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The origin of inner isophotal twists in elliptical galaxies★

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Abstract. The analysis of the projected geometry of 99 elliptical galaxies listed in the *Revised Shapley–Ames Catalog of Bright Galaxies* reveals that 16 of them have inner isophotal twists larger than 20 degrees, which cannot be attributed to internal dust absorption. For 12 of them, the profiles of the position angle, ellipticity and axisymmetric coefficients of the Fourier expansion of their isophotal contours, show features all correlated with each other, a result consistent with the assumption that these objects are at least two-component systems. Detailed features in the profiles of these parameters resemble scale-down structures found in a comparison sample of SB0 galaxies, which indicates the presence of bars generally accompanied with disks. It is suggested that: (a) a significant fraction of isophotal twists, in relation with changes of isophotal shapes and internal kinematics, is due to the SB0-like or (more generally) to the two-component nature of many E galaxies, (b) large-scale disks in E's are cold systems formed dissipatively at early stages in the history of these galaxies and not in recent mergings, (c) there is a strong continuity in morphological properties between S0/SB0s and E's where bars and disks have been unambiguously detected, and (d) a significant percentage of triaxial systems may not have the form of pure ellipsoids.

Key words: galaxies: ellipticals – elliptical galaxies: structure, isophotal shapes, kinematics, formation

1. Introduction

Isophotal twists have provided a major observational constraint on our attempts to understand the nature and the three-dimensional shapes of elliptical galaxies. They clearly plead in favor of those ellipticals showing these features being triaxial systems (Williams & Schwarzschild 1979; Williams 1981), although much effort has been made to sort out simpler preferential shapes, from either statistical arguments (see, e.g. Marchant & Olson 1979; Richstone 1979; Olson & de Vaucouleurs 1981; Fasano 1990, and the recent review of Merritt 1991) or from observational evidence either based on gas and dust morphologies (Bertola & Galletta 1978) or from stellar kinematics (Davies et al. 1983; Davies & Illingworth 1983; Davies & Birkinshaw 1986, 1988; Carter 1987; Bender 1988; Nieto et al. 1988). The conclusion for a general triaxial figure is supported by kinematical measurements that show that many systems are strongly anisotropic (see, e.g. Illingworth 1977; Davies et al. 1983; Bender 1988) and/or minor-axis rotators (Wagner et al. 1988).

A characteristics of isophotal twists is that they correlate with ellipticity, in the sense that the roundest galaxies show the largest twists (Galletta 1980), while very elongated systems show small twists, if any. The largest amplitude twists are found in NGC 596 and NGC 1549, which became the two prototypes of this phenomenon. However, the correlation between twists and ellipticity was feared to be possibly biased by mis-classified SB0s (Galletta 1980; Kormendy 1982; Fasano & Bonoli 1989), but no clear conclusion on this contamination has been discussed clearly in detail. An alternative is that isophotal twists result from tidal effects, but this probably applies more to outer twists than inner twists. See reviews in Kormendy (1982) and Nieto (1988).

The isophotal analysis developed in the recent years (e.g. Lauer 1985; Bender & Möllenhoff 1987; Jedrzejewski 1987) have revealed that deviations from ellipticity are clues of crucial importance for understanding the formation and evolution elliptical galaxies. Specifically, the type of deviation, as defined by the coefficient of the cos 4θ term in the Fourier series describing the isophotal contour (usually called a_4), correlates with specific physical properties (Bender et al. 1989; Nieto & Bender 1989).

The same isophotal analysis technique will be applied in the present paper to E galaxies showing large isophotal twists in their main bodies (excluding, therefore, outer twists and those in the very central regions, found recently by Nieto et al. 1991a), as well as to a sample of SB0s, used as a source of comparison. For this purpose we have gathered (a) a large sample of elliptical galaxies from the *Revised Shapley–Ames Catalog of Bright Galaxies* (RSA, Sandage & Tammann 1981; the best spatially resolved galaxies) for which isophotal analysis was available to us, and (b) a comparison sample of barely resolved SB0s, namely SB0s presenting deviations from ellipticity whose amplitudes are similar

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★ Based on observations made with the Canada-France-Hawaii Telescope, operated by the National Research Council of Canada, the Center National de la Recherche Scientifique of France and the University of Hawaii, USA, the Bernard Lyot Telescope of Pic-du-Midi Observatory, operated by INSU (CNRS), the 2.2 m telescope of the European Southern Observatory (ESO; La Silla, Chile) and at the German-Spanish Astronomical Center, Calar Alto, operated by the Max-Planck Institut für Astronomie Heidelberg jointly with the Spanish National Commission for Astronomy

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(but still more pronounced) to those seen in E's to allow a fair comparison between them. This sample of SB0s has been extracted from a geometric study of early-type galaxies in the Perseus Cluster (Poulain et al. 1991a, b), where high-resolution images (obtained at CFHT and at the Bernard Lyot Telescope of Pic du Midi Observatory) have been obtained to identify unambiguously SB0's. A first analogy between the isophotal contours of E's with large twists and SB0s has been briefly reported in Nieto & Lagoute (1991).

This paper is organised as follows: the two samples of E's with large isophotal twists and SB0s are described in Sect. 2. In Sects. 3 and 4, we describe the morphological characteristics of SB0s and E's, respectively. Section 5 is devoted to a discussion centred on the results that E's with large inner isophotal twists are indeed SB0-like systems. Some consequences of this result are presented in Sect. 6. The problem of isophotal twists has been so classical (cf. the cover of the IAU Symposium 127: "Structure and Dynamics of Elliptical Galaxies") for so long (first mention is in Evans 1951) that we intended to treat it at length; this is why some sections (3 and 4, as well as 5.4) are very technical and detailed. The casual reader may wish to skip them.

2. Samples and reduction procedure

2.1. The reduction procedure

The isophotal analysis technique described by Bender & Möllenhoff (1987) will be used consistently throughout this paper. It is based on least-squares fitting of the isophotal contours with ellipses, then detecting systematic deviations from pure ellipses by expanding the radial deviations r_i in the Fourier series:

$$\Delta r_i = \sum_j a_j \cos(jt) + b_j \sin(jt).$$

The errors on all coeffcients were estimated from the rms of the high-amplitude Fourier coefficients, assumed not to be significant. The geometrical parameters derived from this isophotal shape analysis, as presented in Figs. 2 and 3 for respectively the E and the SB0 galaxies (see below), are: ellipticity (Ell.), position angle (PA), as well as the generally most significant Fourier parameters, a_j and b_j, for $j=3$, 4 and 6, for which error bars are piotted. For more details, see Bender & Möllenhoff (1987).

2.2. The E galaxies

We have restricted this investigation to the galaxies classified E in the RSA, from which we excluded those in very close pairs (NGC 741, NGC 750, NGC 2672 and NGC 2693, whose geometrical parameters are uncertain, because of the contamination by the nearby object) as well as NGC 1275 and NGC 4486 (= M 87). We managed to compile a sample of 99 galaxies (out of the 136 remaining RSA galaxies) for which the coefficients of the best-fit Fourier expansion of the isophotal contours up to a high order were available to us. Most of our data have different sources (which permits cross-checks), some being already published: Bender et al. (1988), from observations made at Calar Alto and providing 41 galaxies, and Nieto et al. (1991b), from observations made at Pic du Midi and with CFHT, providing data on 20 RSA galaxies. They were complemented by unpublished data on 27 galaxies observed in December 1988 at the ESO 2.2 m telescope, and other data obtained either at Calar Alto Observatory or at Pic du Midi Observatory. We also considered the data presented by Franx et al. (1989a; 15 galaxies) and Peletier et al. (1990; 16 galaxies) that contribute nicely because they allow some checks and involve a large angular range. In all of the above references, except the last two, the reduction procedure is strictly that described in Sect. 2.1.

