A NICMOS SURVEY OF EARLY-TYPE GALAXY CENTERS\textsuperscript{1}: THE RELATION BETWEEN CORE PROPERTIES, GAS AND DUST CONTENT, AND ENVIRONMENT

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ABSTRACT

We present a NICMOS 1.6 \(\mu\)m imaging isophotal study of 27 early-type galaxies. Core galaxies have reduced ellipticity and boxiness near and within their core or break radius. This supports a core formation mechanism that mixes or scatters stars such as scattering caused by a binary black hole. We find the same trends between central surface brightness and luminosities as the WFPC studies. We find no correlation between core properties and dust mass or X-ray luminosity, suggesting that processes determining the current gas content (e.g., such as minor mergers and cooling flows) are unrelated to processes occurring during core formation. Core galaxies exist in a variety of environments ranging from poor groups to large clusters. A combined sample suggests that galaxy groups may harbor more luminous power-law galaxies than clusters such as Virgo and Fornax.

\textit{Subject headings:} galaxies: clusters: general — galaxies: elliptical and lenticular, cD — galaxies: kinematics and dynamics — galaxies: structure — infrared: galaxies

1. INTRODUCTION

Optical imaging surveys carried out with the \textit{Hubble Space Telescope} (HST) find that almost all early-type galaxies harbor dust (van den Bosch et al. 1994). Even though projection effects cause a bias against detecting dust features in most of these galaxies (e.g., van Dokkum & Franx 1995), small 100 pc scale dust features are observed in a large fraction of galaxies with a variety of morphologies (spiral, warped, or irregular). Peletier et al. (1990) find that asymmetries in the isophote shapes are particularly sensitive to the presence of dust. Because the dust is found near the galaxy nuclei, a simple dust screen model can underestimate the extinction or dust column depth. This implies that a significant fraction of light in the nuclei could be absorbed by dust (e.g., Silva & Wise 1996). Despite this problem, visible WFPC and WFPC2 images from HST have been part of a major effort to classify the nuclear stellar profiles in these galaxies, resulting in the classification of light profiles into two categories, galaxies with shallow inner cusps and galaxies with "power-law" light profiles (Lauer et al. 1995). As discussed extensively in previous works (see for example Faber et al. 1997), this classification is dependent on the angular resolution of the image, and so on the distance of the galaxy.

Near-IR images, which are less sensitive to extinction from dust, provide superior light profiles for dynamical studies of early-type galaxy cores. Although almost all early-type galaxies harbor dust, the samples used to classify light profiles are biased against the presence of dust precisely because of the sensitivity of the optical images to extinction. By using near-IR light profiles we can probe the central light profiles for a class of ellipticals with a higher dust content. Since the dust itself could be related to the formation process and subsequent evolution of the galaxy (related to merger induced accretion, or caused by dissipation in the gas; Dubinski 1994), comparison of IR-observed light profiles between galaxies with varying amounts of dust may test models of core formation.

In this paper we present the results of a survey at 1.6 \(\mu\)m of early-type galaxies. We present high angular resolution images observed with NICMOS Camera 2 on board HST. Surface brightness profiles and isophotal parameters are measured from the images and compared with the most comprehensive summary of the visible-band-based studies (Faber et al. 1997). We investigate the possibility of correlations between core properties and cold gas content (traced by emission from dust in the far infrared), hot gas content (traced by X-ray luminosity) and cluster environment.

2. OBSERVATIONS

2.1. The Sample

Twenty-seven early-type galaxies, listed in Table 1, were observed in F160W (1.6 \(\mu\)m) on camera 2 of NICMOS primarily as part of a snapshot program. Galaxies were chosen preferentially to have existing \textit{HST} visible-band images so that color maps could be made. This included a wide variety of early-type galaxies, including some galaxies with kinematically distinct cores (those studied by Carollo et al. 1997). We then added galaxies from the RSA (Revised Shapley Ames Catalog) listed by Roberts et al. (1991) as having higher dust contents so as to insure that our sample was not as grossly biased against dusty galaxies. Our sample was initially chosen to be representative of the distribution of ellipticals in terms of cold ISM content, however only a third of our 80 target galaxies were observed and our final sample (listed in Table 1) is not as representative of dust content as we had initially selected. In Figure 1 we show a histogram of dust masses estimated from \textit{IRAS} far-infrared emission in our sample compared to the RSA (compiled by Roberts et al. 1991) and sample of visible \textit{HST} images compiled by van Dokkum & Franx (1995). Using a nonparametric rank sum U-test we find that the probability that the WFPC2 sample was drawn from

