ISOPHOTE SHAPES

R. I. Jedrzejewski
Mount Wilson and Las Campanas Observatories
813 Santa Barbara Street
Pasadena
CA 91101

ABSTRACT. The shapes of the isophotes of elliptical galaxies are discussed. Ellipticity and position angle variations with distance from the centres of galaxies are described, as well as deviations from perfectly elliptical shape. The factors contributing to these deviations, in particular edge-on disks and boxiness, are described and portrayed.

1. INTRODUCTION

As their name suggests, elliptical galaxies are characterised by having isophotes that are very closely elliptical. With this in mind, I will first discuss what we can learn from the ellipse parameters of galaxies, and then describe in what ways the isophotes deviate from this simple picture.

2. ELLIPSE PARAMETERS OF ISOPHOTES

2.1. Ellipticity Variations with Radius

Firstly, it has been known for some time that the ellipticities of the isophotes of elliptical galaxies vary with radius, sometimes strongly so. Many types of behaviour are found (Figure 1), including nearly constant ellipticity (IC 4296), a sharp rise to approximately E4 shape followed by a decline outside roughly 1 effective radius (eg NGC 2865, NGC 3377, NGC 4387), a change from E2 in the central regions to almost round in the outer parts (NGC 3311, NGC 4374) and more complex behaviour (NGC 3923, NGC 4976). Most galaxies seem to fall in the last of these categories.

2.2. Isophote Twists

Recently, the phenomenon of variations of the position angle of the isophotes with radius has been observed, and this has been ascribed to

T. de Zeeuw (ed.), Structure and Dynamics of Elliptical Galaxies, 37–46.

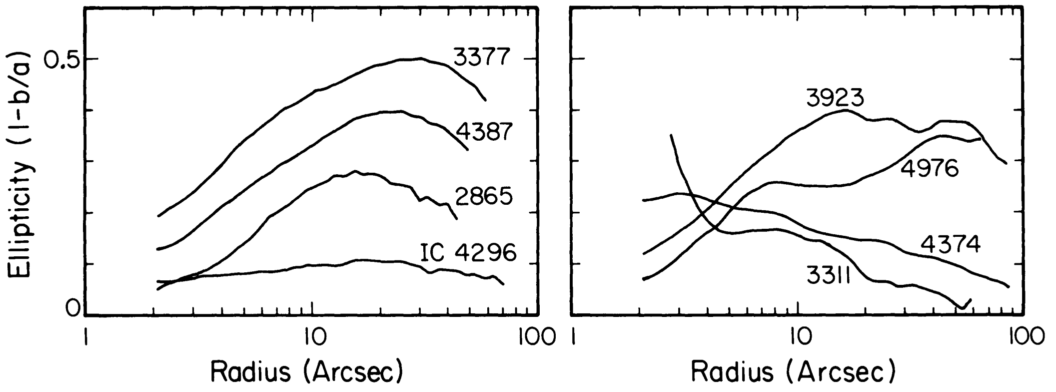


Figure 1. Ellipticity profiles of selected NGC and IC galaxies.

the intrinsic shapes of the galaxies being triaxial. This subject has been nicely described in Mihalas & Binney (1981) and Kormendy (1982).

Note that in the triaxial hypothesis, an isophote twist will only be observed if the axis ratios change with radius, and that no twist will be observed if the galaxy is viewed along any of its principal planes. Also, if the axis ratios change slowly with radius, then we should expect to find few galaxies that are very flattened and have substantial twists (but see Williams, this conference). Observationally, this is found to be the case, which lends support to this combination of hypotheses, but it should be noted that this is not the only model to explain this phenomenon.

Kormendy (1982) argues that some of the observed twists may be tidal in origin, and Gerhard (1983) has produced an N-body model from a merger event with isophote twists that are due to the intrinsic axes of the figure pointing in different directions at different radii, which is stable over many dynamical times. It seems likely that most galaxies are triaxial, but some of the observed twists are possibly due to other effects, such as interaction with a massive neighbour - see, for example, the photograph of M32 in Kormendy (1982).