We have plotted in Fig. 1, for each galaxy, the maximum isophotal twists, as measured from the available data described above, vs. the RSA Hubble type, that indicates flattening. Out of the 99 E galaxies, we found (Table 1) 16 having internal isophotal twists greater than 20°, and apparently not being due to dust. It is important to realize that, since we are essentially dealing with CCD images that do not cover the whole galaxy in most of the cases, the twists that are discussed here are *internal*. This is important in the sense that outer isophotal twists are likely to result from interactions with the environment, besides the fact that their amplitude may be subjected to strong flat-fielding and sky subtraction errors (Fasano & Bonoli 1990). Most of the geometrical data can then be found in the literature (see references in Table 1) although, in several cases, our recent unpublished data are of better quality. We thus present in Fig. 3 the geometrical parameters of the three protypical cases, NGC 596, NGC 636 and NGC 1549, as well as those of two galaxies that were not published earlier: NGC 3158 and NGC 3415. (The isophotal shapes of these galaxies are not very informative in the sense that the deviations from ellipticity are too small to be visible by eye; see an example on the cover of IAU Symposium 127) To help the discussion on and interpretation of the projected

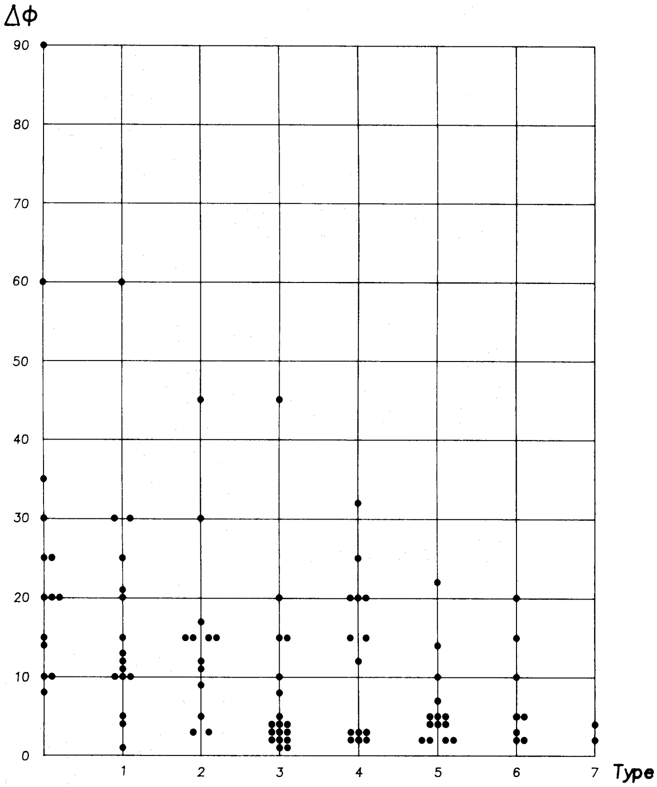

Fig. 1. This diagram shows the maximum isophotal twist (measured on the available data, from CCD images) vs. Hubble type (from RSA) for 99 early-type galaxies classified E in the RSA

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Table 1. RSA galaxies with the largest isophote twists ($\Delta PA > 20°$)

Name (1)	Ang. range (arcsec) (2)	tw. (3)	Ref. (4)	SB0 type (5)	Fig. (6)	$-M_{B}$ (7)	r_{e} (8)	 (9)	r(tw) (10)	 (11)
NGC 596	1–35	90	a, f, i	UGC 2656	3a	19.57	30.0	5.0	0.7	
NGC 636	2–80	60	a, f, g	UGC 2708	3b	19.08	18.9	3.1	1.1	
NGC 1379	2–70	35	b, g	No dev.		19.08	42.4	5.3	?	**
NGC 1395	2–100	30	b, g	UGC 2708		20.06	45.4	6.4	0.4	
NGC 1537	2–50	20	b	UGC 2708		18.93	26.1	2.9	< 1.0	
NGC 1549	2–70	45	b, g, i	UGC 2656	3c	19.28	47.5	4.9	0.7	
NGC 3158	1–40	45	f, i	UGC 2708	3d	21.29	21.7	13.1	1.0	
NGC 3309	1–30	30	c	UGC 2708		20.42	31.4	10.2	0.7	
NGC 3415	1–40	22	d, i	Spiral	3e	19.75	16.1	2.6	1.4	
NGC 3872	1–50	32	d	UGC 2708		20.02	17.7	5.0	1.8	
NGC 4278	2–120	25	a, h	UGC 2708		18.40	32.9	2.2	1.1	
NGC 5198	1–30	30	f	No dev.		19.37	28.6	6.3	< 0.4	**
NGC 5812	8–45	30	a	?		19.68	23.8	4.4	0.3	**
NGC 5831	2–75	27	a, h	UGC 2708		19.60	26.7	4.0	0.7	
NGC 7144	8–60	25	g	No dev.		19.60	40.5	6.7	0.6	**
NGC 7145	6–60	60	g	UGC 2708		19.36	38.6	6.4	0.8	

Column headings:
(1) Name of the galaxy
(2) Angular range where the geometrical parameters are available
(3) Amplitude of the isophotal twist (in degrees)
(4) Corresponding reference (where original data can be found): (a) Bender et al. (1988); (b) Bender and Nieto (unpub.): CCD data in the V and R bands obtained at the ESO 2.2 m German Telescope (December 1988); (c) Bender and Surma (unpub.): CCD data obtained at Calar Alto; (d) Nieto et al. (1991b); (e) Poulain et al. (1991a, b); (f) Nieto et al. (unpub.): CCD data obtained at the Bernard Lyot telescope of Pic du Midi; (g) Franx et al. (1989a); (h) Peletier et al. (1990) (i) This paper (see figures)
(5) Name of the SB0 prototype having similar geometrical parameters (see Sect. 3)
(6) Figure number where the geometrical parameters are described
(7) Absolute magnitude, (8) and (9) Effective radius, in arcsec and in pc respectively: total magnitudes and effective radii (measured from aperture photoelectric photometry or simulated aperture photometry from CCD images) were taken from several sources: RC2 (de Vaucouleurs et al. 1976), or RSA (for which we applied, for consistency, Galactic absorption from RC2), Faber et al. (1989) or Poulain (1988); distance moduli are from de Vaucouleurs and Olson (1984) and Faber et al. (1989), usually consistent with each other. Otherwise, $H_0 = 100$ km s^{-1} Mpc^{-1} was adopted
(10) Distance where the steepest gradient in the twist(s) occurs, in r_e units (which clearly shows that most twists are indeed internal, as occurring within less than $1.5 r_e$)
(11) *Double stars* stand for rejected galaxies (see Sect. 4.4)

Notes on individual galaxies:
NGC 1395: X-ray galaxy (Forman et al. 1985; Canizares et al. 1987)
NGC 1549: Detected by IRAS at 100 μm (Jura et al. 1987)
NGC 3158: This galaxy is the brightest cluster member in Abell 972 (RC2). This is by far the brightest galaxy of the sample, among the brightest in the RSA catalogue
NGC 3309: In pair with NGC 3311 in the center of the Hydra Cluster (Abell 1060). Strong radio source detected by Disney & Wall (1977), with a radio jet (Lindblad et al. 1985). No "minor-axis" rotation (Bertola et al. 1988)
NGC 3415: Our data indicate $r_e = 16.1$ (V band) and V = 12.18 in good agreement with Sandage & Visvanathan (1978). de Vaucouleurs & Olson give a distance modulus of 29.09, in strong disagreement with the (adopted) distance induced from redshift (3300 km s^{-1})
NGC 3872: This galaxy has the highest flattening in our list, from its Hubble type (Fig. 1), and in this sense, departs from the isophotal twist – flattening correlation: E5 in RC2 and E4 in RSA. However, isophotal shape analysis (Nieto et al. 1991b) shows that its maximum ellipticity is 0.28. This is the only galaxy of our sample where the twist is not internal
NGC 4278: Radio galaxy (Dressel & Condon 1978, from Arecibo survey at 2380 MHz), with a H I outer ring kinematically decoupled from stars (Knapp et al. 1978). Galaxy known as "Feeding the Monster" (Gunn 1979) galaxy. Detected by IRAS at 60 and 100 μm (Jura et al. 1987)
NGC 5812: Note a 2 magnitude difference in the distance moduli derived by de Vaucouleurs & Olson (1984) and by Faber et al. (1989). The second determination was adopted

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geometry of the galaxies listed in Table 1, we describe first the comparison sample, which consists of SB0 galaxies.

2.3. The comparison sample of SB0s: description

Since we want to measure small deviations from ellipticity, the comparison sample is made of rather remote SB0 galaxies (the distance effect blurring slightly the different sub-components of the systems) or SB0 galaxies known to contain a small bar. We took as sources of comparison:

(i) NGC 3384 (Fig. 2a): this S0 galaxy is known to have a very central protuberance first described by Pease (1920) and rediscussed by Davoust et al. (1983) and Ferrario & Capaccioli (1991) to be a small inner bar; CCD images of this galaxy used here were obtained at Pic du Midi; Fig. 2a shows the geometrical parameters.

(ii) SB0s and other early barred spiral systems lying in the Perseus Cluster, as reclassified by Poulain et al. (1991a) from CCD images obtained in excellent seeing conditions (see Poulain et al. 1991b) at Pic du Midi and with the CFH Telescope. We limited the investigation to the clearest typical cases of SB0 structures: UGC 2534, UGC 2656 (=BGP 40), BGP 61, UGC 2708, BGP 104. The geometrical characteristics are presented in Figs. 2: isophotal contours in (b) and parameters in (c). These SB0 galaxies clearly are less resolved versions of the several prototypes of SB0 galaxies: see, e.g. the *Hubble Atlas* (Sandage 1961); a more appropriate approach for the geometry of well-resolved SB0s can be found in Athanassoula et al. (1990). In the following, when describing the projected geometries of these objects, we shall proceed with simple effects first.