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The NICMOS Images

The NICMOS observation sequences were MULTI-ACCUM with 13 samples of step32 with a sequence exposure time of 192s. The galaxies were observed in the F160W (1.6 μm) filter with this sequence at four different positions on the sky separated by ~0.56, resulting in a total exposure time of 12.8 minutes per galaxy. Images were reduced with on-orbit flats and darks taken near the time the data were observed. No correction was made to remove differences in the dark in each quadrant of the array (known as pedestal removal). The galaxy nuclear regions have sufficiently high surface brightness that the pedestal and the thermal background in the F160W filter are expected to be extremely small in comparison. Correspondingly no sky was subtracted from the images. Each set of four images in a given filter were shifted and median combined. The pixel size for the NICMOS camera 2 is 0.0076. Flux calibration for the NICMOS images was performed using the conversion factors based on measurements of the standard stars P330-E and P172-D during the Servicing Mission Observation Verification program (M. Rieke 1999, private communication). Explicitly, we converted to Johnson H-band fluxes using the following: $m_H$ (in mag) = $-2.5 \log (\text{flux in ADU s}^{-1}) + 21.74$.

The NICMOS images, coupled with visible broadband images observed with WFPC2 on board HST when available, are shown in Figure 2. Galaxies lacking WFPC2 images are shown in Figure 3. These images show the improved ability of the 1.6 μm images to measure stellar surface brightness profiles in the presence of moderate amounts of dust. For example, in NGC 524, NGC 1400, NGC 1553, NGC 3056, NGC 4261, NGC 4278, NGC 4374, and NGC 7626 we can more accurately measure isophote profiles from the NICMOS images than possible with the WFPC2 images. However, we do find galaxies, such as NGC 7052 and NGC 4150, that show evidence for large extinctions from dust even at 1.6 μm. Though we can make better measurements than possible from visible wavelength images, even in the near-IR the presence of the dust in these galaxies hampers our ability to accurately measure the central stellar surface brightness profiles.

2.3. Isophote Fitting

To measure properties of the stellar cores, we fitted ellipses to the isophotes using the ellipse routine in the

\begin{table}
\centering
\caption{Sample of Early-Type Galaxies}
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Galaxy & Type & $B_I^2$ & $V_{\text{sys}}$ & $D$ & $\sigma$
\hline
NGC 524 & S0 & 11.3 & 2416 & 23.1 & 270
NGC 821 & E6 & 11.9 & 1716 & 28.6 & 215
NGC 1052 & E3/S0 & 11.5 & 1475 & 21.5 & 204
NGC 1172 & S0 & 12.6 & 1669 & 29.8 & 113
NGC 1331 & E2 & 14.1 & 1375 & 22.0 & 
NGC 1351 & S0 & 12.6 & 1527 & 17.8 & 144
NGC 1400 & S0 & 11.6 & 549 & 21.5 & 269
NGC 1426 & E4 & 12.2 & 1443 & 21.5 & 157
NGC 1553 & S0 & 10.4 & 1280 & 16.0 & 184
NGC 1600 & E4 & 11.8 & 4687 & 50.2 & 323
NGC 2636 & E0 & 14.6 & 1896 & 33.5 & 85
NGC 2907 & S0 & 12.8 & 2090 & 26.0 & 
NGC 3056 & S0 & 12.6 & 1017 & 13.0 & 
NGC 4150 & S0 & 12.4 & 244 & 4.0 & 85
NGC 4261 & E3 & 11.4 & 2200 & 35.0 & 339
NGC 4278 & E1 & 11.1 & 643 & 18.4 & 243
NGC 4291 & E3 & 12.3 & 1715 & 37.9 & 295
NGC 4374 & E1 & 10.2 & 1033 & 15.3 & 296
NGC 4589 & E2 & 11.8 & 1985 & 37.9 & 295
NGC 4636 & E0/S0 & 10.2 & 937 & 15.3 & 217
NGC 5198 & E1 & 12.9 & 2569 & 46.6 & 212
NGC 5845 & E & 13.4 & 1450 & 28.2 & 244
NGC 5859 & E3 & 12.0 & 2936 & 39.0 & 248
NGC 7052 & E4 & 12.0 & 4920 & 61.5 & 275
NGC 7626 & E1 & 12.2 & 3416 & 44.8 & 270
ESO507-G045 & S0 & 12.0 & 4825 & 60.3 & 325
A2052 & ........... & E & 13.7 & 10200 & 127.5 & 238
\hline
\end{tabular}
\end{table}
FIG. 2.—NICMOS 1.6 μm (F160W) images of galaxies are shown with visible WFPC2 images and color maps made from the two images. Contours are shown every 0.25 mag. The color maps are shown on a logarithmic scale. In the F160W images the faintest white contour corresponds to 14.0 H mag arcsec$^2$. For the optical images the faintest white contour is shown at 17.0 mag arcsec$^2$ where, magnitudes are given in Vega magnitudes for the particular filter shown (calibration from Whitmore 1995). The position angles of the image y-axes are listed in Table 2.

