ± 0.002	-6 ± 2	-0.03 ± 0.05	0.03	0.31	1.55	—	—	3.63 ± 0.13	16.04 ± 0.05	I
4365	10.52	0.234 ± 0.001	1 ± 2	-0.56 ± 0.03	0.02	0.15	1.29	—	—	1.88 ± 0.02	15.97 ± 0.02	I
4473	11.16	0.396 ± 0.001	-3 ± 2	0.95 ± 0.04	0.04	0.47	1.65	—	—	2.77 ± 0.06	14.87 ± 0.03	II:
4261	11.41	0.255 ± 0.001	-7 ± 4	-1.70 ± 0.06	0.02	0.27	1.38	—	—	2.15 ± 0.08	16.57 ± 0.04	I
4570	11.84	0.454 ± 0.006	20 ± 2	1.08 ± 0.09	0.19	—	—	1.12	1.28	—	14.51 ± 0.04	II
4564	12.05	0.414 ± 0.006	20 ± 3	0.90 ± 0.11	0.10	—	—	1.10	1.25	—	14.73 ± 0.03	II
4168	12.11	0.154 ± 0.002	-6 ± 4	0.37 ± 0.04	0.02	0.26	1.20	—	—	1.81 ± 0.05	16.99 ± 0.04	I
4478	12.36	0.204 ± 0.002	2 ± 4	-0.70 ± 0.04	0.04	—	—	0.86	0.81	—	15.49 ± 0.04	II:
4550	12.56	0.608 ± 0.003	10 ± 2	1.49 ± 0.04	0.08	—	—	0.89	1.00	—	15.34 ± 0.03	II
4476	13.01	0.376 ± 0.005	-20 ± 10	0.40 ± 0.21	0.11	0.21	1.76	—	—	2.77 ± 0.07	16.92 ± 0.05	II:
4623	13.24	0.578 ± 0.005	11 ± 3	0.40 ± 0.12	0.12	—	—	0.92	1.05	—	16.51 ± 0.06	II
4342	13.41	0.610 ± 0.003	10 ± 2	5.12 ± 0.09	0.19	—	—	1.47	1.75	—	14.03 ± 0.03	II

Notes: Column (2) gives the total apparent blue magnitude from the RSA for each galaxy reported in column (1). Columns (3) (4) and (5) give the mean ellipticity, the mean variation in ellipticity, multiplied by 1000 and the mean $\cos(4\theta)$ Fourier coefficients, multiplied by 100, in the interval between 5 and 15 arcsec from the center. The errors reported in columns (3), (4) and (5) are 1σ deviations. Column (6) gives the parameter $\Delta\mu$ which parametrizes the difference between the major and minor axis profile (see description in the text). In columns (7) and (8) are reported the slopes of the profile along the major axis at small and large radii respectively for Type I galaxies, while column (9) and (10) give the indices of the best fitting power laws for Type II galaxies, along the major and minor axis respectively. The rms errors for the slopes reported in columns (7) to (10) are typically of the order of a few percent. Column (11) gives the core radius, as defined in the text, in arcsec. Column (12) gives the surface brightness, in F555W magnitudes arcsec $^{-2}$, at $r = 0.2$ arcsec from the center. Column (13) reports the final classification into Type I and II. A colon indicates that the classification is uncertain (see section 3.5 for further details).

between the regimes at large and small radii. Formula (5) was also used to fit the profiles of NGC 4261 and NGC 4374 in the regions not affected by dust, and of NGC 4486 for radii larger than 0.3 arcsec, in order to exclude the contribution of the unresolved nucleus. For all other Type I galaxies, the profile was fitted at radii larger than 0.2 arcsec, to exclude the inner region that could be affected by the deconvolution procedure.