3. Detailed geometry of SB0s

3.1. Effect of a protruding bar in the geometry parameters

NGC 3384: The effect of the small inner bar (very inclined with respect to the major axis) on the Fourier expansion of the isophotal contours (Fig. 2a) can be clearly identified at $r \simeq 15''$, where appear: (a) a strong, very well-localized hump-like isophotal twist, (b) negative a_4/a and b_4 values ($= -0.02$), and (c) non-zero higher order Fourier coefficients (a_6 and b_6), in an otherwise disky structure (as shown by the a_4 profile). The non-zero value of b_4 means that the boxy deviations are not aligned with the major axis of the best-fit ellipse.

The case of UGC 2534 (Fig. 2b1 and 2c1) is slightly more complicated than the NGC 3384 picture, since pointed isophotes appear within the bar. There is a small ($r \simeq 5''$) boxy (?) bulge within a large ($r \simeq 15$–$20''$) bar oriented 80° away, but within this larger bar, appear strongly pointed isophotes ($r \simeq 8''$; the central bulge may also contain disky isophotes in the 3 central arcsec). This whole structure is surrounded by a flow surface brightness lens oriented almost like the inner bulge. For the geometrical parameters, this results in (i) a dramatic hump in the orientation profile, (ii) the ellipticity profile showing a local maximum ($6'' < r < 12''$) surrounded by two local minima, and (iii) $b_4 > 0$ (as well as non-zero higher coefficients), since the pointed isophotes are not aligned with the major axis of the system. Note that these pointed isophotes occur in an angular range where strong isophotal twists are present. Similar behavior can be found in other galaxies of the Perseus Cluster, such as BGP 83 and CR 47, whose isophotal shapes clearly show an SB0 structure and which are smaller-size examples of the two galaxies above (see Poulain et al. 1991a).

3.2. SB0s: jumps in the PA profile

In the previous examples, the regions on the two sides of the bar have the same orientation; this results in a hump in the PA profile. In the following examples, there are an inner bulge, a bar (within which disky isophotes exist), and an outer lens, which does not have the same orientation as the inner bulge, so that the isophotal twist does not show a hump (as above), but "jumps" frome one value to another.

UGC 2708 (Figs. 2b2 and 2c2): The central part is made of a roundish bulge oriented 80° away from the very external isophotes. The intermediate system is a bar, within which very peaked isophotes exist ($a_4/a > 0$ and even $a_6/a > 0$). Note the very steep decrease in the a_4 profile outwards. A non-zero b_4 reflects a small misalignment of the pointed/boxy isophotes with the major axis of the best-fit ellipse. Higher-order deviations exist whose maximum is exactly at the distance of maximum a_4. Outside of this region, a third component appears at a 20° angle from the bar and whose boxy isophotes may tentatively be interpreted as being due to the bar dominating the underlying lens, so that the isophotal shapes are slightly boxy ($a_4/a \simeq -0.03$).

BGP 61 (Figs. 2b3 and 2c3): Description similar to UGC 2708. Note that, in this case, the bar does not necessarily imply a negative a_4, but instead, a zero a_4 and a non-zero a_6, resulting from the superposition, on the same isophote, of both type of deviations (similar phenomena have been discussed in some E's by Nieto & Bender 1989).

3.3. SB0s: Bar inclined with respect to the lens

UGC 2656 (=BGP 40) (Figs. 2b4 and 2c4): The main bar of this system produces a strong isophotal twist (at $r \simeq 8''$ where $a_4/a \simeq -0.03$) with respect to the major axis of the outer lens ($a_4/a \simeq 0.03$). Note that, in this case, the bar locally increases the ellipticity. At the distance where the bar dominates, the b_4 strongly differs from zero since the box-type deviation is inclined with respect to the main axis of the isophote.

3.4. Early spirals: isophotal twists and "spurious" boxiness

BGP 104 (Figs. 2b5 and 2c5): The galaxy is a very good example of boxy-like deviations produced by arms sticking out of an elliptical bulge: the a_4 deviation appears boxy close to the bulge and disky outwards. This also produces a hump in the PA profile, a high value of the b_4 tern and non-zero higher order coefficients. Qualitatively, the effects are similar to the above examples of SB0s, but the isophotal twists are not as strong. BGP 78, UGC 2598 and NGC 1250 are similar typical cases in the Perseus Cluster (see Poulain et al. 1991b).

3.5. Brief conclusion

We shall consider hereafter two main types of SB0 galaxies, exemplified by UGC 2656 and UGC 2708, and essentially defined by the shape of the outer contour: UGC 2656 is disk-dominated outside, such as, e.g. NGC 936 (see Athanassoula et al. 1990 or Kormendy 1982 for illustrations) or NGC 4262

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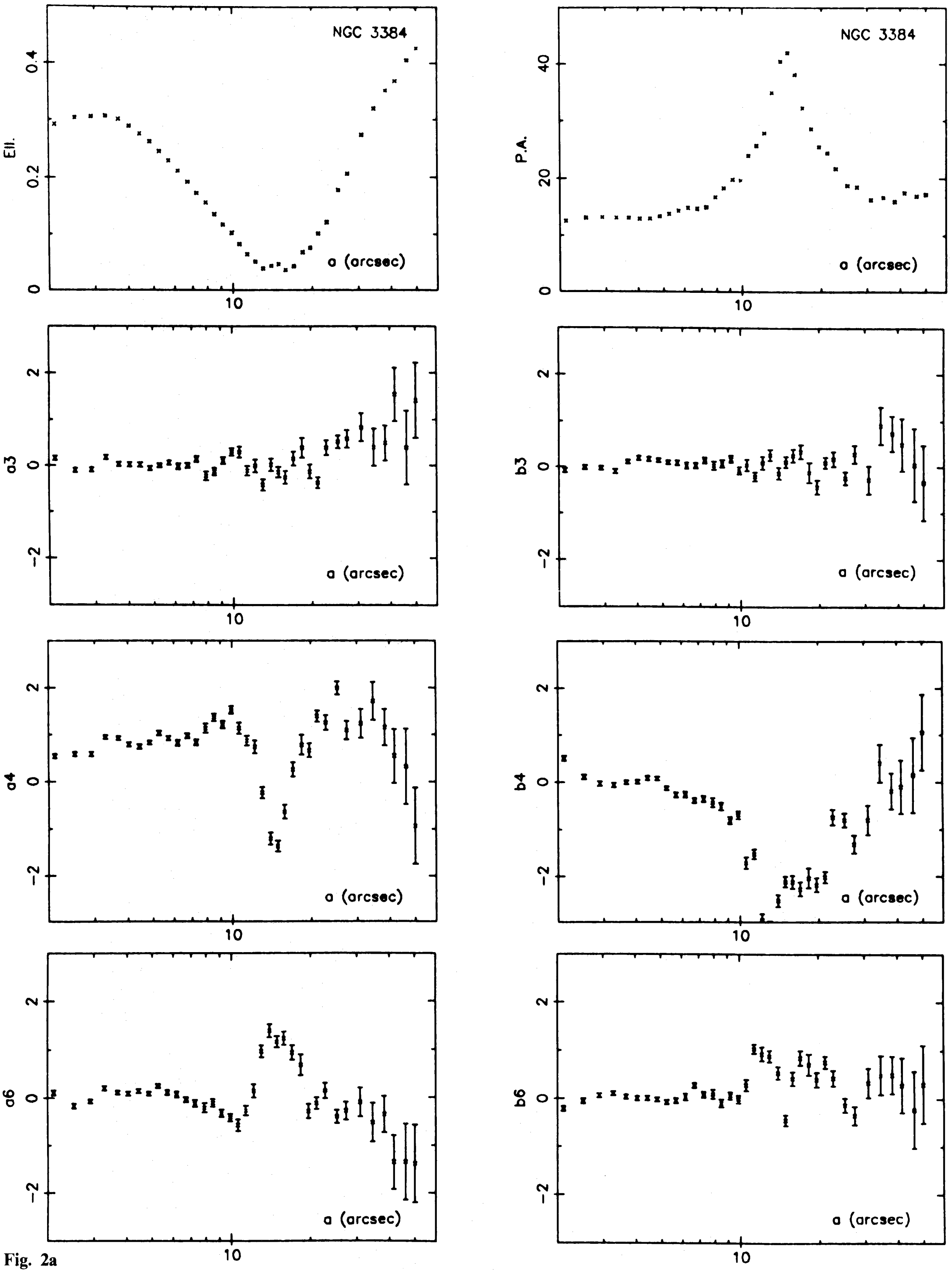