Note that if ellipticals are triaxial, then these 2 phenomena, ellipticity variations and isophote twists, are caused by the same effect: variations of the intrinsic axial ratios of the triaxial isodensity surfaces with radius. What causes such variations? The models of Wilson (1975) appeared to show convincingly that the variations were linked to rotation, but the discovery that most bright ellipticals do not owe their global shapes to rotation but instead to velocity anisotropies implies that the local shapes are probably anisotropy-driven. For fainter galaxies that are more consistent with isotropic oblate rotators (Davies et al. 1983), Wilson's models are likely to be closer to the truth.

2.3 Examples

Williams (1981) modelled the complex photometric and dynamical behaviour of NGC 596 using a triaxial model, and found three-dimensional models that reproduce the observed behaviour and

https://doi.org/10.1017/S0074180900185043 Published online by Cambridge University Press

that would appear relatively normal whichever direction they are viewed from. Since NGC 596 is one of the most twisted galaxies known, other galaxies can probably be fit by even milder triaxial models.

Another galaxy that has a strong twist is NGC 1549, shown in Figure 2. The ellipticity is approximately constant at 0.1, while the position angle twists through about 40 degrees from 5 arcseconds to 60 arcseconds. Note also that the isophotes are not perfectly elliptical, inside 30 arcseconds they are slightly boxy (0.5 to 1% or so) while outside this they have a bar-like perturbation of about the same amplitude. White (1983) describes some structural properties of galaxies formed by merging in N-body simulations; these include box-shaped isophotes (Quinn 1982) for disk-disk mergers and bar-like perturbations if the merger is between spherical progenitors in an oblique collision. Most simulated merger remnants seem to be triaxial and hence may show isophote twists. Malin and Carter (1983) have produced a picture of a shell structure common to NGC 1549 and NGC 1553, only 8 arcminutes distant, so it is clear that some interaction has occurred (or is occurring) between the 2.

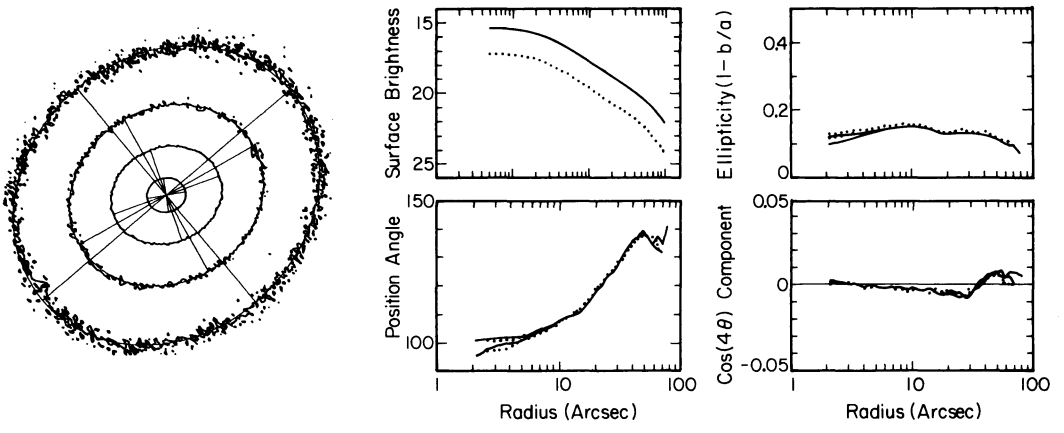


Figure 2. a) Contour map with major and minor axes overlaid and b) surface photometry diagrams for NGC 1549. The solid lines refer to the R band, dotted lines to B.