The double power law (5) provides a good fit to the brightness profiles of Type I galaxies up to the largest radii observed with *HST*; typical rms residuals after the fits are between 0.008 and 0.013. Type II galaxies, however, do not show a resolved core, and a double power law does not give a sensibly better fit to the profile than a single power law. Therefore, for Type II galaxies we have used a single power law:

$$I = I_0 \times r^{-\beta}. \quad (6)$$

For Type II galaxies, typical rms residuals after the fit are in the range 0.08 to 0.15. In Table 1, whenever a double power law provides a significantly better fit than a single power law, we report the values of β_1 and β_2 , the power law slopes at small and large radii along the major axis. Since major and minor axis profiles are very similar for these galaxies, we did not repeat the analysis along the minor axis. For those galaxies for which the double power law does not provide any real improvement to a single power law, we report the values of β along both the major and minor axis.

For the galaxies which have been fitted by a double power law, we also list the core radius r_c as defined above. r_c represents a more reliable measure of the core radius than the Half Width Half Power (HWHP) radius which has been frequently used in the past. For galaxies with nuclear dust, the estimated central surface brightness is lower than the real one, and therefore the HWHP is overestimated. More importantly, in the presence of any central peak or cusp, the mea-

sured central surface brightness is very sensitive to instrumental blurring, seeing, and deconvolution technique. In these cases the profile width at half maximum is poorly related to the core radius, even if the profile contains a well resolved core.

In Fig. 6, we compare the two initial quantities used for classification: the slope of the major axis profile in the inner

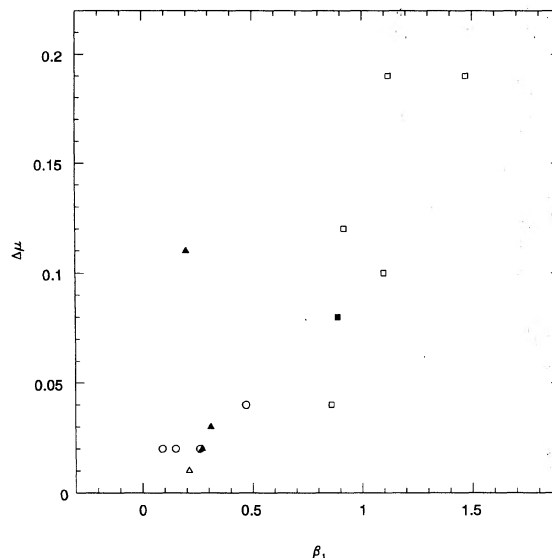


FIG. 6. Correlation between the slope of the profile at small radii (β_1 for Type I galaxies and β for Type II) and the parameter $\Delta\mu$, describing deviations between the major and minor axis profiles. Circles represent galaxies that are classified as Type I on the basis of the shape of the profile and the symmetry between major and minor axis profiles, squares are for Type II galaxies and triangle are for galaxies which cannot easily be binned in one or the other class. Filled symbols refer to galaxies for which dust affects the observable parameters.