Fig. 2a

Fig. 2a–c. Geometrical characteristics (isophotal shapes, and geometrical parameters) of comparison galaxies harboring bars. Note that the zero points of PA's is arbitrary and that the Fourier coefficients are normalized to the semi-major axis and multiplied by 100: **a** NGC 3384, from a Pic du Midi image (B band, FWHM = 1.2″; for the isophotal shapes of this galaxy, see Davoust et al. 1983); **b** Isophotal shapes of the Perseus Cluster SB0 galaxies: (b1) UGC 2534 (classified earlier E by Kent & Sargent 1983), from a Pic du Midi image (R band, FWHM = 0.″84); **b2** UGC 2708 (classified S0 by Kent & Sargent), from a Pic du Midi image (R band, FWHM = 0.″84): **b3** BGP 61 (classified E by Kent & Sargent), from a CFHT image (R band, FWHM = 0.″68); **b4** UGC 2656 (= BGP 40, classified E by Kent & Sargent), from a CFHT image (R band, FHWM = 0.″60); **b5** BGP 104 (classified S0 by Kent & Sargent), from a CFHT image (R band, FWHM = 0.″89); **c** Geometrical parameters of the Perseus Cluster SB0 galaxies: **c1** UGC 2534, **c2** UGC 2708, **c3** BGP 61, **c4** UGC 2656 (= BGP 40), **c5** BGP 104

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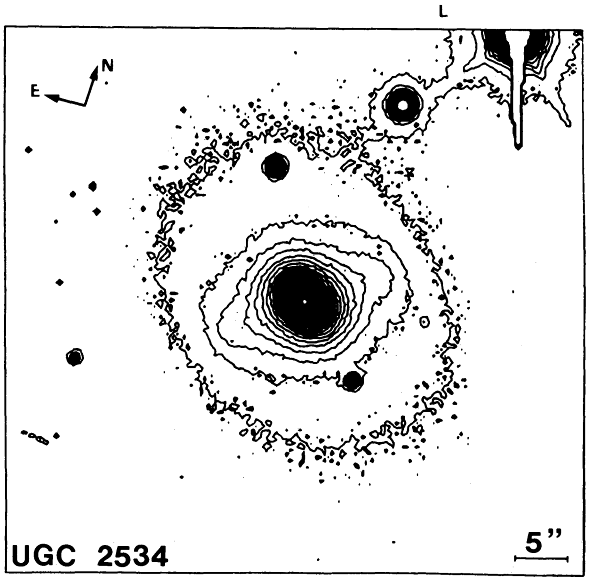

Fig. 2b1

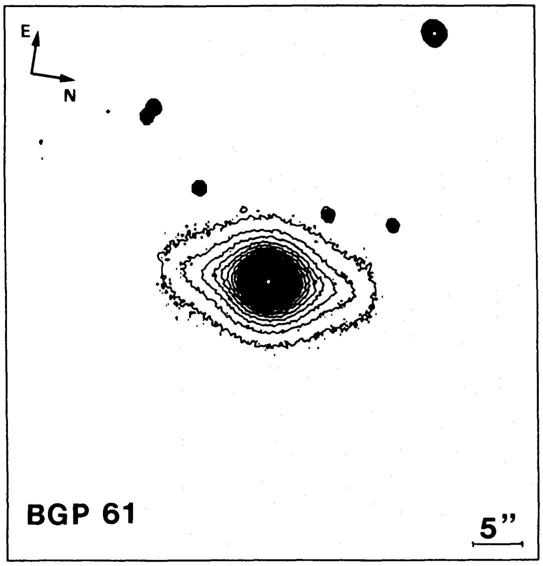

Fig. 2b3

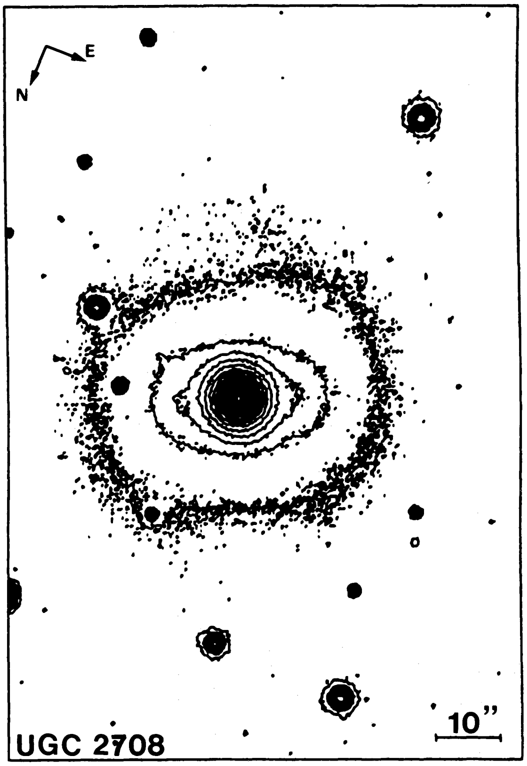

Fig. 2b2

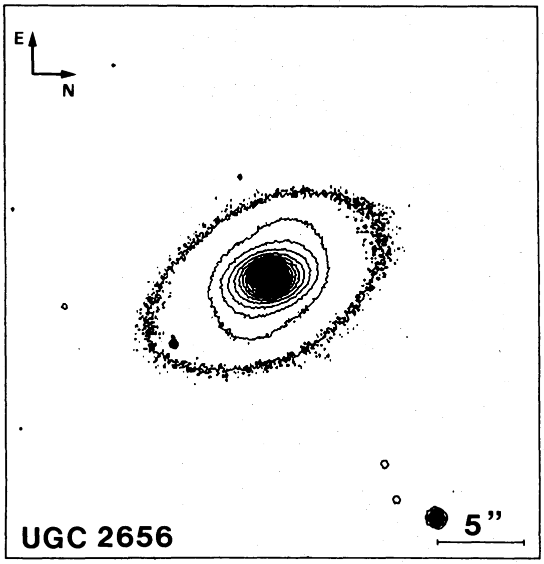

Fig. 2b4

(*Hubble Atlas*) while UGC 2708 is bar-dominated such as NGC 4596 (see Athanassoula et al. 1990) or NGC 5101 (*Hubble Atlas*).

4. Detailed geometry of E galaxies with large internal twists

4.1. UGC 2656-type SB0-like E's

NGC 596 (Fig. 3a): This galaxy has the strongest isophotal twists known (60° beyond 3″). Beyond that distance, the PA of this galaxy presents two plateaus from 6 to 18″ and from 25″ outwards, separated by a 45° jump. At the distance where this jump occurs, the a_4 profile also jumps from a minimum ($\simeq -0.01$) to a maximum ($\simeq +0.01$), and the ellipticity profile jumps from 0.08 to values higher than 0.2. At that distance also, the b_4 term becomes negative. By analogy with the above description of UGC 2656 (=BGP 40), this clearly suggests an abrupt change from an inner bar oriented at PA$\simeq$100° to an inclined outer disky system whose orientation is $\simeq$40°s. This idea of a bar (characterized to have a sharp edge) is strongly supported by the comparison of the Pic du Midi data presented here (Fig. 3a; FWHM = 1.3 and 1.0″) with those of Bender et al. (1988; FWHM = 2.5″), where the changes in ellipticity, PA and a_4 appear much smoother.

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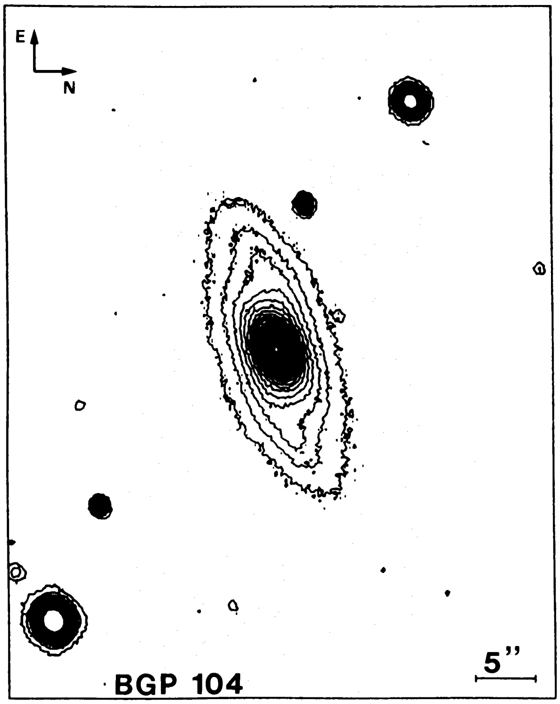

Fig. 2b5

NGC 1549 (Fig. 3c): The same qualitative description as NGC 596 applies to NGC 1549, whose isophotal twist reaches 45°. At 30″, we note simultaneous changes of the position angle and all Fourier coefficients (except b_3). The change in a_4 is abrupt, which suggests an SB0 system similar to UGC 2656 (BGP 40), with an abrupt change from a dominant central bar-like component to a dominant disk-like component. Note that Franx et al. (1989a) also mention that this system could be interpreted in terms of two components, but say that the interpretation is not straightforward because of the large isophotal twists.