STSDAS package of IRAF, which uses an iterative method described by Jedrzejewski (1987). We also deconvolved our images with 20 iterations of the Lucy-Richardson method (from the STSDAS package of IRAF) to take into account the point-spread function of the telescope. For deconvolution we used a model point-spread function created by the program Tinytim (Krist et al. 1998) at the position of the nucleus of each galaxy on the camera. With the position of the PAM at best focus and during the observation set to 0.6 and using an F160W filter table. We then reran our ellipse fitting algorithm on the deconvolved images. The results of the ellipse fitting are shown in Figure 4.

The “Nuker Law” (e.g., Faber et al. 1997) was then fitted to the surface brightness profile derived from the deconvolved images. This profile is described by

$$I(r) = I_e 2^{(β−γ)/γ} \left(\frac{r}{r_h}\right) \left[1 + \left(\frac{r}{r_h}\right)^{γ−β}/α\right]$$

See J. Krist, & R. Hook 1997, The Tiny Tim User’s Guide, at http://scivax.stsci.edu/~krist/tinytim.html.
Here $I_b$ is the surface brightness at $r_b$ and the logarithmic slope inside the break radius $r_b$ is $-\gamma$ and that outside is $-\beta$. The parameters resulting from this fit are given in Table 2. Surface brightness profiles are classified as either "power-law" galaxies or "core" galaxies. To identify a galaxy as having a core we require that the absolute value of inner logarithmic slope be $\gamma < 0.3$ (e.g., Faber et al. 1997).

The fitted values of $r_b$ are meaningful only for the core profiles where they represent a physical change in the nature of the stellar distribution (see for example the discussion by Faber et al. 1997). The range of radii we fitted (10' from the nucleus) is comparable to that of the visible-band studies. These studies restricted the range of their fits because outside a radius of 10' a deVaucouleurs law might
WFPC2 images. See Fig. 2 caption for more information. The images are

A square.

we denote as a limit on the surface brightness at this radius. (5) For power-law galaxies only our angular resolution sets an upper limit on a radius inside which a shallow core could 

\( \beta \) (degrees east of north). (6) Exponents resulting from a fit to the "Nuker" surface brightness profile law. (7) Core break radius. (8) Position angle of F160W image y-axis (degrees east of north). (9) Mean major axis position angle (degrees east of north).

be a better description of the profile. The Nuker Law was used to fit Planetary Camera images and is intended precisely to fit over a short range of radius. However, the parameters resulting from such a fit are necessarily highly correlated. The quality of our fits is identical to that of Byun et al. (1996).

2.3.1. Comparison with Previous Visible-Band Fits

We have 14 galaxies in common with previous HST-based visible-band studies (Faber et al. 1997, Carollo et al. 1997, and Ferrarese et al. 1994). We compare the results of our fits (see Fig. 5) to those found from these previous studies. For the most part our break radii and exponents agree with those found from the previous studies. This suggests that a component of evenly distributed dust is not a likely explanation for the shallow central surface brightness profiles observed in core galaxies (as proposed by Silva & Wise 1996). NGC 2636 was excluded from this comparison since no break in surface brightness profile was listed by Faber et al. (1997). Outliers (or those galaxies with fitting parameters that grossly disagree with those found previously) mostly correspond to power-law galaxies where the measured break radii and inner exponent value are not particularly meaningful (in this case NGC 1172 and NGC 1331). We do find a small bias toward measuring smaller break radii from the well-resolved core galaxies in the NICMOS images compared to previous visible-band–based

![Fig. 3.—NICMOS 1.6 μm (F160W) images of galaxies lacking archival WFPC2 images. See Fig. 2 caption for more information. The images are 15' square.](image)