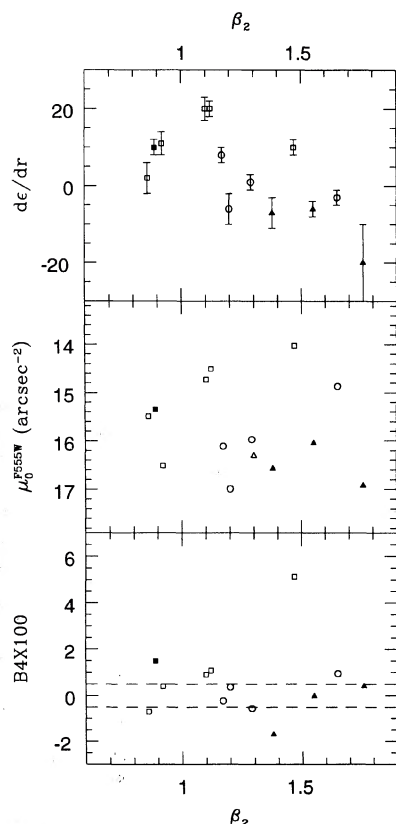


FIG. 7. Correlation between the slope of the profile at large radii (β_2 for Type I and β for Type II) and (1) the average radial variation of the ellipticity $d\epsilon/dr$ in the 5 to 15 arcsec range, (2) the fourth-order Fourier coefficient B_4 in the same radial range, (3) the surface brightness at $r=0.2$ arcsec. Symbols are as in Fig. 6. When not plotted, the errorbars are smaller than the plotted symbols. The dashed lines in the β_2 vs B_4 plot delimit the range $-0.5\% < B_4 < 0.5\%$ outside which deviations of the isophotes from pure ellipses are significant. Type II galaxies show disk isophotes, high central surface brightness and large variations in ellipticity when compared to Type I.

region (β_1 for Type I and β for Type II) is plotted against $\Delta\mu$. In Figs. 6 to 9, circles represent Type I galaxies, squares Type II, triangles galaxies for which the classification is uncertain. Filled symbols represent galaxies for which the isophotal parameters are not well determined due to the presence of dust (NGC 4261, NGC 4374, NGC 4476, and NGC 4550). In Fig. 6, the points clearly segregate in two areas, confirming the existence of a dichotomy between Type I and Type II galaxies: Type I galaxies are found in the lower left corner of the diagram, while the right part of the diagram is populated by Type II galaxies.

An accurate determination of β_1 relies on well resolved observations of the cores. Therefore, we also investigate the suitability of β_2 , the profile slope at large radii, as a potential discriminator between Type I and Type II for galaxies observed from the ground, or galaxies at larger distances than Virgo.

In Fig. 7, β_2 (or β for Type II galaxies) is plotted against three different photometric parameters: the average B_4 Fourier coefficient, measured in the interval between 5 and 15

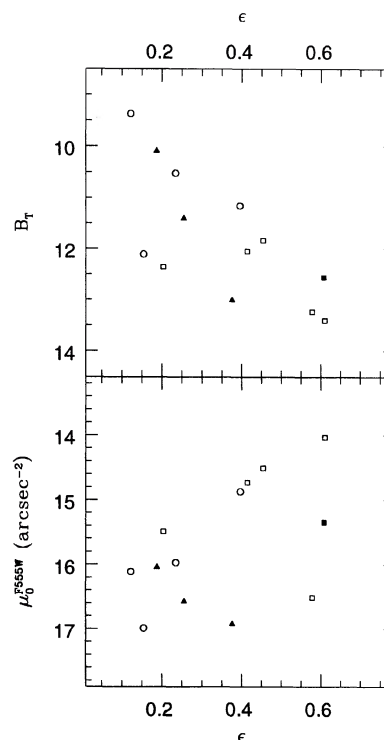


FIG. 8. Correlation between the average ellipticity in the 5 to 15 arcsec range and (1) the surface brightness at 0.2 arcsec, (2) the total magnitude B_T (from the RSA). Symbols are as in Fig. 6. The errorbars are smaller than the plotted symbols. Type II galaxies tend to be more elongated and fainter than Type I.

arcsec (from Paper II), the surface brightness at 0.2 arcsec from the galaxy center (the smallest radius at which the profile is accurately reproduced by deconvolution) and the average variation of the ellipticity with radius $d\epsilon/dr$ in the 5 to 15 arcsec interval (from Paper II). As before different symbols are used for the different types of galaxies classified on the basis of the value of $\Delta\mu$. We see that galaxies of different types cluster in distinct areas in each plot. Type I galaxies present steeper profiles at large radii than Type II. In addition, Type II galaxies show significant positive variations in ellipticity, have higher central surface brightness than Type I galaxies, and have disk isophotes (positive B_4 , see Paper II).

