

Boxy isophotes, discs and dust lanes in elliptical galaxies

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Summary. CCD images of 42 elliptical and S0 galaxies are examined for low-contrast structures or subtle distortions of the isophotes from perfect ellipses. 75 per cent of the galaxies have isophotes completely describable as concentric ellipses to within the photometry errors. ‘Boxy’ isophotes, stellar discs, and dust lanes are detected in the remaining 25 per cent of the sample. The boxy elliptical galaxies appear dynamically indistinguishable from normal ellipticals and are therefore different from boxy bulges, which rotate rapidly. Most of the galaxies with faint discs, however, appear dynamically similar to S0 galaxies. Nearly edge-on dust lanes are found in four galaxies, which suggests that dust lanes may commonly occur in elliptical galaxies.

1 Introduction

Elliptical galaxies are so named for the appearance of their isophotes on photographic plates. Quantitative analysis of the isophote shapes shows that the superficial impression that isophotes are elliptical in functional form is accurate to a high degree. Indeed, most images of elliptical galaxies can be specified completely by fitting the isophotes with concentric ellipses, allowing the only free parameters to be the isophote surface brightness, position angle, and eccentricity (Carter 1978; Williams & Schwarzschild 1979). The picture presented is that the galaxies themselves can be described by radial stellar density profiles decreasing monotonically from their centres with ellipsoidal surfaces (of possibly varying axial ratios) of constant density. With the availability of high signal-to-noise CCD images of elliptical galaxies, however, it is now possible to search for any deviations real galaxies may show from this idealized picture. This paper presents such an examination of elliptical galaxies for ‘non-elliptical’ structures. This work was done as a sidelight to a programme to observe the core structure of elliptical galaxies (Lauer 1985, hereafter Paper I). Analysis of images obtained for this programme turned up many ‘normal’ elliptical galaxies with weak stellar discs, dust lanes, or slightly ‘box’ shaped isophotes. These structures are interesting as possible diagnostics into the structure and dynamics of elliptical galaxies.

Section 2 presents a summary of the observational material. Section 3 presents the procedures used to detect faint structures and isophote distortions in the galaxies, and discusses the nature of the structures so identified. Section 4 summarizes the results and conclusions of this paper.

2 Observations

Forty-two elliptical and S0 galaxies were observed for this project. A journal of observations is given in Table 1. As noted above, the sample was selected to observe the core structure of elliptical galaxies rather than to search for interesting structures within their envelopes; as such most of the objects are well-studied nearby ‘normal’ elliptical galaxies. Morphology classifications from the RSA (Sandage & Tammann 1981) or the RC2 (de Vaucouleurs, de Vaucouleurs & Corwin 1976) are given in Table 1. The S0 galaxies were so classified by the appearance of their envelopes rather than the presence of clearly visible stellar discs; these galaxies are either transition objects which strongly resemble elliptical galaxies, or S0₁ galaxies with high bulge-to-disc luminosity ratios.

A brief summary of the observations and their reduction is presented below – for a more complete discussion, the reader is referred to paper I. Images of the galaxies were obtained with CCDs mounted at the $f/17$ Cassegrain focus of the Lick Observatory Nickel 1-m reflector. The images were taken through a 6000–7000 Å bandpass filter. This spectral range corresponds both

Table 1. Journal of observations.

NGC	Type (RSA)	Type (RC2)	Boxy Isophotes	Stellar Disks	Dust Lanes
545	...	S0 ⁻	...	...	...
547	...	E1	...	...	...
584	S0 ₁	E4	...	×	...
596	E0	E2	...	...	...
636	E1	E3	...	...	...
720	E5	E5	...	...	...
741	E0	E0	...	...	...
821	E6	E6	...	×	...
1052	E3/S0	E4	...	...	×
1199	E2	E3	...	...	×
1395	E2	E2	...	...	...
1400	E1/S0 ₁	S0 ⁻	...	...	...
1407	E0	E0	...	...	...
1426	...	E4	...	...	...
1439	E1	E1	...	...	...
1453	E2	E2	...	...	...
1600	E4	E3	×	...	...
1700	...	E4	...	...	...
3379	E0	E1	...	...	...
4261	E3	E2	×	...	...
4365	E3	E3	...	...	...
4374	E1	E1	...	...	×
4406	S0 ₁ /E3	E3	...	...	...
4472	E1/S0 ₁	E2	...	...	...
4552	S0 ₁	E0	...	...	...
4621	E5	E5	...	×	...
4636	E0/S0 ₁	E0	...	...	...
4649	S0 ₁	E2	...	...	...
4742	E4	E4	...	...	...
5845	...	E3	...	×	...
5846	S0 ₁	E0	...	...	...
6086	...	E2	...	...	...
6702	...	E3	...	...	×
6703	...	S0 ⁻	...	...	...
7052	...	E4	...	...	...
7454	...	E4	...	...	...
7457	S0 ⁻	S0 ⁻	...	...	...
7562	...	E2	...	...	...
7619	E3	E2	...	...	...
7626	E1	E1	...	...	...
7768	...	E2	...	...	...
7785	E5	E5	×	...	...