4.2. *UGC 2534 type SB0-like E's*

NGC 636 (Fig. 3b; see also Franx et al. 1989 for data at $a > 50''$) presents a 45° twist between 2″ and 50″, and more specifically a 35° twist between 15″ and 40″. In this angular range, both the a_4 and the ellipticity profiles show a hump, such as in UGC 2534, which is probably due to a similar phenomenon: pointed isophotes appearing within a bar-like system, as suggested by the negative a_4 coefficient at $a > 40''$ (see Franx et al. 1989a). Note that the non-zero a_3 found by Bender et al. (1988) is not confirmed by the other data (see Table 1); however detail in the outer structure is also present, as inferred by non-zero coefficients (Franx et al. 1989a). Inwards, a very small negative a_4 deviation may suggest a slightly bar-like bulge oriented at PA = 75°. This description is consistent with a *two-component structure*, an inner disk plus outer bar structure, both systems having different orientations.

The same kind of description is valid for NGC 3158 at 20″ from center (this is a brightest member of Abell 972; Fig. 3d), NGC 4278, NGC 5831, and probably also NGC 1537 (where the coefficients of the Fourier expansion exactly mimic those of BGP 61). These geometrical parameters strongly suggest that these systems are SB0s, with an inner bulge and a boxy system (a bar) dominating outside. Note additionally that in the case of NGC 3158 a possible small inner feature exists at 5″ from the center (possibly a bar or spiral arms; however, non-zero a_3 and b_3 may indicate a more complicated phenomenon, such as dust). Specific phenomena may also be present in the centers of NGC 1537 and NGC 4278 (see Nieto et al. 1991a).

Four other galaxies, NGC 1395, NGC 7145, NGC 3309 and NGC 3872 appear to be very much like these systems except that the inner a_4 deviations, although significantly different from zero, do not present any feature reminiscent of a disk, such as a hump. At the distance where the a_4 deviation becomes negative, all Fourier coefficients are different from zero, and isophotal twists are strong. These objects are replicae of SB0 systems like UGC 2708 and BGP 61 (and thus NGC 636, 3158, 4278, 5831, and 1537), with the difference being that the very small range with strong hump-like a_4 deviations does not exist, probably because the bar does not contain pointed isophotes (due to orientation effects?). The idea of a two-component structure is strengthened by the fact that the geometry profiles of these galaxies are very similar to those of the boxy-disky ellipticals ("boxy lemons") such as NGC 3377 and NGC 3610 (see Nieto & Bender 1989).

4.3. *Spiral-like E's*

NGC 3415 (Fig. 3e): This galaxy, which shows an isophotal twist of 22°, had been discarded from a list of genuine elongated E's (Nieto et al. 1991b) for showing subtle but real spiral structure. This was confirmed by line (Hα) observations by Kim (1989). For the purpose of the present paper, we made the isophotal shape analysis of the images presented by Nieto et al. (1991b): the spiral arms produced isophotal twists and a negative a_4 value (boxy isophotes) in a very small angular range; this effect is strictly identical to the effect due to the "weak-disk or ring-like structure" on the geometrical parameters of NGC 1700 (that may well be caused by faint spiral arms; see Franx et al. 1989a; Nieto et al. 1991b). The similarity with BGP 104 and BGP 78 is striking.

4.4. *Others (E galaxies with insignificant deviations)*

NGC 5812: The only data available are those of Bender et al. (1988) that show a strong inner isophotal twist within the central 15″. The behavior of geometrical parameters are different at different wavelength bands, which possibly suggests the presence of dust. NGC 1379, NGC 5198 and NGC 7144 show no deviation significantly different from zero. Note that all these galaxies are rather round: the maximum ellipticity measured in NGC 1379 is smaller than 0.05, it is $\simeq 0.10$ in NGC 5812; it is therefore not surprising that the deviations from ellipticity are small, from the a_4-ellipticity relation found by Bender et al. (1988). These four galaxies (marked with a double star in column 11 of Table 1, where they are listed or completeness) will not be considered further in the subsequent discussion.

5. Results and discussion

We have found that, among 99 galaxies classified E's in the RSA, 16 show internal isophotal twists larger than 20°. In at least 12 of them, this isophotal twist is well correlated with the behavior of

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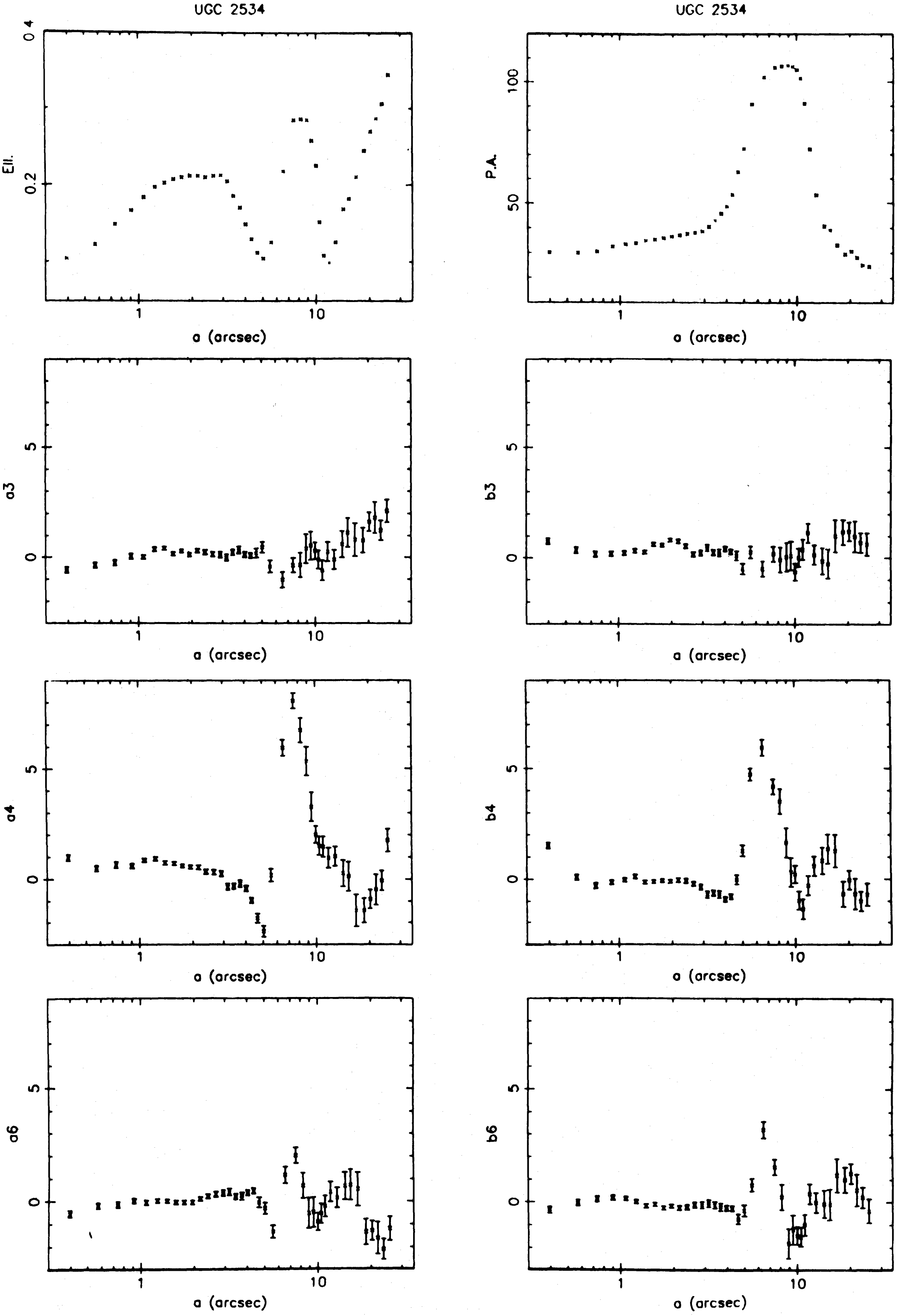