Therefore, the dichotomy originally defined on the basis of the slope in the inner 100 pc also determines the morphology at the 1 kpc scale. Figure 8 shows some more correlations. The average ellipticity in the 5 to 15 arcsec range correlates very well with the total magnitude. Type II galaxies are in general more elongated and fainter than Type I.

We interpret Type II galaxies to be composite systems, containing a bulge, an “outer” disk and a distinct nuclear disk, 150 to 200 pc in diameter (cf. Paper II). Depending on their relative brightness, ellipticity, and inclination, different components dominate at different radii and position angles, leading to the complex morphological properties observed. The presence of the nuclear disk explains the high central surface brightness, the lack of a well defined flat core along

the major axis and the diskiness of the isophotes at small radii. The outer disk of relatively large scale length explains the properties at radii greater than a few arcsec: the high ellipticity (when the disk is seen edge on), the diskiness of the isophotes at large radii, the flatter brightness profiles, and the dissimilarity between the brightness profiles along the major and minor axes. The transition from outer to inner disk, occurring between 1 and 2 arcsec, explains the rapid fluctuations in ellipticity seen near the centers of many of these galaxies (see also Paper II).

A dichotomy of early type galaxy morphology has already been stressed in the past from ground based observations. It is well established that bright ellipticals ($M_B < -20.5$) are typically pressure supported triaxial systems, while fainter ellipticals are rotationally supported (Bertola & Capaccioli 1975; Illingworth 1977; de Zeeuw & Franx 1991). From the study of the ellipticity distribution of all S0 galaxies in the RSA, van den Bergh (1990) concluded that all early type galaxies fainter than $M_B > -20$ are in fact lenticulars, while Capaccioli *et al.* (1990), from a sample of 18 elliptical galaxies in the Virgo cluster, speculate that around 50% of all ellipticals consist of the superposition of a bulge and a thin faint disk. Bender (1988), Bender *et al.* (1989), Nieto *et al.* (1991) have pointed out that galaxies with a resolved core have either elliptical or boxy isophotes, and that both characteristics correlate with nuclear activity. Capaccioli *et al.* (1993) show a clear break in essentially all global properties between "ordinary" elliptical galaxies ($M_B > -19.3$) and "bright" ellipticals.

With these insights we can re-examine the classification of our galaxies. We also keep in mind that of the plotted parameters, the total magnitude B_T is essentially independent of the inclination of the disks, while β_1 , β_2 , β , and μ_0 are moderately dependent, and B_4 and ϵ are strongly dependent. From Fig. 7 and Table 1 we see that NGC 4374 and 4261, whose cores are partially obscured by dust, are probably of Type I, based on the values of β_2 , B_4 , μ_0 , and $d\epsilon/dr$. Bender *et al.* (1988) point out that NGC 4550 harbors a disk; this is consistent with our findings of the asymmetry between major and minor axes, the low value of β_2 , the diskiness of the isophotes (positive B_4), and the high values of μ_0 and $d\epsilon/dr$. Therefore, we classify NGC 4550 as a Type II. NGC 4473 was classified as a Type I on the basis of the brightness profile shape and symmetry of the minor and major axis profiles, but it is more probably a disk system seen at intermediate inclination angle, given its high central surface brightness, and its high values of ϵ and B_4 . The classification of NGC 4478 and NGC 4476 is more uncertain. NGC 4476 seems more likely to be a Type II based on the low total magnitude B_T and the steepness of the profile at small radii, but the presence of dust at most of the radii considered here makes any classification uncertain. NGC 4478 shows all the characteristics of Type II galaxies, but is in many ways a peculiar galaxy. The discussion in Paper II indicates that NGC 4478 shows a very complex nuclear morphology. In addition, the galaxy is a companion of NGC 4486, and has been classified as a compact elliptical (Prugniel *et al.* 1987), because of the lack of an extended envelope. The influence of NGC 4486 is evident in the large twist of the outer iso-

photos of NGC 4478 (Peletier *et al.* 1990; Michard 1985; Caon *et al.* 1990). Finally, NGC 4486 is probably a Type I galaxy, given the high luminosity, low ellipticity, and the flattening of the profile at small radii (if the contribution of the unresolved nucleus is excluded).