to the darkest part of the night sky spectrum and the highest sensitivity of the CCDs. Most images were obtained with a thinned, rear-illuminated Texas Instruments 500×500 pixel CCD. A 135-mm camera lens was used with this chip to reduce the plate scale to $0.432 \text{ arcsec pixel}^{-1}$ and to provide a full field of $3.6 \times 3.6 \text{ arcmin}^2$. The observations were completed with a General Electric Corporation 576×386 pixel CCD. This chip had larger pixels than the TI chip, and was used without the camera lens for a plate scale of $0.267 \text{ arcsec pixel}^{-1}$ and a $2.6 \times 1.7 \text{ arcmin}^2$ field. Images taken with both chips always had a minimum detected signal of $10^4 \text{ photons pixel}^{-1}$ in the centre of the galaxy, and often exceeded this level by a factor of two. The exposure level of the sky background was well above the regime in which charge transfer inefficiencies dominate the CCD response. The median seeing for the sample was 1.69 arcsec FWHM .

All image reductions were done with VISTA (Lauer, Stover & Terndrup 1983) on Lick Observatory's VAX 11/780 computer. The first step in the reductions was to apply corrections for non-linear response to low light levels. Dome 'flat-fields' and blank sky images were then used to remove sensitivity variations across the chips. In practice, residual sensitivity variations across an image could be reduced to about 3 per cent of the night sky background level. The sky levels of the images were measured with a histogram estimator algorithm. The median sky level for the sample was $19.54 \text{ } R \text{ magnitudes per square arcsec}$.

Surface photometry profiles were measured for the galaxies by fitting the isophotes with concentric ellipses. The isophote measuring algorithm was based on a program written by Steven Kent (1983). The centre of the isophotes was taken to be the centroid of the core. Isophotes were then measured for each integral pixel step in isophote major axis length. Although the centres of the isophotes were fixed, their intensities, eccentricities, and position angles were allowed to be arbitrary. The isophotes were typically measured out to 40 arcsec from the cores; the surface brightnesses of the galaxies were typically 1.5 mag below the sky level at this point. For most galaxies in the sample this means that the results presented here pertain to only their central regions.

3 Non-elliptical structures

3.1 DETECTION OF NON-ELLIPTICAL STRUCTURE

The galaxies were examined for non-elliptical structures by comparing their original images to images reconstructed from their surface photometry profiles. The reconstructed images were faithful to the measured isophote brightness, position angle, and ellipticity profiles but had perfectly elliptical and concentric isophotes. The reconstruction algorithm was originally developed as a first step in the seeing deconvolution of the images, and is described in Paper I; its use here permitted direct testing of the assumptions of perfectly elliptical and concentric isophotes. In practice, this was done for a given galaxy both by dividing its original image by its reconstruction and by subtracting the two. Galaxies matching the ideal would have flat residual images, while any non-elliptical structures present in the original image would show up cleanly against a smooth background. The division procedure was judged to be the best way to look for faint structures near the bright centres of the galaxies, as it worked best where the relative effects of shot noise on the pixel intensities were small. The subtraction comparison worked best in the fainter envelopes but failed near the centres, where the *absolute* contribution of shot noise was large. The division-residual image could also be smoothed to look for structures in the envelopes. Both comparison procedures were judged to be greatly superior to alternative schemes for looking for structures, such as comparing the original images to smoothed images or simple models, as the current procedures cleanly removed the underlying luminosity gradients of the galaxies on all spatial scales.