**TABLE 2**

| Galaxy     | Core Type | \( I_\text{lim} \) (mag arcsec\(^{-2}\)) | \( I_b \) (mag arcsec\(^{-2}\)) | \( \beta \) | \( \gamma \) | \( \alpha \) | \( r_b \) (arcsec) | ORIENTAT (deg) | PA Major Axis (deg) |
|------------|-----------|----------------------------------------|-------------------------------|------|------|------|-----------------|----------------|-----------------|
| NGC 0524   | \( \circ \) | 13.29                                  | 1.34                           | 0.25 | 0.93 | 1.10 | 21.67           | 165.57         |
| NGC 0821   | \( \circ \) | 10.72                                  | 1.14                           | 0.78 | 1.20 | 1.25 | 31.18           | 149.53         |
| NGC 1052   | \( \circ \) | 11.77                                  | 1.27                           | 0.18 | 2.16 | 0.44 | 56.81           | 143.89         |
| NGC 1172   | \( \circ \) | 11.35                                  | 1.26                           | 0.62 | 0.78 | 0.32 | 40.94           | 137.09         |
| NGC 1331   | \( \circ \) | 13.47                                  | 1.29                           | 0.57 | 3.44 | 2.91 | 89.30           | 16.40          |
| NGC 1351   | \( \circ \) | 11.42                                  | 1.31                           | 0.78 | 3.78 | 1.00 | 110.28         | 99.92          |
| NGC 1400   | \( \circ \) | 11.35                                  | 1.52                           | 0.35 | 1.06 | 0.86 | 57.53           | 100.87         |
| NGC 1426   | \( \circ \) | 11.18                                  | 1.28                           | 0.84 | 2.51 | 1.10 | 80.69           | 123.61         |
| NGC 1553   | \( \circ \) | 10.77                                  | 1.43                           | 0.74 | 3.82 | 5.72 | 59.74           | 30.26          |
| NGC 1600   | \( \circ \) | 11.46                                  | 0.91                           | 0.04 | 2.50 | 1.61 | 90.91           | 8.99           |
| NGC 2636   | \( \circ \) | 12.57                                  | 1.72                           | 1.03 | 1.26 | 3.61 | 133.51         | 46.49          |
| NGC 2907   | \( \circ \) | 10.99                                  | 1.78                           | 0.58 | 0.52 | 1.96 | 54.95           | 3.75           |
| NGC 3056   | \( \circ \) | 11.28                                  | 1.80                           | 0.90 | 2.07 | 4.11 | -72.14         | 165.14         |
| NGC 4150   | \( \circ \) | 11.05                                  | 1.17                           | 0.82 | 8.96 | 0.13 | 99.17           | 80.83          |
| NGC 4261   | \( \circ \) | 13.51                                  | 1.39                           | 0.16 | 2.47 | 1.85 | -94.05         | 165.85         |
| NGC 4278   | \( \circ \) | 12.70                                  | 1.40                           | 0.03 | 1.70 | 1.12 | 96.29           | 4.01           |
| NGC 4291   | \( \circ \) | 12.01                                  | 1.40                           | 0.11 | 2.21 | 0.44 | -169.46        | 84.16          |
| NGC 4374   | \( \circ \) | 13.17                                  | 1.49                           | 0.15 | 2.12 | 2.45 | -116.33        | 3.03           |
| NGC 4589   | \( \circ \) | 12.03                                  | 1.19                           | 0.09 | 1.51 | 0.28 | -179.16        | 102.36         |
| NGC 4636   | \( \circ \) | 14.20                                  | 1.33                           | 0.16 | 2.06 | 2.85 | -114.18        | 114.18         |
| NGC 5198   | \( \circ \) | 11.69                                  | 1.21                           | 0.88 | 1.29 | 0.17 | -136.71        | 81.71          |
| NGC 5845   | \( \circ \) | 10.72                                  | 1.30                           | 0.51 | 2.11 | 1.38 | -132.42        | 48.12          |
| NGC 5982   | \( \circ \) | 13.01                                  | 1.43                           | 0.19 | 1.07 | 0.80 | -162.04        | 72.04          |
| NGC 7052   | \( \circ \) | 13.50                                  | 1.19                           | 0.16 | 2.76 | 0.77 | -62.87         | 11.27          |
| NGC 7626   | \( \circ \) | 11.94                                  | 1.28                           | 0.15 | 2.79 | 0.51 | 6.38           | 162.12         |
| ESO507     | \( \circ \) | 12.49                                  | 1.26                           | 0.16 | 1.34 | 0.33 | -95.79         | 176.99         |
| A2052      | \( \circ \) | 14.26                                  | 1.50                           | 0.54 | 1.00 | 0.43 | -126.74        | 110.64         |