NGC 4342 is in most respects a prototypical Type II galaxy, but lies separated in Fig. 7 from the other Type II galaxies because of its steep outer slope, β_2 . This is probably due to the fact that the scale length of the outer disk is small, so that at radii larger than 10 arcsec on the major axis, which were included in our determination of β , the steeper power-law bulge component dominates (cf. Fig. 3). Nevertheless, the inner disk is very bright, as shown by the high value of the central surface brightness, $\mu_0 = 14.03$, and in spite of the high value of β_2 , there is no question that NGC 4342 is a Type II galaxy.

If we compare our final classification scheme (see Table 1) with the classifications in the RSA and RC2 we find that our six Type I galaxies are all classified as E1–E3 in the RSA. Seven of the eight Type II galaxies are classified as E5–E7 in the RSA and five are given as S0 in RC2.

The only galaxy classified by us as Type II and which appears in both catalogs as a low ellipticity galaxy (E2) is NGC 4478 for which our classification is uncertain and which many represent a separate type of compact ellipticals (see above). The other two Type II galaxies which are classified as ellipticals in both the RSA and RC2 are NGC 4564, which is a clear Type II (low β_2 , high μ_0 , high $d\epsilon/dr$, low B_T , disk isophotes), and NGC 4473 which, as discussed above, is probably a disk system seen at intermediate inclination angle. Even if some of the Type II galaxies are undoubtedly S0s we refrain here from using this term because our provisional classification system is based on characteristics at radii of 10 to 1000 pc, while the standard Hubble classification is based on observations at 1 to 10 kpc. The identity of S0 galaxies and our Type II galaxies remains to be examined.

In conclusion, although our sample is small, we find in it an indication that there may not be any highly flattened genuine elliptical galaxies. All galaxies which satisfy our criteria for being disk-free are classified E1–E3. It would be of interest to extend our study to a larger sample of elliptical and S0 galaxies.

3.5 Power-Law Cusps

Contrary to naive expectations, we find steep, bright nuclear cusps only in the passive (radio-quiet) Type II systems, rather than in the massive, active Type I galaxies where the existence of a central black hole has been presumed (e.g., Rees 1984). Theoretical models of the stellar distribution around a black hole often predict a steep power-law cusp in the stellar density profile in the region where the mass is dominated by the black hole (Bahcall & Wolf 1976; Young 1980). The slope depends on the initial stellar distribution, the rate of growth of the black hole mass, and the mechanisms by which stars change their orbital parameters. Bahcall & Wolf (1976) predict a spatial density profile $\sim r^{-7/4}$ which corresponds to a surface brightness profile $\sim r^{-3/4}$. Young