The major finding of the comparisons is that the great majority (75 per cent) of the galaxies are well described by concentric elliptical isophotes and show no detectable structures or coherent deviations from this idealization to 1 to 3 per cent of their surface brightnesses at any point. Quantitative limits on deviations of the isophotes from perfect ellipses are discussed below; the isophotes appear to be concentric in all galaxies to within 0.2 arcsec. This number is actually fairly large, considering that the sharp intensity gradients in the cores make it easy to see any shifting of the isophotes' centres; unfortunately, systematic effects prevent further reduction of this limit. As discussed in Paper I, the PSF (Point Spread Function) had asymmetric wings which caused the centroid of the cores to be slightly offset from that of their envelopes, which would obscure any weak intrinsic non-alignment of the isophote centres.

In the remainder of the sample, the comparisons reveal the presence of dust lanes, stellar discs, and slightly 'boxy' isophote shapes, although, in all cases, the structures are small perturbations on the underlying galaxy and have little effect on the surface photometry profiles. These three types of structures are discussed below.

3.2 BOXY ISOPHOTE SHAPES

Three galaxies, NGC 1600, 4261, and 7785, are found to have slightly 'box-shaped' isophotes. The nature of their isophotes are clearly visible in the original images; a contour map of best example, NGC 7785, is presented in Fig. 1. Comparison of these images to their reconstructions highlights the deviations from perfectly elliptical isophotes and shows that the residuals form a

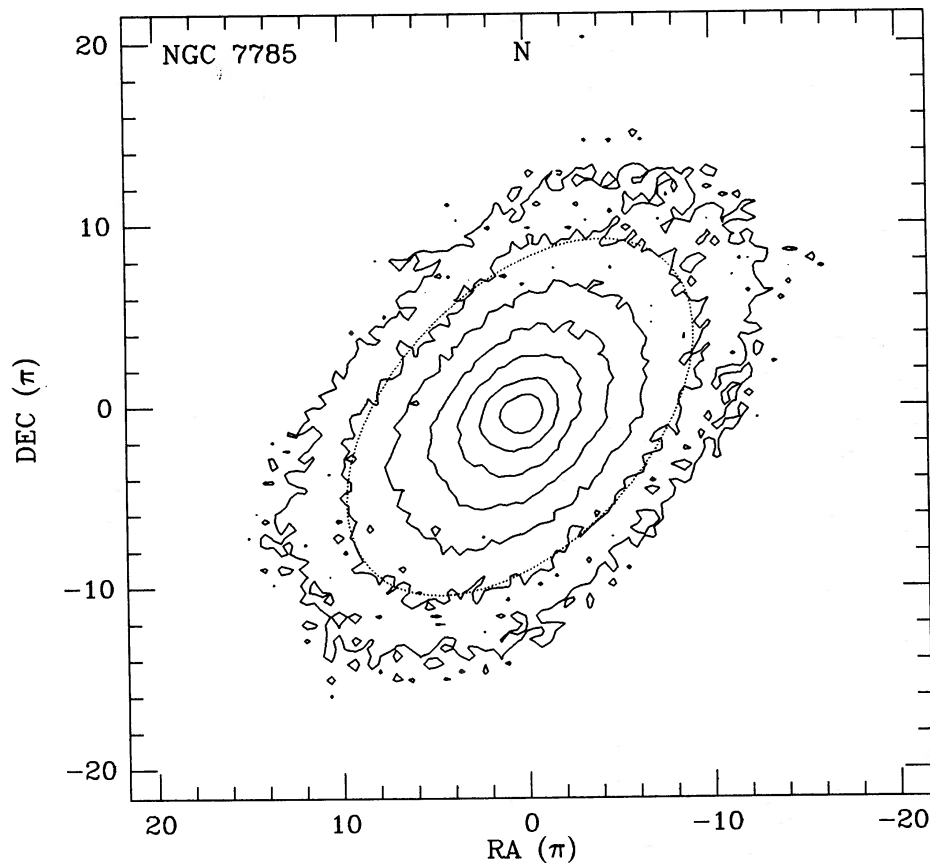


Figure 1. Contour map of NGC 7785. Contours are spaced $0.5 \text{ mag arcsec}^{-2}$ apart. The dotted line is the best-fitting ellipse to the $19.0 \text{ R mag arcsec}^{-2}$ isophote. The observed isophote extends beyond the ellipse at positions midway between the major and minor axes; this is especially visible on the north-east side of the galaxy.

global pattern. As discussed below, 'boxy' isophotes in elliptical galaxies are interesting in the context of current studies which seek to understand the structural and dynamical differences between ellipticals and the bulges of S0 and spiral galaxies. Briefly, boxy isophotes have come to be associated with large amounts of rotation (see below) and have not been seen previously in elliptical galaxies.