2.4. Overall Shapes

There are two limiting cases of apparent shape that are seen rarely or never: very flattened galaxies (>E7) and very round objects. My thesis data on 49 ellipticals produced only 2 galaxies that are rounder than E1 at all measured radii (5-100arcsec), and Lauer's (1985a) sample gave only 2 round galaxies out of 42. Similarly, there are <u>no</u> galaxies flatter than E7 that have no disk component. I have also found that very flattened galaxies (>E4.5) almost never have isophotes that are perfectly described by ellipses - either the isophotes are slightly pointed along the major axis, as in NGC 4697,

https://doi.org/10.1017/S0074180900185043 Published online by Cambridge University Press

or else they are slightly boxy (eg NGC 6909). These observations indicate that some dynamical processes conspire to inhibit the longevity of very round and very flattened objects, and recent theoretical work on bar instabilities in spherical galaxies with radial anisotropy (Barnes et al. (1985), Merritt and Aguilar (1985)), and on the fire-hose instability in flattened galaxies (Fridman and Polyachenko 1984) is providing fresh insight into the distribution of apparent shapes.

3. DEVIATIONS FROM PERFECT ELLIPSES

The quality of data has now reached the point where we can begin to look for departures from elliptical shape in the isophotes of elliptical galaxies. In particular, CCD's allow investigation of the shapes in the central regions that are not reliably measurable using photographic plates.

3.1. Types of Deviation

What can cause the isophotes of elliptical galaxies to appear non-elliptical? The most obvious agent is dust. Whether in grand dust-lanes (as in Cen A) or more 'blobby' structure (as in NGC 4696) or filaments (Fornax A), dust can certainly alter the shapes of the isophotes of elliptical galaxies. A recent survey by Sadler and Gerhard (1985) indicates that as many as 40% of elliptical galaxies may have dust, although several recent CCD studies (Sparks et al. (1985), Lauer (1985b), Jedrzejewski (1985)) indicate lower numbers of about 20-30%. One notable feature of dust absorption is that it affects blue light more than red, so the ratio of a red image to a blue one will, if the signal-to-noise ratio is high enough, map out the distribution of reddening material. Since dust will be covered by others in these Proceedings, I will say no more about it.

A second cause of non-elliptical isophotes is an edge-on disk component. If the galaxy is mistakenly classified as an elliptical (on the basis of its light profile in the outer parts when the central regions are saturated), but is in fact an edge-on S0 galaxy, the isophotes will show points along the major axis, rather like a lemon. As the galaxy is tilted to become more and more face-on, the points will become softer and softer, and finally disappear from view. The true nature of the galaxy will then be hidden, unless the bulge-to-disk ratio is very small and the disk close to exponential, when we might learn the type from study of the luminosity profile.

Thirdly, we have the phenomenon of 'boxy isophotes'. This term was coined to describe the isophotes of, among others, the bulge of NGC 128. In this case the isophotes look more like an athletics track, consisting of curved ends connected by long 'straights'. It has been found that box-shaped bulges are relatively common in spiral and S0 galaxies (see Jarvis 1986), but not seen up till recently in elliptical galaxies. This has been used as evidence that ellipticals and bulges are different types of animal (Illingworth 1983), but the recent discovery of boxy isophotes in ellipticals negates this.

Lastly, there is the observation that many galaxies show 'shells' or 'ripples'. These appear as sharp edges in the brightness profiles at large distances from the centre of the galaxy, and have been extensively modelled by Quinn. Since they will probably be mentioned at length during this Symposium, I will leave discussion to those more familiar with the subject.

3.2. Displaying the Deviations

The best way to study the small departures from ellipses in the isophotes of elliptical galaxies is to use the fact that the isophotes are, in fact, close to being elliptical. If the ellipse parameters of the isophotes are measured using one of the many fitting programs available (Cawson's PROF, Lauer's VISTA, etc), these numbers can be used to make a noise-free reconstruction of the galaxy that has perfectly elliptical isophotes. The procedure involves making a 'CCD frame', where for each pixel (i,j), one has to determine which isophote that pixel lies upon. The equations are not analytic if the ellipse parameters vary with radius, but a simple iterative scheme almost never runs into problems. However, the ellipse parameters need to be measured very accurately, or else artifacts will be produced at radii where the parameters are wrong.

An example of this technique is shown in Figure 3 for NGC 7144, a 'normal' elliptical galaxy with no obvious distortions of the isophotes. The first picture shows the direct frame of NGC 7144, the second shows the noise-free reconstruction with perfectly elliptical isophotes, and the third shows the difference picture. Note the complete absence of any significant features in the residual map.