Fig. 2c1

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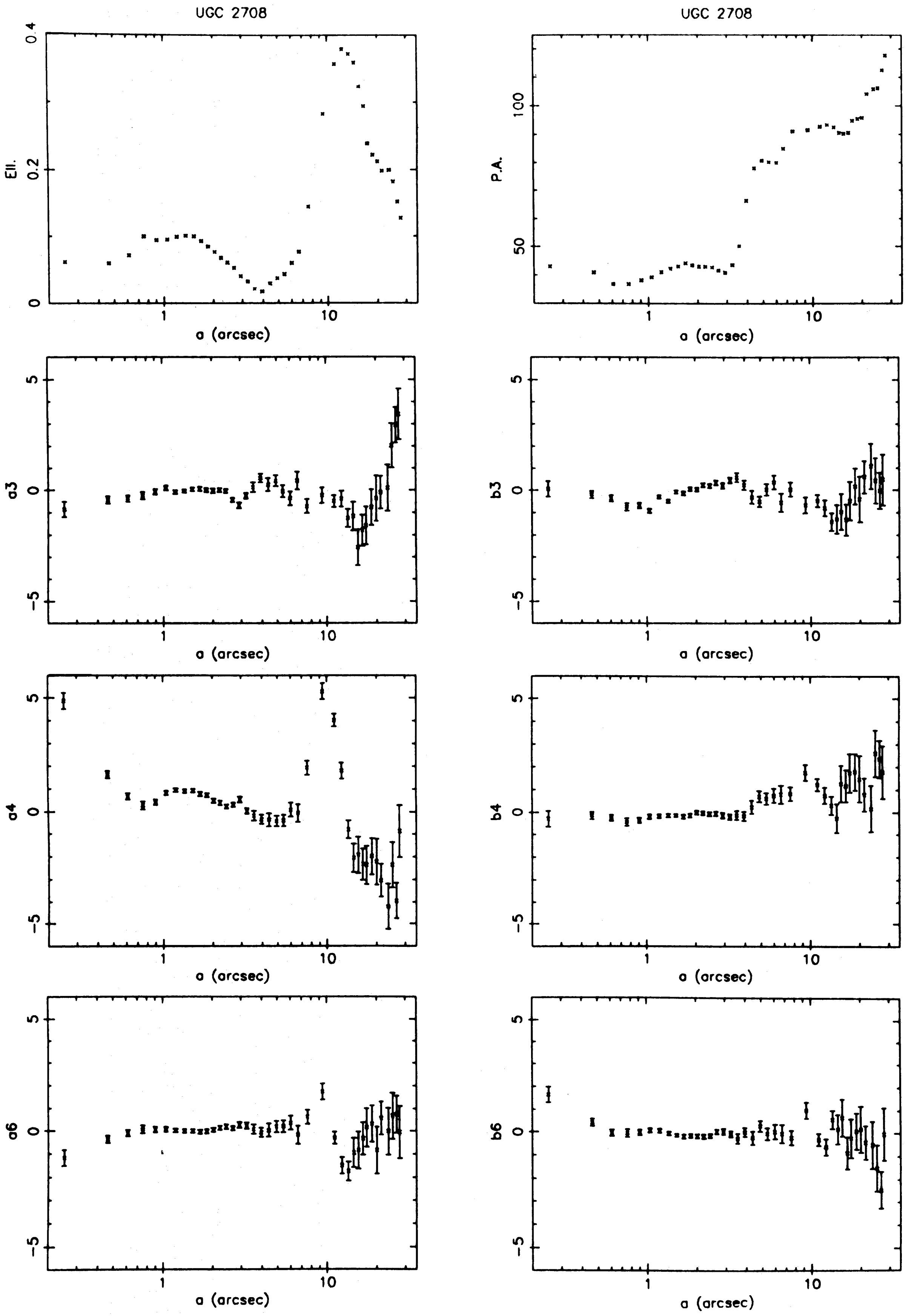

Fig. 2c2

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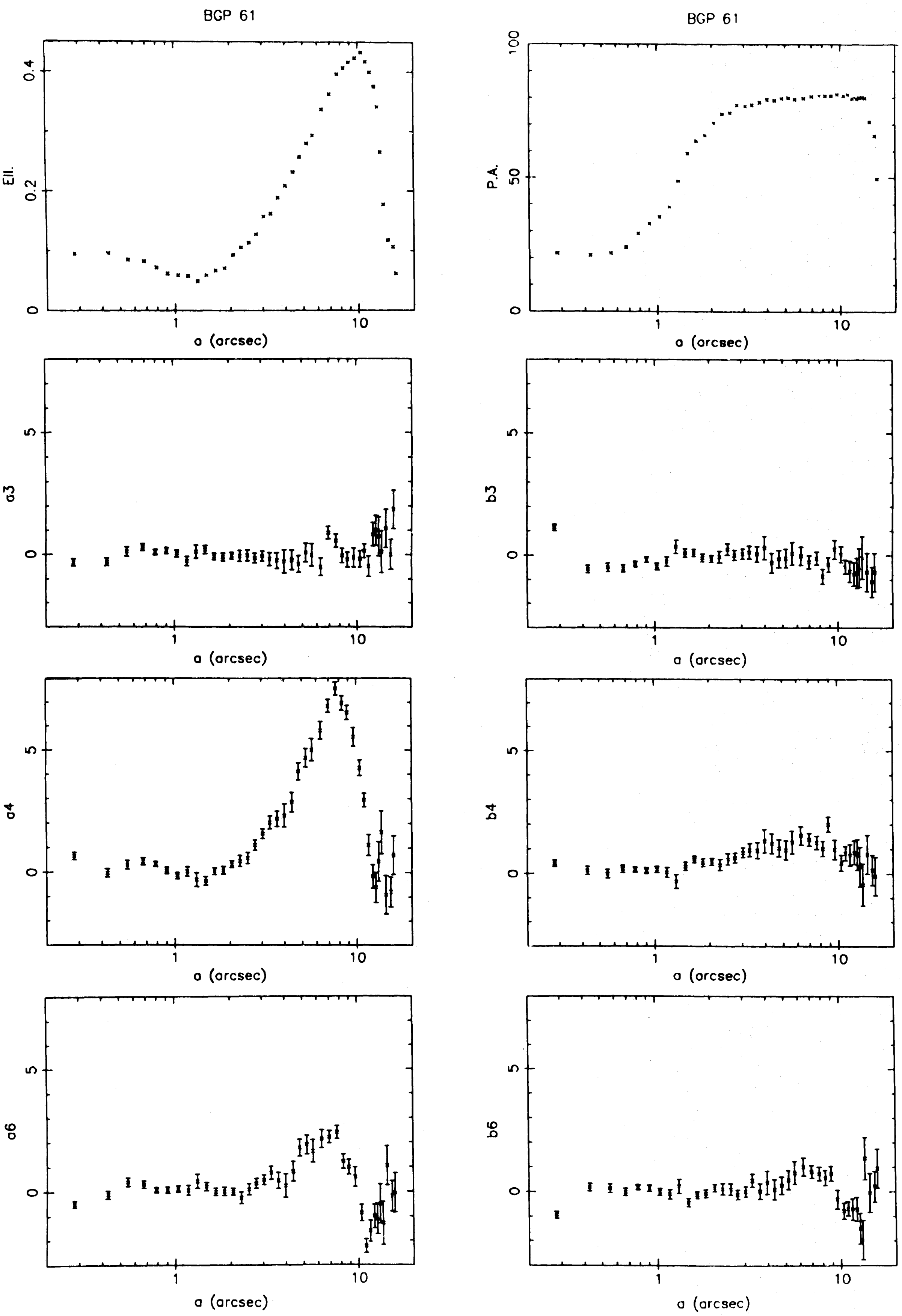