As discussed in Paper I, the position angle and eccentricity of the ellipse best fitting a given isophote are calculated iteratively from the second Fourier harmonics of the pixel intensities falling about an initial estimate of the isophote. The fourth Fourier harmonics then account for low-order distortions of the isophote from the best fitting ellipse. Boxy isophotes in particular are well described by superimposing a 4ϕ cosine-wave on top of an ellipse, but 180° out of phase with the major and minor axes. That is, the 'boxy' shape is caused by pulling the isophote in towards the centre of the galaxy on the major and minor axes, but pushing it out 45° in between. The isophote measuring procedure actually calculates the fourth Fourier components based on how much the galaxy surface brightness rises above and falls below the average surface brightness of the ellipse as a function of polar angle. The fourth cosine coefficient of a given isophote, B_4 , is converted into an equivalent measure of the relative *radial* non-ellipticity deviations of the isophote, δ_4 , by the relationship

$$\delta_4 = \frac{-B_4}{I\gamma}, \quad (1)$$

where I is the isophote surface brightness, and γ is the slope of the logarithm of the semi-major axis surface brightness profile evaluated at the isophote.

Most programme galaxies have both fourth cosine and sine coefficients amplitudes less than 1 per cent of the local isophotal intensity, which translates into radial non-ellipticity measures of less than 0.5 per cent or so. The three galaxies listed above, however, have B_4 amplitudes of over 2 per cent and resulting δ_4 values of over 1 per cent. Their fourth sine coefficients are also much smaller than the cosine coefficients, which is consistent with boxy isophote shapes. The values of δ_4 for these galaxies are presented in Table 2 as a function of isophote semi-major axis. The tabulated values represent the averages of successive bins of 10 isophotes; the errors given are standard deviations of the mean. No δ_4 values are given for the other galaxies (with the exception of NGC 3379 and the galaxies with discs) as many of the galaxies appear to suffer from variable systematic errors at low levels of B_4 (0.5 to 1 per cent) and show no dominance of the cosine over the sine coefficients. (It should be remembered that the present 'boxy' galaxies were selected by visual inspection rather than by large B_4 coefficients.) It is interesting to note that some galaxies do appear to have zero B_4 values within errors due purely to photon shot noise. NGC 3379 is selected as one such elliptical galaxy that appears to be perfectly elliptical. Its δ_4 values given in Table 2 indicate that its isophotes are elliptical to 1 part in 1000; non-ellipticities seen in the present boxy galaxies are an order of magnitude larger.

Table 2. Semi-major axis non-ellipticity profiles.

NGC	$\delta_4 \times 100$				
	6"5	10"8	15"1	19"4	23"8
584	0.2 ± 0.1	0.0 ± 0.1	0.7 ± 0.2	0.8 ± 0.2	0.6 ± 0.2
821	1.0 ± 0.1	1.5 ± 0.1	2.9 ± 0.2	3.1 ± 0.1	2.6 ± 0.2
1600	-0.6 ± 0.2	-1.4 ± 0.1	-1.5 ± 0.1	-0.9 ± 0.2	-0.4 ± 0.1
3379	0.1 ± 0.1	0.1 ± 0.1	0.0 ± 0.1	0.1 ± 0.1	0.0 ± 0.1
4261	-1.9 ± 0.1	-1.7 ± 0.2	-1.3 ± 0.2	-1.4 ± 0.1	-1.2 ± 0.2
4621	1.8 ± 0.2	1.6 ± 0.2	1.2 ± 0.2	2.3 ± 0.2	1.3 ± 0.3
5845	-0.5 ± 0.1	-0.1 ± 0.1	1.9 ± 0.2	2.3 ± 0.1	2.8 ± 0.3
7785	-1.5 ± 0.2	-2.3 ± 0.2	-1.9 ± 0.4	-2.3 ± 0.4	-0.9 ± 0.3