3.3. Box-shaped Galaxies

Now the same trick is tried with NGC 4387. The direct frame shows that the isophotes are slightly boxy, and the residual picture reveals a cross-shaped pattern that is characteristic of boxy isophotes (Figure 4a&b). The distortion can best be parametrised by calculating the 4th harmonic of the intensity around the best-fitting ellipse, and a significant $\cos(4\theta)$ term is found in this isophote (Figure 4c).

NGC 4478 shows a similar pattern, and here the galaxy has a significant isophote twist of about 15°. The boxy cross in the residual picture also twists, but interestingly the phase lags behind the position angle twist such that there is a significant $\sin(4\theta)$ term mixed in. NGC 3605 also has boxy isophotes. What do these galaxies all have in common? Note that they are all low-luminosity galaxies with much brighter companions: NGC 4478 is about 9 arcminutes from M87, NGC 4387 is 10 arcminutes from both NGC 4374 and NGC 4406, and NGC 3605 is only 3 arcminutes from NGC 3607. A reasonable guess would be that the influence of the massive neighbour is significant here.

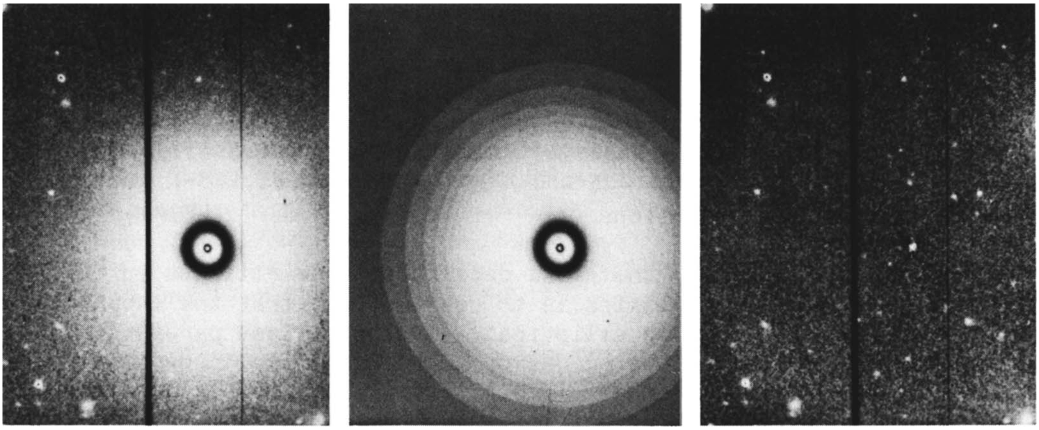


Figure 3. Illustrating the subtraction of a model galaxy with perfectly elliptical isophotes for NGC 7144. a) Direct picture b) Elliptical reconstruction c) Residual picture formed by subtracting b) from a). These are 'pseudo contour' representations, with contours spaced evenly in surface brightness. The dark vertical bars are bad columns on the CCD.

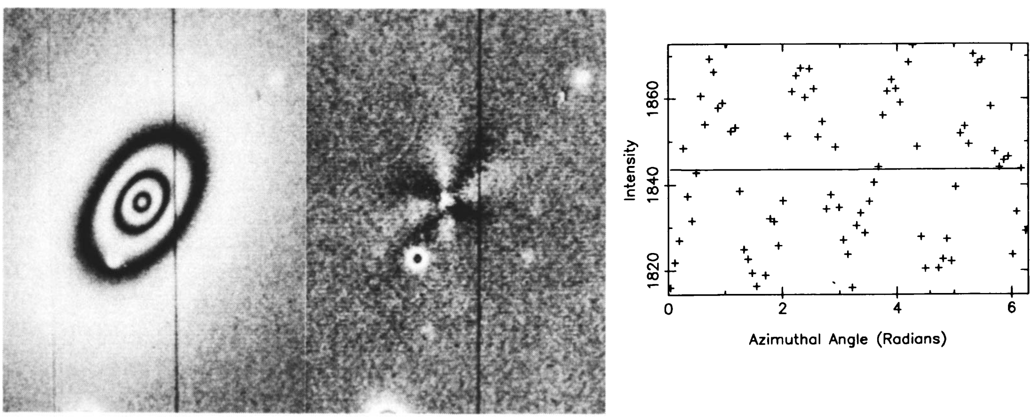


Figure 4. NGC 4387 a) Direct picture b) Residual picture c) Plot of the galaxy intensity as a function of azimuthal angle around the best fitting ellipse for a certain boxy isophote. Note the highly significant cos(4θ) component