Fig. 2c3

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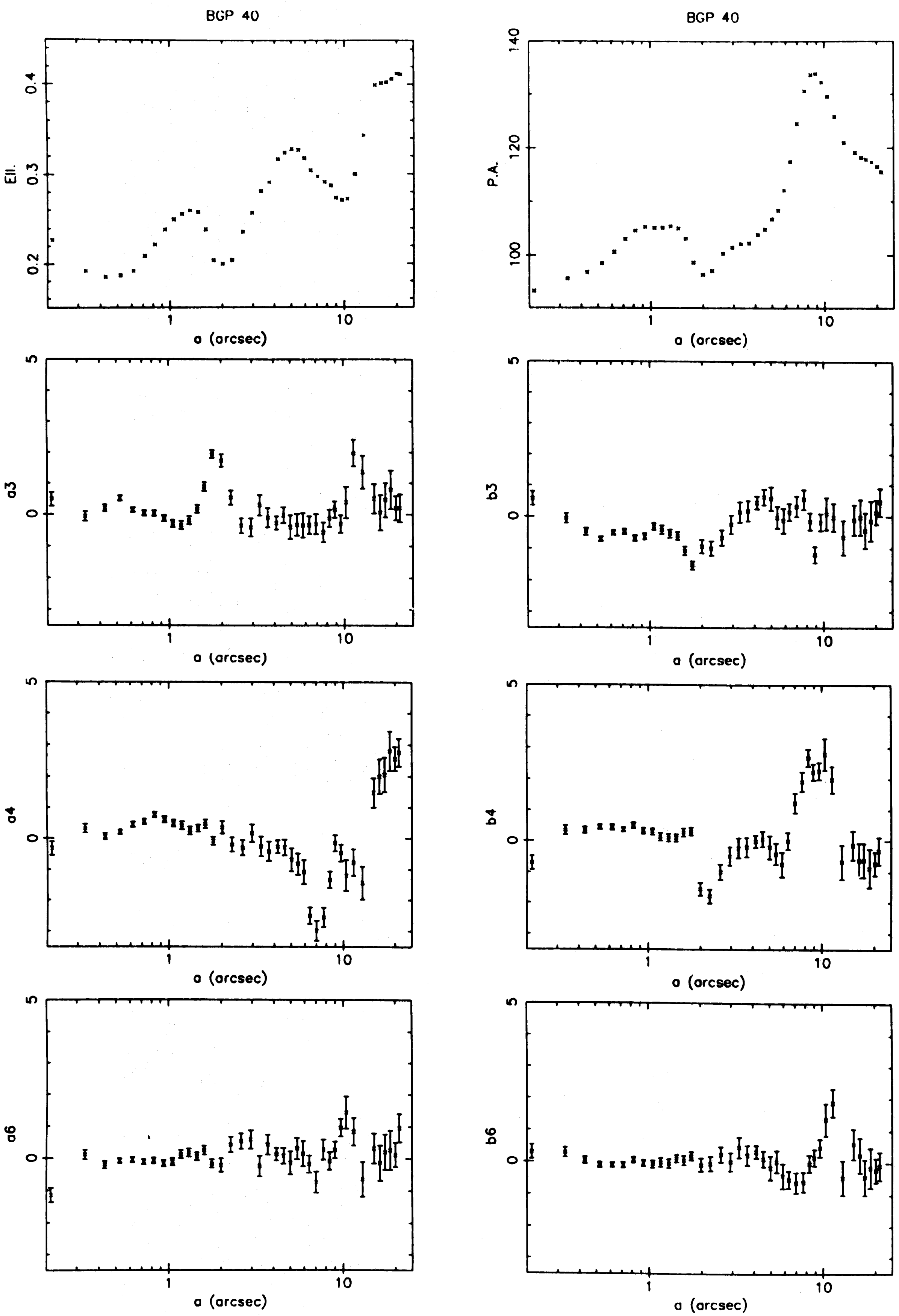

Fig. 2c4

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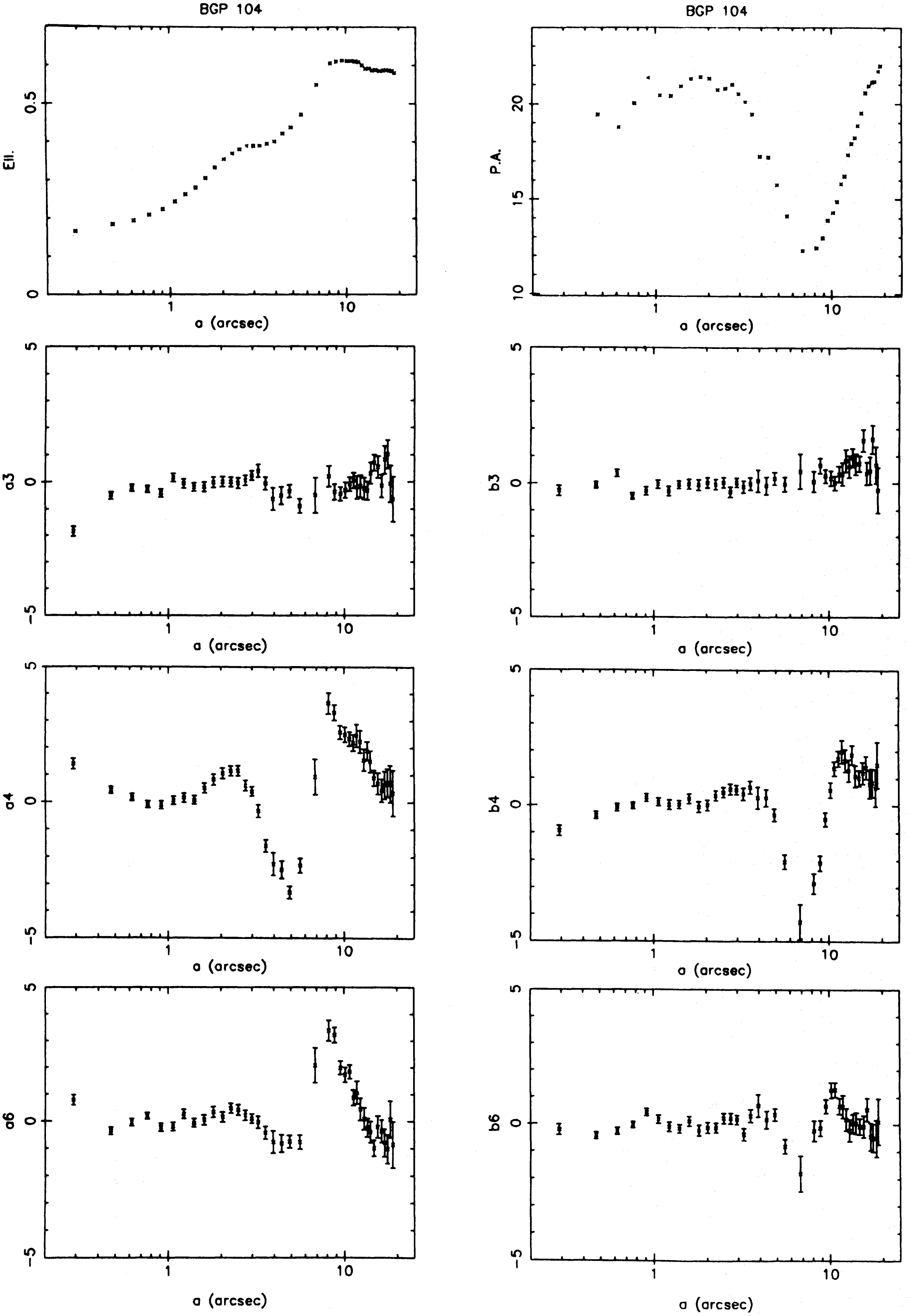

Fig. 2c5

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the cos 4θ term in the Fourier expansion of the deviations of the isophotal contours from perfect ellipses, in the same way as barely resolved SB0 galaxies. The four others show no deviations, probably because of an unfavorable orientation (or because they are purely ellipsoidal systems).

5.1. *E with large isophotal twists = SB0s?*

The above description shows that strong morphological similarities exist between those E's having large inner isophotal twists and SB0s. The earlier fear that Galletta's effect could be contaminated by SB0s (Galletta 1980; Kormendy 1982) is, in a sense, fully confirmed, but at deviations from elliptical contours that do not exceed a few percents. These data are, therefore, very consistent with the fact that *E's showing strong isophotal twists are SB0's with substructures strongly overlapping each other, or at least two-component systems.*

Further elements support this view:

(a) Galletta's sample. A few galaxies showing large isophotal twists in Galletta's sample lie in the Perseus Cluster, and have been reclassified from isophotal analysis of high-resolution images as being SB0s, or even being early spirals by Poulain et al. (1991b); this is the case for NGC 1274 ($\Delta\Phi = 18°$) and CR 32 ($\Delta\Phi = 63°$).

(b) Poulain et als sample. Similarly, many other galaxies, classified E's in earlier studies, not listed in the RSA, and showing large isophotal twists, appear clearly as SB0 systems. In addition to the galaxies discussed above (Sect. 3 and Fig. 2), this could be exemplified by other early-type galaxies in the Perseus Cluster such as UGC 2598, NGC 1250 or NGC 1294, classified E by Kent & Sargent (1983) (see Poulain et al. 1991a, b).

(c) In the same spirit, it is likely that all *isolated* elliptical galaxies with isophotal twists discussed by Fasano & Bonoli (1989) can be interpreted, as the authors suggest, in the same way. Out of their 43 galaxies, rather distant or faint, observed with average seeing, 4 of those having the largest isophotal twists are suggested by Fasano & Bonoli to contain bars, a few being perceived as "boxy" (from visual inspection since no quantitative isophotal analysis was made). It is therefore likely that an isophote analysis of images of those galaxies obtained at sub-arcsec resolution (a resolution that allow to identify very clearly SB0s among E's in the Perseus Cluster) would lead one to a higher percentage of imbricated bars or spiral arms. This is illustrated by the one galaxy in common in their list and that of Poulain et al. (1991b): UGC 2656, for which Fasano & Bonoli adopted the UGC classification (= E), whereas the 0\".60 R image of CFHT reveals an undoubtedly SB0 structure (see Fig. 2b4). (Note also that, in their list, NGC 3265 showing moderate isophotal twists, 15°, is in fact a low-mass starbust object, see Nieto et al. 1991b).