Previous to this study, there were no known elliptical galaxies with clearly boxy isophotes. Carter (1978) reported non-zero B_4 coefficients for some of the elliptical and cD galaxies in his sample, but the significance of his results is difficult to assess. No contour plots were presented for such galaxies and the purely statistical errors in the coefficients are not much smaller than their absolute values. Bulges of S0 and spiral galaxies often have readily discernible boxy isophotes, on the other hand; an extreme example of a box-shaped bulge can be found in NGC 128, in which the 4ϕ cosine components of the isophotes are so strong that the galaxy is indented along the minor axis, giving the bulge a 'peanut'-shaped appearance (Sandage 1961). Recent dynamical studies of bulges (*cf.* Kormendy & Illingworth 1982) further suggest that such box-shaped isophotes occur in rapidly rotating bulges, where the bulge appears to rotate differentially along concentric cylinders. Kormendy & Illingworth, for example, show the rotation of the box-shaped bulge of NGC 4565 to continue undiminished to large distances above the central plane of the bulge. This behaviour is also seen in the box-shaped bulge of NGC 1381 (Davies & Illingworth 1985, in preparation).

Observations suggest that rapid cylindrical rotation is not associated with the current set of boxy ellipticals, however, as none of these galaxies can be considered to be oblate rotators with isotropic velocity dispersions (although no observations have been made above or below the major axes to test this directly). Schechter & Gunn (1979) detected no rotation in NGC 1600, for example, and the rotation they did find in NGC 7785 is only half the amount needed to support the shape of the galaxy if it has an isotropic velocity field (Davies *et al.* 1983). Jenkins (1981) further finds that NGC 4261 appears to rotate about its *minor* axis (although the errors are large). It is also noteworthy that this study finds no discs visible in any of the three galaxies [although Barbon *et al.* (1984) find NGC 4261 to have an exponential light profile at faint isophotal levels], in contrast to the suggestion by Davies & Illingworth (1983) that box-shaped structures are uniquely associated with discs.

It may be that box-shaped structures can be associated with even small amounts of rotation, however presently available dynamical data reveal no significant differences between boxy and normal elliptical galaxies. NGC 720, for example, is nearly as eccentric as NGC 7785 and derives nearly as much support from rotation as does NGC 7785 (Davies *et al.* 1983) but appears to have completely elliptical isophotes to within 0.5 per cent or less at all radii. An explanation of boxy isophotes advanced by Binney & Petrou (1985), however, suggests a way around this objection. These investigators propose that boxy isophotes are created by the slow cannibalism and orbital decay of relative low luminosity galaxies into a host bulge or elliptical. The high orbital angular momentum of the stars initially associated with the cannibalized galaxy causes them to populate highly a small portion of action space in the host. The subsequently overpopulated box orbits in the host give rise to the boxy isophotes. When the cannibalized galaxy is luminous enough, its residual orbital angular momentum also gives rise to the appearance of rapid cylindrical rotation. Less luminous galaxies may produce the subtle isophote perturbations seen here without grossly affecting the host's dynamics. In this case, the only difference between the boxy and normal ellipticals is that the former galaxies have cannibalized low-luminosity systems. The cannibalism origin of boxy isophotes is also interesting since the only common structural property of the boxy ellipticals other than their isophote shapes is that they are among the more luminous galaxies in the sample. On the other hand, two galaxies in the sample, NGC 1395 and 4552, are found to have shells in their envelopes (Malin & Carter 1983), which means they may have recently cannibalized cold galactic discs (Quinn 1982), but appear to have perfectly elliptical isophotes. Further, if the cannibalism picture is correct, then one might expect to find rapidly rotating and strongly boxy spheroids without discs; so far, such objects have not been seen. In any event, more observations are needed; the shell catalogue of Malin & Carter presents a set of elliptical galaxies which might be checked further for boxy isophotes.

3.3 STELLAR DISCS

Four galaxies, NGC 584, 821, 4621, and 5845, show signs of stellar discs. A contour map of the best example, NGC 821, is presented in Fig. 2. The discs in all four galaxies are difficult to make out in the original images but are visible as subtle ansae along the isophote major axes. In all four galaxies the disc luminosity is much smaller than the bulge luminosity; only NGC 584 has been classified as an S0 (Sandage & Tammann 1981) on the basis of its morphology. No decomposition of the galaxies into separate bulge and disc components is attempted, but in NGC 584, 821, and 5845, the discs can be traced out to the last isophote measured. The discs in these three galaxies have significant breadth, although whether this is due to their inclination or intrinsic thicknesses is not known. The disc in NGC 4621 is quite thin and can be traced out to only 25 arcsec in radius. Its surface brightness is also extremely low, only about 2 per cent of the local surface brightness of the underlying galaxy.