Note—Columns: (1) Galaxy. (2) Core classification. \( \circ \) refers to galaxies with core type surface brightness profiles. \( \backslash \) refers to galaxies with power-law profiles. (3) \( I_\text{lim} \) is the surface brightness at the break radius, \( r_b \), given in H mag arcsec\(^{-2}\) (calibration of the F160W images is from M. Rieke private communication). (4) For power-law galaxies only our angular resolution sets an upper limit on a radius inside which a shallow core could exist \( r_\text{lim} < 0.1 \). We denote \( I_\text{lim} \) as a limit on the surface brightness at this radius. (5)-(7) Exponents resulting from a fit to the "Nuker" surface brightness profile law. (8) Core break radius. (9) Position angle of F160W image y-axis (degrees east of north). (10) Mean major axis position angle (degrees east of north).
Fig. 4.—Results of ellipse fitting to the F160W 1.6 μm images. Solid triangles are from fits to the images before deconvolution, whereas open squares are from fits after Lucy-Richardson deconvolution. The B4 parameter corresponds to boxy isophotes when negative and disky isophotes when positive. The position angle is given with respect to a mean major axis position angle, which is listed for each galaxy in Table 2.

studies. We consider these cases: NGC 1600, NGC 4374, NGC 4261, and NGC 5845.

NGC 4374, NGC 4261, and NGC 5845 contain prominent dust features within their break radii. The visible-band images suffer from absorption in their central regions. This would result in measurement of a smaller break radius or a shallower central surface brightness profile. We do not feel that the discrepancy between our measured break radius for NGC 1600 is significant given that the parameters of the Nuker fit are highly correlated and that the NGC 1600 visible image used to measure surface brightness profile properties was not a WFPC2 image and so may be suffering from point-spread function artifacts. We find that dust features in the optical images are the main source of discrepancies of core classification and Nuker fitting parameters between our work and previous visible-band studies.

Figure 6 shows correlations from bulk elliptical galaxy properties (dispersion and effective radius) and a comparison between break radius and surface brightness at this radius with galaxy luminosity. As found in previous works (e.g., Faber et al. 1997 and references therein) the galaxies display a dichotomy: those with measurable core break radii and low break surface brightnesses correspond mainly to higher visual luminosity galaxies, and those with steep central profiles and high central surface brightness correspond to lower visual luminosity galaxies. We do see a
correlation between break radius and surface brightness at this radius (as proposed by Faber et al. 1997 and shown here in Fig. 7).

2.3.2. Classification between Core and Power-Law Galaxies

Our classifications agree in all cases with those previously found (from Faber et al. 1997, Ferrarese et al. 1994, and Carollo et al. 1997), except for NGC 7262, NGC 1400, and Abell 2052.

In NGC 7626 our fit to the F160W surface brightness profile results in $c_0 = 0.46$, $r_b = 0.5$. We therefore classify this galaxy as a power-law galaxy. However Carollo et al. (1997) classified it as a core galaxy based on WFPC2 F814W and F555W images. These images display a small warped dusty disk at $r < 0.45$, and consequently these authors note that their fit (with $\gamma = 0$, $r_b = 0.32$) is uncertain within $r < 0.45$. Since extinction from dust artificially lowers the central surface brightness it is likely that the NICMOS images are a better trace of the stellar surface brightness. This galaxy is likely to have the steep surface brightness profile typical of a power-law galaxy.

In NGC 1400, our fit to the F160W surface brightness profile results in $c_0 = 0.35$, $r_b = 0.85$. This value of $c_0$ is slightly above 0.3 that divides power-law from core galaxies. Faber et al. (1997) classifies it as a core galaxy (with $\gamma = 0$ and $r_b = 0.33$). In this particular case, the classification is uncertain.

Abell 2052 is quite distant and luminous, so we expect it to be a core galaxy. Though we do not resolve its break radius from our images, a shallow central profile was
Fig. 4.—Continued

Fig. 5.—Comparison of core fits from the 1.6μm (F160W) NICMOS images with fits from previous work on visible-band WFPC images (Faber et al. 1997; Carollo et al. 1997; Ferrarese et al. 1994) for galaxies in common. Dotted lines are drawn for a slope of 1. Lower left: comparison of break radii. Lower right: comparison of inner exponents. Dashed lines show the line separating core and power-law type cores. Upper right: comparison of outer exponents.
resolved in the WFPC2 images (Byun et al. 1996), which have slightly higher angular resolution than the NICMOS images. We therefore list it as a core galaxy.