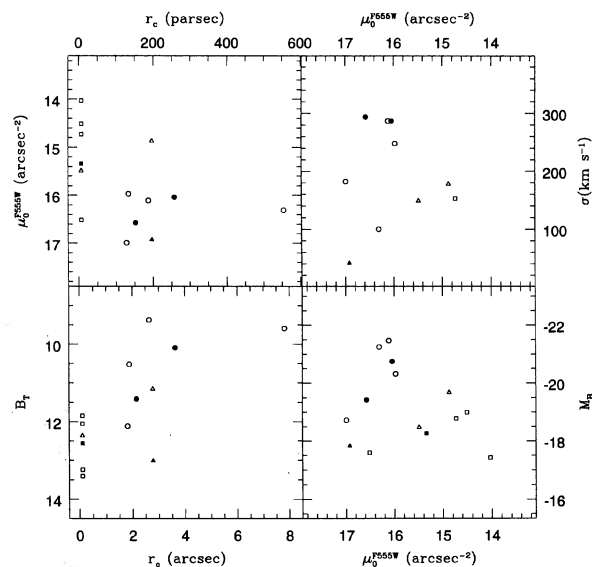


FIG. 9. Projection of the fundamental plane correlations for the galaxies in our sample. Values of the velocity dispersions are taken from Djorgovski & Davis (1987) and Dressler *et al.* (1987). M_B is the absolute magnitude, calculated from B_T assuming a distance of 14.7 Mpc to the Virgo cluster. In the same way, the core radius r_c has been converted from arcsec to parsecs. Symbols are as in Fig. 6, but now reflect the final classification into Type I and Type II. No clear correlation is seen between r_c , M_B , μ_0 , and σ .

(1980) finds a variety of solutions where the logarithmic slope of the central surface brightness vary from $-1/2$ to $-5/4$.

Figure 3 and Table 1 show that all the surveyed galaxies have sub-arcsec cusps, in the sense that the profiles extend as non-zero power laws, even to the smallest measured radius of $0''.2$. However, *none* of the galaxies classified as Type I has a central slope steeper than -0.31 . Either Type I galaxies do not contain black holes that dominate the mass within 20 pc of their centers, or the assumptions in the theoretical calculations of the slopes are oversimplified. The second possibility seems more likely since, in NGC 4486 (M87), recent *HST* observations strongly support the presence of a $3 \times 10^9 M_\odot$ central black hole, in spite of the shallow stellar surface brightness profile in the inner few arcsec (Ford *et al.* 1994; Harms *et al.* 1994).

3.6 Correlation Between Luminosity, Central Surface Brightness, and Core Radius

Previous authors (Kormendy 1987, 1989; Djorgovsky & Davies 1987) have found, from ground-based observations, correlations between the central surface brightness μ_0 , the core radius r_c , the total magnitude B_T , and kinematic parameters. In particular, lower luminosity ellipticals are found to have higher central surface brightness and smaller core radii. Kormendy (1989) concludes from these observations that dissipation must play an important role during galaxy formation.

Keeping in mind that we have a small, though statistically complete sample, we discuss here to what extent we find these correlations in our measurements. Figure 9 shows the

relation between total magnitude, central surface brightness, and core radius for all the galaxies in the sample. We have arbitrarily assigned a core radius of 0.1 arcsec to Type II galaxies; we note however that this does not necessarily mean that Type II galaxies do not have a core at all. If a bulge and disk component(s) are present in these galaxies, then the disk would hide the bulge core, even if this extended to the arcsec scale. We also plot the central surface brightness against the central velocity dispersion as measured by Djorgovski & Davis (1987) and Dressler *et al.* (1987). A velocity dispersion measurement is not available for all the galaxies. The symbols used in Fig. 9 are the same as those used in Figs. 6 to 8, except now we adopt our final classification, also reported in Table 1, and include NGC 4486, NGC 4261, and NGC 4374 as Type I, NGC 4473, NGC 4478, and NGC 4476 as uncertain (probably Type II).

We consider first the six Type I galaxies, which have resolved cores. We find that five have core radii in the narrow range between 120 and 250 parsecs, and the sixth, NGC 4486 is somewhat larger: 550 pc. Two galaxies whose classification is questionable, NGC 4476 and NGC 4473, have measured core radii in the same narrow interval. The central surface brightnesses of the Type I galaxies also fall in a restricted interval, $16 \lesssim \mu_0 \lesssim 17$. Although our Type I galaxies span three magnitudes in B_T we find no evidence for a correlation of either r_c or μ_0 with magnitude.