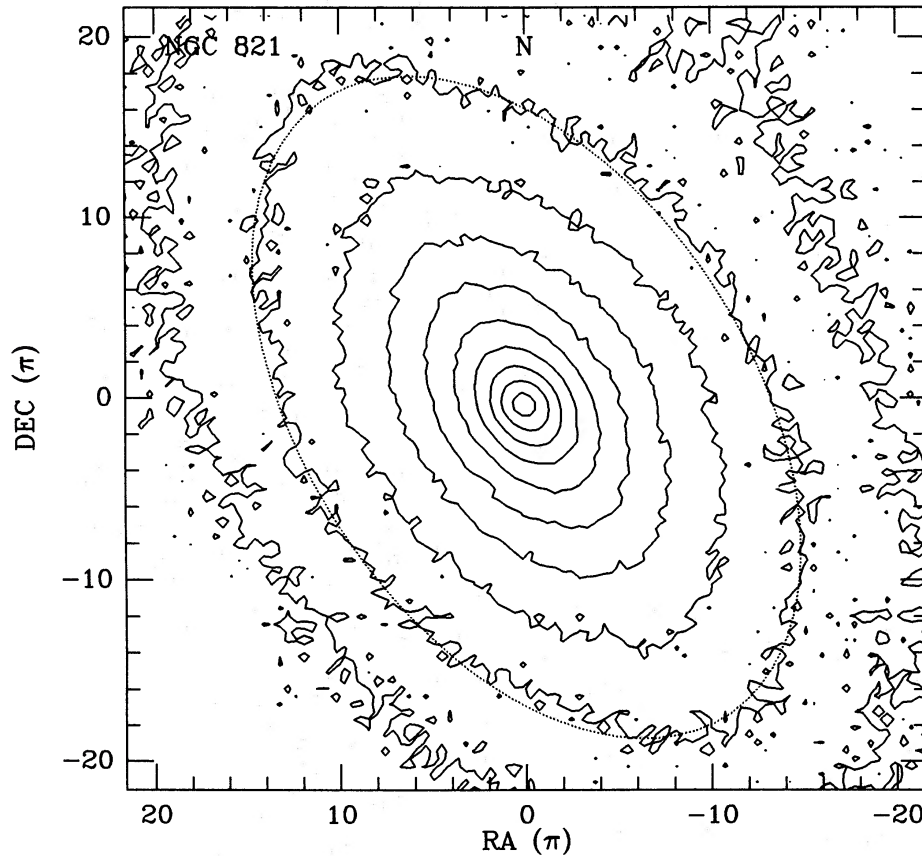


Figure 2. Contour map of NGC 821. Contours are spaced $0.5 \text{ mag arcsec}^{-2}$ apart. The dotted line is the best-fitting ellipse to the $19.5 \text{ mag arcsec}^{-2}$ isophote. The disc is visible as ansae in the observed isophote along the major axis of the best fitting ellipse.

The presence of the discs is more visible in the residuals of the original versus reconstructed image comparisons and in the B_4 coefficients of the isophote fits presented in Table 2. The B_4 values have opposite signs from those of the boxy ellipticals, as expected, since a disc causes the isophotes to bulge outward along the major axis when compared to a perfect ellipse, while a box shape pulls the isophotes in. It should be noted, however, that the B_4 coefficients cannot completely specify the distortion of the isophotes due to a disc, especially if the disc is thin. The discs in the four galaxies listed above only affect the isophotes close to their major axes; a complete specification of the isophote shapes would require yet higher Fourier harmonics. That

is, the discs appear to be distinct components apart from the underlying spheroids, rather than being global distortions of the spheroids themselves. In contrast the global isophote shape of the boxy elliptical galaxies is well described by a 4ϕ cosine wave superimposed on an underlying ellipse.