These are not the only boxy galaxies. NGC 4374 and NGC 5898 show the same property in their residual maps, as does the extremely flattened NGC 6909. Lauer's study turned up NGC 1600, NGC 4261 and NGC 7785, and these are all bright objects. NGC 4261, another boxy galaxy, has been found by Davies & Birkinshaw (1986) to rotate along its minor axis, and so is probably prolate. My estimate would be that about 20 percent of elliptical galaxies show boxiness at the 0.5%

https://doi.org/10.1017/S0074180900185043 Published online by Cambridge University Press

level or more. It is because we now have CCD's that they are only now beginning to be revealed.

There appears to be a one-to-one correspondence between box-shaped bulges and a cylindrical velocity field (Illingworth 1983), although the sample size is small. We need to know whether the same is true for boxy ellipticals.

3.4. Edge-on disks

Another type of perturbation is that produced by an edge-on disk embedded in the elliptical isophotes. Now the isophotes are slightly pointed along the major axis. Once again, a simple ellipse cannot fit the shape perfectly, and the best that can be done is to increase the flattening slightly - see Figure 5. Now the distortion appears as a cos(4θ) term again, but this time the sign is the reverse of the boxy case. This representation is not ideal - some of the intensity from along the major axis has been redistributed onto the minor axis by the reduction in ellipticity such that the average deviation is zero. The residual map of NGC 7029 shows this effect (Figure 6).

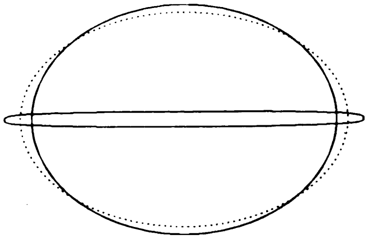


Figure 5. Illustrating the best-fit ellipse (dotted) to an isophote made up of an elliptical bulge and edge-on disk (solid).

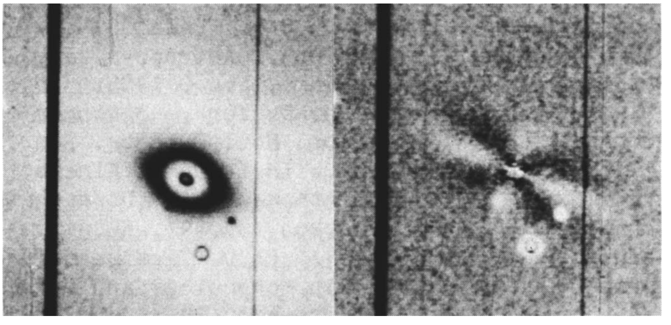


Figure 6. NGC 7029 a) Direct picture b) Residual picture.

The relative numbers of ellipticals that have 'disk-like' perturbations are strongly dependent upon how many S0's creep into the sample. Of the 29 galaxies in my sample that are classified as elliptical in the Revised Shapley-Ames Catalogue (Sandage & Tammann 1981), 7 have significantly boxy isophotes and 4 have significantly pointed isophotes. Of the galaxies classified as E4 or flatter, about half have pointed isophotes. Not all ellipticals are harbouring a faint disk - some very flattened galaxies have isophotes that are boxy rather than pointed.

4. CONCLUSIONS

The isophotes of elliptical galaxies are true ellipses to better than

2% in most cases. The observations of ellipticity gradients and isophote twists are best explained by triaxial models, which have been shown from N-body experiments to be a natural product of many elliptical galaxy formation mechanisms. Boxiness and edge-on disks are the most important contributors to deviations from perfect ellipses, and these deviations are displayed by subtracting a model with perfectly elliptical isophotes. About 20% of galaxies have isophotes that are boxy to 0.5% or more, while about half of all ellipticals may have a weak disk.