2.4. Ellipticity and Boxiness Reduction near the Break Radius

In Figure 8 we show trends observed in ellipticity and boxiness near the break radius for the core galaxies. Core galaxies tend to exhibit a reduction in both boxiness (when boxiness is exhibited) and ellipticity between about two times the break radius and the break radius. No galaxy is observed to be boxy within its break radius. Many of the cores are well resolved, so this is not caused by smoothing due to the point-spread function. There are some galaxies that stand out from this pattern, however. NGC 7052 clearly contains a gas disk that is probably affecting measurement of the B4 component describing boxiness or diskiness. NGC 1600 gains ellipticity and has disky (positive B4) isophotes within its core. We suspect that this galaxy might contain a weak stellar disk.

Two processes are predicted to reduce ellipticity and boxiness: (1) the orbit stochasticity caused by the central black hole (Norman, May, & van Albada 1985; Gerhard & Binney 1985; Merritt & Valuri 1996) and (2) scattering from a binary black hole.

We consider whether the morphology change in the stellar isophotes near the break radius is consistent with the black hole scattering model for the formation of the cuspy or shallow core. Boxiness is a symptom of an uneven distribution function of stellar orbits in phase space (Binney & Petro 1985). In other words this function is peaked around orbits with a narrow range of shapes. A scattering process would be likely to smooth the distribution function in phase space and so reduce boxiness. After scattering, the angular momentum of a particle will have changed, so we expect the distribution of scattered stars to be closer to spherical. A population of scattered stars should therefore reduce both boxiness and ellipticity. A binary black hole will scatter stars at a particular mean escape velocity (e.g., Quinlan 1996) that depends on the binary semimajor axis and the...
binary mass ratio. This particular velocity should then manifest as a particular length scale over which a change in the isophote shapes is observed. This would naturally result in a particular range of radius over which we see a reduction in ellipticity and boxiness. This would correspond to the region of order a few times the break radius over which we observe the change in boxiness and ellipticity in these core galaxies.

We now discuss an alternate possibility whereby the isophote change is instead caused by the stochasticity induced by the black hole (Norman et al. 1985; Gerhard & Binney 1985; Merritt & Valuri 1996; Merritt & Quinlan 1998). This mechanism reduces triaxiality but would not likely account for such an association with the break radius or a large change in ellipticity as well as boxiness. We would expect this mechanism to result in a smooth isophotal shape variation with radius since the diffusion timescale is primarily dependent on the local dynamical time (Ryden 1999). Since we observe a shape change over a small region (a few times the break radius), we find that scattering from a black hole binary gives a more natural explanation for the isophotal shape changes observed near the break radius. However stochasticity induced by the central black hole would still be a natural explanation for smooth shape changes observed over larger scales (Ryden 1999; Bender & Saglia 1999).

2.5. Core Properties versus Dust Content

The ability to observe these galaxies at 1.6 μm allows us to study galaxies that were excluded from visible-band studies precisely because of their dust content (e.g., NGC 4150 was excluded by Faber et al. 1997 precisely for this reason). This allows us to investigate the possibility that core properties are related to dust or cold gas content. If dust is long-lived in elliptical galaxies, then a high dust content may indicate a previous gas rich merger which might have resulted in a binary black hole with more extreme binary black hole mass ratio and a smaller core or break radius. Alternatively if black hole coalescence requires gigayeors to take place (Begelman, Blandford, & Rees 1980) then we might expect recently formed elliptical galaxies to have growing cores, again suggesting that dusty galaxies should have smaller core or break radii. However,

Fig. 7.—Correlation between core radius and surface brightness at this radius. Points plotted for the power-law galaxies are limits only. Core galaxies are labeled “c,” and power-law galaxies are labeled “p.”

Fig. 8.—(a) We plot ellipticity for the core galaxies as a function of semimajor axis in units of core radius r_p. The thicker solid line is the average of all the galaxies shown as thinner lines. We see a trend for the ellipticity to drop in the region 1 ≤ sma/r_p ≤ 3 (where sma is the semimajor axis). (b) Boxiness (B4) as a function of semimajor axis for the boxy core galaxies. The thicker solid line is the average of all the galaxies shown. When B4 < 0 the isophotes are boxy. We see a trend for boxiness to be reduced in the region 1 ≤ sma/r_p ≤ 3.
Fig. 9.—Core properties vs. dust mass. Dust masses estimated from far-infrared IRAS fluxes are compared to $M_V$ and the core break radius $r_b$.

if an elliptical galaxy gains sufficient gas then star formation can occur within its core (e.g., NGC 7052), a process that might increase the central density and reduce the core size. However as we show in Figure 9 we see no correlation between dust content and core properties. For the power-law galaxies we have plotted lower limits for $r_b$. Data are taken from Tables 1 and 3.