The published correlations of elliptical properties (Kormendy 1987, 1989; Djorgovsky & Davies 1987) include galaxies spanning 6 magnitudes in M_B , while our sample covers only half of that range. In part, these earlier observed correlations arise from samples which mix Type I and Type II ellipticals. In any such mixed sample the Type II galaxies appear with high central brightness, low luminosity, and small core radius, thus inducing a correlation of these properties, even if the correlation is absent among each type when considered separately. This effect does not explain the presence of some very bright, large core radius galaxies among the ground based samples. These galaxies, however, are in large part central cluster, cD galaxies, which are morphologically different from the ordinary “giant” ellipticals that constitute our Type I galaxies. The larger core radius found for NGC 4486 may illustrate this trend. NGC 4486 is a dominant cluster galaxy, although not a cD; its core radius is more than twice that of the other ellipticals in our sample, including the brighter galaxy NGC 4472. Thus although we do not observe a correlation between r_c , μ_0 , and B_T , we can not exclude that this correlation exists within a broader definition of elliptical galaxies.

4. CONCLUSIONS

We have presented the core brightness profiles of a magnitude limited sample of fourteen elliptical galaxies in the Virgo cluster. The profiles have been derived from 90 mas resolution *HST* PC images.

We have built an extensive set of models and shown that, in spite of the spherical aberration affecting the *HST* primary mirror, deconvolution techniques allow recovery of the original surface brightness profile with an error smaller than 0.05

mag arcsec⁻² for radii larger than 0.2 arcsec, and an error smaller than 0.15 mag arcsec⁻² for radii smaller than 0.2 arcsec.

By comparing the *HST* data with ground-based data previously published, we found that indeed, substantial differences in the brightness profile are present in the critical inner 2 arcsec, because of seeing affecting the ground-based observations.

Photometric evidence for multiple components in kinematically complex galaxies is weak in NGC 4550 and NGC 4365, and absent in NGC 4472.

We found that none of the galaxies has an isothermal core. Highly elongated galaxies, classified as E5 to E7 in the RSA, are fainter and have power-law like profiles, with a steadily increasing surface brightness towards the center. Rounder galaxies (E1 to E3) are brighter and have resolved cores, with the surface brightness levelling off towards the center. In addition, rounder galaxies show similar brightness profiles along the major and minor axis, and have elliptical or boxy isophotes. More elongated galaxies have disk-like isophotes, different profiles along the major and minor axis and show large changes in the ellipticity in the inner 15 arcsec. The steepness of the profile at radii larger than a few arcsec is lower for elongated galaxies than for rounder ones. These observations have prompted us to divide the sample in two groups, which we call Type I and Type II, corresponding to the galaxies with resolved and unresolved cores respectively.

The dichotomy between Type I and Type II galaxies is probably related to the presence of disk components, both on the 1 arcsec and 10 arcsec scales. For example, for Type II galaxies, the high central surface brightness is due to the inner disk seen edge on, the diskiness of the isophotes at large radii is due to the outer disk, and the rapid variations in ellipticity are caused by the transition between the inner and outer disk. Indeed for three galaxies in the sample, a stellar

nuclear disk, 70 to 100 parsecs in diameter, has been detected (Paper II). Although some of the Type II galaxies are classified as E/S0 or S0 in either the RSA or the RC2, the correspondence between Type II and S0 is not one to one. Only the Type I galaxies in our sample can be considered "true" ellipticals, in the sense of being disk-free, we therefore conclude that *based on our sample*, "true" elliptical galaxies are between type E1 and E3.

The possibility that some of the rounder galaxies could be Type II seen face on cannot be excluded on the basis of the photometry alone. The disk components of a Type II galaxy would not contribute much to the surface brightness when viewed face on, the diskiness of the isophotes would be lost, and so would the differences between the major and minor axis brightness profiles. If the brightness profile of the bulge of a Type II galaxy is described by a double power law, a Type II galaxy would be classified as a Type I when viewed face on. Of all the properties that distinguish Type I galaxies from Type II, only the total luminosity is independent on the viewing angle. It is therefore possible that some of the fainter galaxies classified as Type I or uncertain (NGC 4168 and NGC 4473) are indeed face on disk systems.

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