The direct detection of discs in NGC 584, 821, and 5845 is interesting in the context of the recent dynamical studies of Dressler & Sandage (1983), Davies *et al.* (1983), and Davies & Illingworth (1983). All of these investigators find the three galaxies to be consistent with the dynamics of isotropic oblate rotators and suggest that they might be S0 galaxies on the basis of their dynamics alone. NGC 4621, on the other hand, shows only a modest amount of rotation (Peterson 1978) and therefore has dynamics more appropriate to elliptical galaxies. NGC 4621 does stand out in the present sample, however, on the basis of its extremely sharp core ($r_c < 64$ pc) when compared to galaxies of the same luminosity. This disc, therefore, may be an example of Larson's 'incipient discs', which he finds associated with compact cores in his highly dissipative galaxy formation models (Larson 1975).

3.4 DUST LANES

Dust lanes are found in four galaxies, NGC 1052, 1199, 4374, and 6702. Diameters, position angles, and inclinations of the dust lanes are presented in Table 3. The position angles are accurate to about 6° , and the inclinations to about 50 per cent. No optical depths are given for the lanes; the absorption of light by the dust is 10 per cent or less for all of the lanes, but the lanes are quite thin and are probably strongly smeared out by seeing. The dust lane in NGC 4374 is well

Table 3. Dust lanes.

NGC	Major-Axis Diameter	Position Angle	Inclination
1052	18"	31°	7°
1199	13"	52°	8°
4374	12"	82°	7°
6702	17"	143°	5°

known, having first been reported by Wade (1960), the dust in NGC 1052 has been seen before by Knapp, Gallagher & Faber (1978), and the dust in NGC 1199 is discussed by Nieto (1983); the detection of dust in NGC 6702 appears to be original to this study. It is interesting to consider the possibility that dust lanes are ubiquitous in elliptical galaxies; the lanes in the present galaxies appear to be nearly edge-on and the images were taken in the red and therefore poorly suited for detecting dust.

Comparison of the position angles of the dust lanes to that of the galaxies shows that the only dust lane aligned with the galaxy major axis is in NGC 1199; the dust lanes in NGC 1052 and NGC 6702 are aligned with the *minor* axes. The dust lane in NGC 4374 is not aligned with either the major or minor axis and has been investigated by van Albada, Kotanyi & Schwarzschild (1982) in the context of plausible triaxial models of NGC 4374.

4 Conclusion

The most important result from this study is to refine and extend to a larger sample the findings of Carter (1978) and Williams & Schwarzschild (1979) that most elliptical galaxies have accurately elliptical and concentric isophotes. Besides constraining the true figure shapes of elliptical galaxies, this result also provides a point of departure for investigating merging or interacting ellipticals by characterizing the isophote structure of undisturbed ellipticals. This result not

withstanding, however, a number of ellipticals have boxy isophotes, weak stellar discs, and dust lanes. These features are most easily found by comparing high signal-to-noise CCD images of elliptical galaxies to idealized images reconstructed from their surface photometry.

The boxy ellipticals seen here appear to be dynamically different from boxy bulges, which exhibit rapid cylindrical rotation, but dynamically indistinguishable from ordinary ellipticals. It may be difficult, therefore, to explain this phenomenon by the effects of rotation alone. Binney & Petrou (1985) have proposed that boxy isophotes may occur in systems that have cannibalized low-luminosity galaxies. This mechanism is an attractive explanation for the boxy ellipticals identified here; the boxy isophotes result from a minor perturbation to an otherwise dynamically normal elliptical galaxy. Further, all three galaxies are highly luminous, which makes them more likely to have cannibalized less luminous systems. It is unclear, however, if cannibalism can account for the entire set of boxy spheroids known. The extreme cases of boxy spheroids are always associated with discs (Davies & Illingworth 1983) and there are no known examples of rapidly rotating boxy ellipticals without discs. Since cannibalism takes place when the host galaxy interacts with an external galaxy, the presence of a disc should be irrelevant.

Weak stellar discs are seen in four galaxies. Three of this set have kinematics appropriate to S0 galaxies. NGC 4621, however, appears to be a normal elliptical galaxy. Its disc may be an example of Larson's incipient discs which appear in his highly dissipative models (Larson 1975); the extremely compact core in this galaxy suggests that a prolonged process of gaseous dissipation took place during its formation.

Dust lanes are seen in four galaxies. the orbital planes of the dust in these galaxies are all nearly parallel to the line-of-sight. Such a strongly biased result raises the possibility that dust lanes may be fairly common to elliptical galaxies. The missing dust lanes with more inclined orbital planes may be washed out by intervening starlight. Further, the present images were taken in the red and were therefore poorly suited for the detection of dust.

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