2.6. Core Properties versus X-Ray Luminosity

We also investigate the possibility that X-ray luminosity may be related to elliptical core properties (see Fig. 10). X-ray and optical luminosities of early-type galaxies are
Virgo and Fornax Clusters (only)

Combined Sample

Fig. 11.—(a) Number of power-law (dotted histogram) and core galaxies (solid histogram) as a function of luminosity in the Fornax and Virgo clusters. For these moderately rich clusters there is a dichotomy of galaxy types that is a strong function of luminosity. However, it may be that the dichotomy is partly due to an inability to resolve the cores in the fainter galaxies. (b) Same as (a), but for the entire sample of galaxies from this work and that of Faber et al. (1997). The dichotomy is much less strong. However some of the overlap could be caused by the larger distribution of galaxy distances in this sample. The luminous power-law galaxies are mostly members of poorer groups.

TABLE 3

| Galaxy (1) | $M_V$ (mag) | log $r_c$ (log (pc)) | log $r_{lim}^{core}$ (log (pc)) | log $M_{dust}$ (log (M$_\odot$)) | log $L_B$ (log (ergs s$^{-1}$)) | log $L_X$ (log (ergs s$^{-1}$)) |
|------------|-------------|----------------------|----------------------------------|-------------------------------|--------------------------------|-------------------------------|
| NGC 524... | −21.4       | 2.09                 | 5.45                             | 43.77                         | 40.43                          |
| NGC 821.... | −21.3       | 2.24                 | 1.14                             | 5.97                          | 43.73                          |
| NGC 1052... | −21.0       | 1.66                 | 5.00                             | 43.63                         | 40.49                          |
| NGC 1172... | −20.7       | 1.66                 | 1.16                             | 43.50                         | 39.92                          |
| NGC 1331... | −18.4       | 2.49                 | 1.03                             | 42.60                         |
| NGC 1351... | −19.4       | 1.94                 | 0.94                             | 5.26                          | 43.01                          |
| NGC 1400... | −21.1       | 1.95                 | 1.02                             | 5.99                          | 43.59                          |
| NGC 1426... | −20.3       | 2.06                 | 1.02                             | 43.34                         |
| NGC 1553... | −21.5       | 2.65                 | 0.89                             | 4.69                          | 43.84                          |
| NGC 1600... | −22.7       | 2.59                 | 4.88                             | 44.26                         |
| NGC 2636... | −18.9       | 2.77                 | 1.21                             | 42.76                         |
| NGC 2907... | −20.2       | 2.39                 | 1.10                             | 5.65                          | 43.27                          |
| NGC 3056... | −18.8       | 2.41                 | 0.80                             | 42.77                         |
| NGC 4150... | −16.3       | 0.40                 | 0.29                             | 3.90                          | 41.82                          |
| NGC 4261... | −22.3       | 2.50                 | 4.42                             | 44.11                         |
| NGC 4278... | −21.2       | 2.00                 | 5.33                             | 43.65                         |
| NGC 4291... | −21.6       | 1.90                 | 4.42                             | 44.11                         |
| NGC 4374... | −21.6       | 2.26                 | 4.74                             | 43.85                         |
| NGC 4589... | −22.0       | 1.71                 | 5.53                             | 44.01                         |
| NGC 4636... | −21.7       | 2.33                 | 4.57                             | 43.86                         |
| NGC 5198... | −21.4       | 1.58                 | 1.36                             | 43.75                         |
| NGC 5845... | −19.9       | 2.28                 | 1.14                             | 43.13                         |
| NGC 5982... | −21.8       | 2.18                 | 6.12                             | 43.94                         |
| NGC 7052... | −22.9       | 2.36                 | 6.48                             | 44.35                         |
| NGC 7626... | −22.0       | 2.05                 | 1.34                             | 44.01                         |
| ESO507...... | −22.8       | 1.98                 | 44.33                           |
| A2052........ | −22.7       | 2.43                 | 1.79                             | 44.30                         |