ACKNOWLEDGEMENTS

Among the many people that have stimulated my interest and provided helpful insight, I would particularly like to thank Roger Davies, George Efstathiou, Mike Cawson and Paul Schechter.

REFERENCES

Barnes, J., Goodman, J. & Hut, P., (1985). Astrophys. J., 300, 112.
Davies, R.L., & Birkinshaw, M., 1985. Astrophys. J., 302, L45.
Davies, R.L., Efstathiou, G.P., Fall, S.M., Illingworth, G.D. and Schechter, P.L., 1983. Astrophys. J., 266, 41.
Fridman, A.M. & Polyachenko, V.L., 1985. Physics of Gravitating Systems, Volume 2 (New York: Springer-Verlag).
Gerhard, O.E., 1983. Mon. Not. R. astr. Soc., 203, 19P.
Illingworth, G.D., 1983. In Internal Kinematics and Dynamics of Galaxies, ed. E. Athanassoula (Dordrecht: Reidel).
Jarvis, B.J., 1986. Astron. J., 91, 65.
Jedrzejewski, R.I., 1985. Ph.D. Thesis, University of Cambridge.
Kormendy, J., (1982). In Morphology and Dynamics of Galaxies, Twelfth Saas-Fee Advanced Course (Sauverny: Geneva Observatory).
Lauer, T.R., 1985a. Astrophys. J. Suppl. Ser., 57, 473.
Lauer, T.R., 1985b. Mon. Not. R. astr. Soc., 216, 429.
Malin, D.F. & Carter, D., 1983. Astrophys. J., 274, 534.
Merritt, D. & Aguilar, L.A., 1985. Mon. Not. R. astr. Soc., 217, 787.
Mihalas, D. & Binney, J., (1981). Galactic Astronomy (San Francisco: W.H. Freeman).
Quinn, P., 1982. Ph.D. Thesis, Australian National University.
Sadler, E.M. & Gerhard, O.E., 1985. Mon. Not. R. astr. Soc., 214, 177.
Sandage, A. & Tammann, G.A., 1981. A Revised Shapley-Ames Catalogue of Bright Galaxies (Washington: Carnegie Institution of Washington).
Sparks, W.B., Wall, J.V., Thorne, D.J., Jorden, P.R., van Breda, I.G., Rudd, P.J. & Jorgensen, H.E., 1985. Mon. Not. R. astr. Soc., 217, 87.
White, S.D.M., 1983. In Internal Kinematics and Dynamics of Galaxies, ed. E. Athanassoula (Dordrecht: Reidel).
Wilson, C.P., 1975. Astron. J., 80, 175.
Williams, T.B., 1981. Astrophys. J., 244, 458.

DISCUSSION

King: My impression, based on a small sample, was that galaxies with appreciable central ellipticities have steeper rotation curves, while if a galaxy is round in the center but flattened farther out, it has a rotation curve that rises very slowly. An example is NGC 4406. Do you confirm this?

Jedrzejewski: No, in fact, by looking at a few galaxies with ellipticity profiles that rise outwards, reach a peak at about $1r_e$ and then decline slowly, I get the impression that these are more likely to be rotationally supported, and those that you describe are more likely to be non–rotating. I should emphasise that this is only an impression and not based on hard numbers.

White: When you say that a galaxy does not show "pointy" isophotes at the 1% or 0.5% level, what limit does that translate into on the fraction of the light of the system contributed by a nearly edge–on disk?

Jedrzejewski: I haven't tried to model these objects as two–component systems to estimate constraints on the relative brightness of any 'disk' component, but my guess is that for a galaxy with 1% 'pointed' isophotes a disk has a contribution to the total light of 0.1–1%.

Davies: Carter has modeled NGC 4697 and concluded that 2% of the light comes from the disk component. This corresponds to a B_4 of 0.04 - 0.05. Is there a trend in B_4 with luminosity?

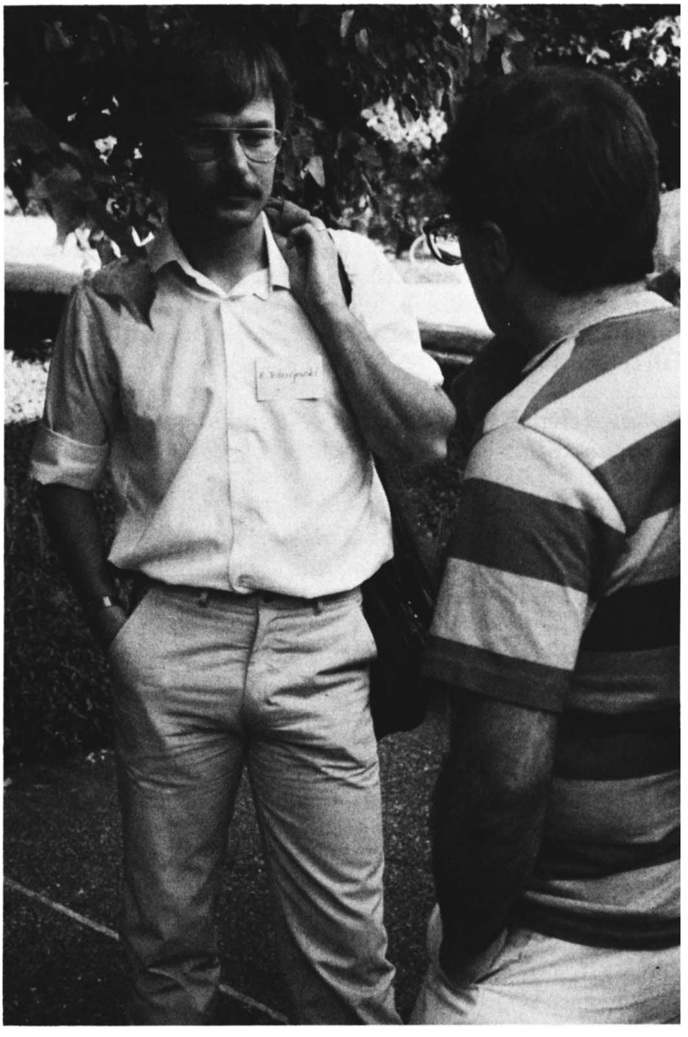
Jedrzejewski: There is no real trend, but it does seem that fainter galaxies have a slightly higher fraction of objects with non–elliptical isophotes. These are divided roughly equally between those with 'boxy' and 'pointed' isophotes.

Jarvis: I would like to make two comments. Firstly, there are considerably better examples of elliptical galaxies having box–shaped isophotes than the ones that you have shown. These can be seen to be box–shaped without any image processing at all. Two such examples are IC 3370 and NGC 4125. For the former galaxy, I have obtained surface photometry and kinematics which show that IC 3370 is strongly cylindrically rotating in a similar way that the bulges of disk galaxies having box– or peanut–shaped bulges do.

Jedrzejewski: I agree, but I wasn't particularly looking for boxy galaxies, instead they appeared in a sample of supposedly 'normal' galaxies. By no stretch of the imagination would I call IC 3370 a normal galaxy, but it is interesting to see that the velocity field is similar to that of 'peanut–shaped' bulges.

Schwarzschild: Your beautiful new data seem to me particularly valuable for the following reason. We theoreticians have built, up to now, mostly models with strictly ellipsoidal iso–density surfaces. But I know of no reason why nature should build ellipticals strictly with ellipsoidal shapes. I feel optimistic that models with a larger variety of shapes than you observe can be constructed.

Jedrzejewski: Until the widespread use of CCD's, attempts to measure departures from strictly elliptical isophotes were generally unsuccessful, so it is perhaps not surprising that emphasis was placed on models with perfectly ellipsoidal contours. It must be remembered, however, that in most cases the deviations are *small*, of at most up to a percent or so.



Robert Jedrzejewski and George Djorgovski discuss isophotes.

https://doi.org/10.1017/S0074180900185043 Published online by Cambridge University Press