Note—Columns: (1) Galaxy. (2) Absolute visual magnitude. (3) The log of the core break radius in pc from the Nuker fits listed in Table 2. (4) For the core galaxies, the log of the maximum break radius (in pc) for a shallow core based on an angular resolution of 0.1. (5) Dust mass derived from IRAS fluxes using the flux densities and relation given in Roberts et al. (1991) and the distances listed in Table 1. (6) The $B$-band luminosity ($u_B'$ at 0.44 μm) estimated from $M_V$ using $B - V$ colors from Faber et al. (1989) or from the RC3. (7) The X-ray luminosity in the energy range 0.5-4.5 kev from the Einstein IPC or HRI observations estimated from fluxes tabulated in Roberts et al. (1991).
correlated with $L_X \propto L_B^{2.0 \pm 0.2}$ (Eskridge, Fabbiano, & Kim 1995). However, the scatter about this relation is enormous, with $L_X/L_B$ varying by factors of 500. There are two approaches toward accounting for this large scatter: (1) evolution models for production of hot gas via supernovae (e.g., Ciotti et al. 1991) and (2) consideration of environmental effects such as ram pressure stripping (e.g., White & Sarazin 1991). In either scenario the formation and evolution of the core might be related, so we might expect a correlation between core properties and X-ray luminosity.

However, we fail to see any strong correlation between core properties and X-ray luminosity or $L_X/L_B$ (see Fig. 10). In our sample we find power-law galaxies with moderate X-ray fluxes, X-ray bright cluster ellipticals as well as luminous ellipticals with low X-ray fluxes. The lack of correlation suggests that the process of core formation is unaffected by whatever processes determine the X-ray luminosities of galaxies.

2.7. Core Properties versus Environment

Our sample combined with that of Faber et al. (1997) contain galaxies that span a range of environments from poor groups to moderately sized clusters such as the Virgo and Fornax clusters. We find poor galaxy groups with brightest members with cores (NGC 524) and poor groups with brightest members without cores (NGC 1553, NGC 2907, NGC 5198, NGC 821, NGC 1172, NGC 1400, NGC 7626). We have identified cluster membership based on compilations by Garcia (1993), Faber et al. (1989) and references therein. Almost all the brighter galaxies ($M_V < -20.5$) in Virgo and Fornax contain cores (see the histograms presented in Fig. 11). However, galaxies of this luminosity or greater without cores appear to be common in poorer environments (e.g., NGC 821, NGC 1172, NGC 1400, NGC 1553, NGC 1700, NGC 3115, NGC 4594, NGC 4697, NGC 5198). As we see in Table 3 and Figure 7 these are not primarily distant galaxies that would have cores that are unresolved (except possibly in the case of NGC 5198). Since the scatter from the fundamental plane for these galaxies (Faber et al. 1997) is much smaller than a magnitude, distance errors are unlikely to account for the difference in the histograms between the Virgo and Fornax cluster galaxies and the whole sample (Figs. 11a and 11b). This suggests that poor galaxy groups can harbor more luminous power-law galaxies than clusters (as first suggested by Faber et al. 1997 in footnote 9). This is an interesting possibility that should be investigated further with bigger samples.

3. SUMMARY AND DISCUSSION

In this paper we have presented a NICMOS imaging study of early-type galaxies. In moderately dusty galaxies these images allow us to measure stellar surface brightness profiles more accurately than possible with visible-band images, which are more strongly affected by extinction from dust. The few discrepancies between core classification and measurement of core properties between our NICMOS images and previous visible-band–based HST studies are primarily due to dust features in the nuclear regions of the galaxies. In most cases our classifications and parameters derived from them agree with those derived from visible-band–based studies. This suggests that a smoothly distributed component of dust is not a good explanation for the observed core/power-law dichotomy (as proposed by Silva & Wise 1996).

We observe a trend in boxiness and ellipticity in the core galaxies. Both boxiness and ellipticity are reduced near and within the break radius. No galaxy is observed to be boxy within its break radius. This is consistent with a core formation mechanism that involves scattering of stars, such as scattering from a binary black hole.

We failed to find correlations between core break radius and dust content or X-ray luminosity. This suggests that the current cold or hot gas content of an elliptical galaxy is unrelated to the process of core formation. The gas content is then more likely to be determined by processes, such as minor mergers and cooling flows, that would occur after the formation of the galaxy or core.

By combining our sample with that of Faber et al. (1997) we find that galaxies from the Virgo and Fornax clusters (together) show a dichotomy of core types that is strongly dependent on luminosity. However, the dependence of core type on luminosity may be weaker in the complete sample including galaxies outside of the Virgo and Fornax clusters. In particular, higher luminosity power-law galaxies may be more common in poorer environments. Since both core classification and cluster identification techniques are strongly dependent on the galaxy distance, care must be taken to ensure that the more luminous power-law galaxies are not the most distant. A larger sample of galaxies (such as is now available in the HST archives) could more thoroughly probe the relation between core properties and environment.

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