Furthermore, the finding that E's with isophotal twists are SB0-like systems gives a natural explanation to the remark by Fasano and Bonoli that the amount of twisting in the "E" galaxies of their sample is related to the shape of the luminosity profiles, galaxies with no twists having luminosity profiles close to an $r^{1/4}$ law, while those with twists presenting more complex profiles.

(d) In NGC 4278, a galaxy known for its outer hydrogen gas not rotating like the stars in the optical galaxy (Knapp et al. 1978; Schechter & Gunn 1979), the apparent skewing of the gas kinematic major and minor axis is most easily accounted for by assuming that the gas moves in oval orbits in a barred potential field (Raimond et al. 1981).

In connection to these arguments, we found it remarkable that the Brightest Cluster Member from our list, NGC 3158, turns out to be an SB0 object. This leads us to suggest that a significant proportion of Brightest Cluster Members showing strong isophotal twists (see Porter et al. 1991) will turn out to be barred systems also.

5.2. *Influence of resolution on morphological classification*

In the past, high-resolution imaging has often revealed that many galaxies conventionally classified as "E" contain fine structures and that their isophotal contours deviate from ellipticity; it has shifted morphological galaxy types toward later stages (see Poulain et al. 1991a, b). A first spectacular instance of the resolution of an imbricated structure is the observation at CFHT by van den Bergh (1980) that NGC 3928, earlier classified as E, is in fact one of the most compact spirals yet discovered. Similarly, NGC 584, recognized to be a good example of E with isophotal twists by Williams & Schwarzschild (1979; 10′, and thus not included in our list) appeared clearly on high-resolution photographic plates to be an SB0 (Capaccioli et al. 1983). This result is indeed supported by isophotal shape analysis (Nieto et al. 1991b), showing two angular ranges where isophotes are found to be disky, and features in the outer diskiness (see also Bender et al. 1988).

5.3. *On some galaxies with smaller isophotal twists*

Besides NGC 584, galaxies with smaller isophotal twists that could be SB0s can be recognised from their two-component structure. Indeed, in most galaxies showing isophotal twists, a correlation between features in the PA profile, the ellipticity profile and the a_4 profile (in the sense that they all occur at the same distance to the center), suggests that isophotal twists are indeed due to sub-structures strongly overlapping each other. Structures similar to NGC 596, 584 and 1549 (inner boxiness, outer diskiness) are found in NGC 2300 ($\Delta\phi = 15°$), NGC 5557 and NGC 7562, but turn out not to be frequent: possible other cases are NGC 4564 and 4660 (see Bender et al. 1988) or NGC 720 (Nieto et al. 1991b). The other case (inner diskiness and outer boxiness) is more frequent (see, e.g. Nieto & Bender 1989), and is easily detected among elongated E's (Nieto et al. 1991b; Nieto & Poulain 1991).

In particular, 40% of elongated E's showing predominantly disk deviations (and thus called "disky") contain also boxy isophotes and are thus recognized as disky E's with a boxy bulge ("boxy lemons"). It is tempting to argue that at least some of these elongated galaxies can be interpreted as edge-on SB0s. Three arguments are in favour of this hypothesis:

(a) This percentage of boxy lemons among elongated disky E's is close to that (1/3 after Bosma 1991) of barred objects among late-type objects;

(b) Numerical simulations by Combes & Sanders (1981) and Combes et al. (1990), show that bar instabilities within a massive (probably more massive than those that are discussed here) disk can produce a fat boxy or peanut-shaped object which, seen face-on, would be called a bar-like bulge.

(c) In the sample of alongated galaxies of Nieto et al. (1991b), a change in the PA profile, even small, in the main body of the

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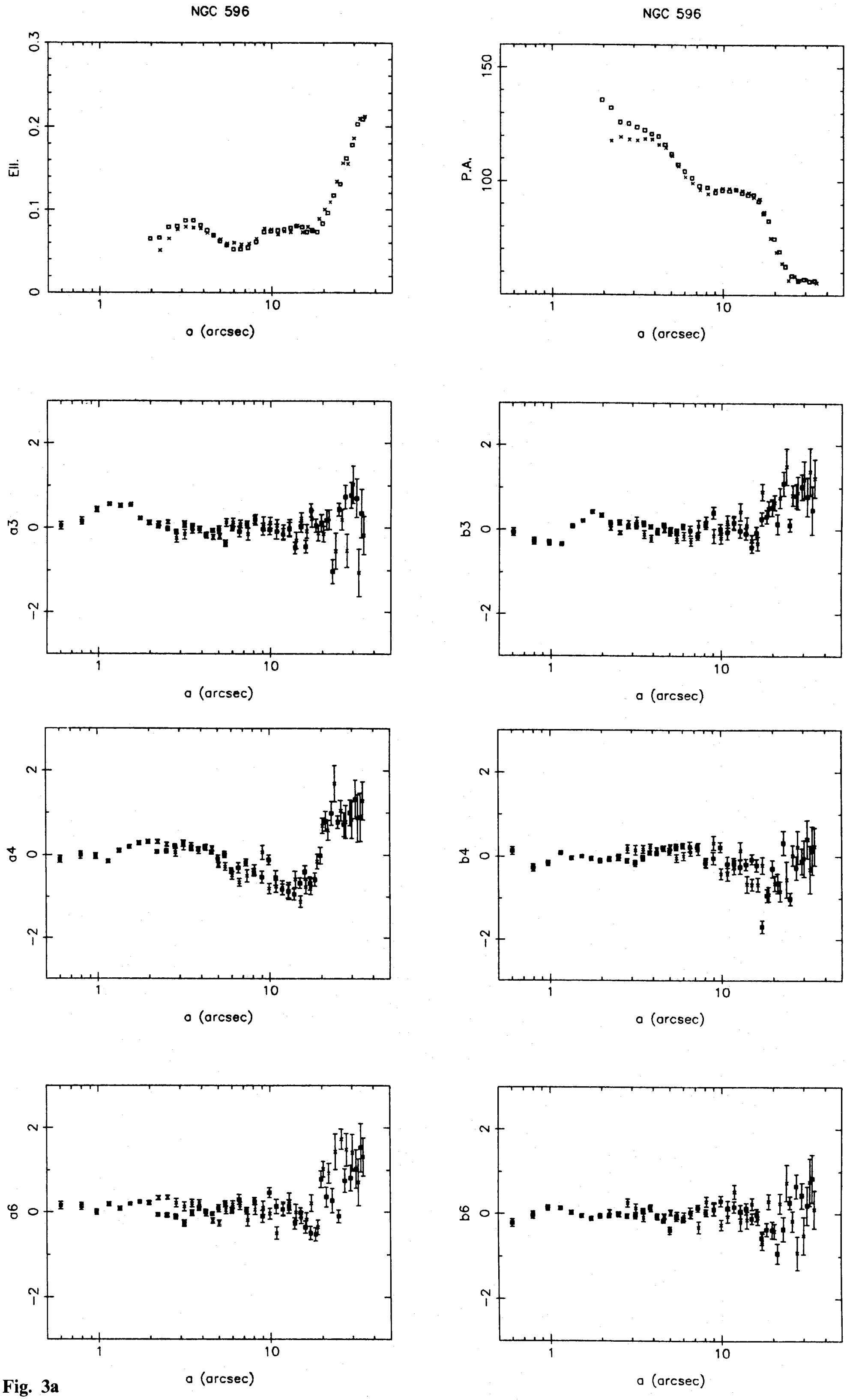

Fig. 3a

Fig. 3a–e. Geometrical parameters of E galaxies with strong isophotal twists from the list in Table 1: **a** NGC 596 (R and V bands, from Pic du Midi images; FWHM = 1.3 and 1.0″, respectively); **b** NGC 636 (R band, from Calar Alto, FWHM = 1.8″); **c** NGC 1549 (R band, from the ESO 2.2 m telescope, FWHM = 1.0″); **d** NGC 3158 (R and V bands, Pic du Midi, FHWM = 1.3″ and 1.2″); **e** NGC 3415 (R and V bands, Pic du Midi, FWHM = 1.6″ and 1.3″). For **a**, **c** and **d** R images are plotted with *crosses*, V images with *open squares*. Note that Fourier coefficients are normalized to the semi-major axis; in **a**, **d** and **e**, the zero points of the position angles are arbitrary, and the Fourier coefficients are multiplied by 100

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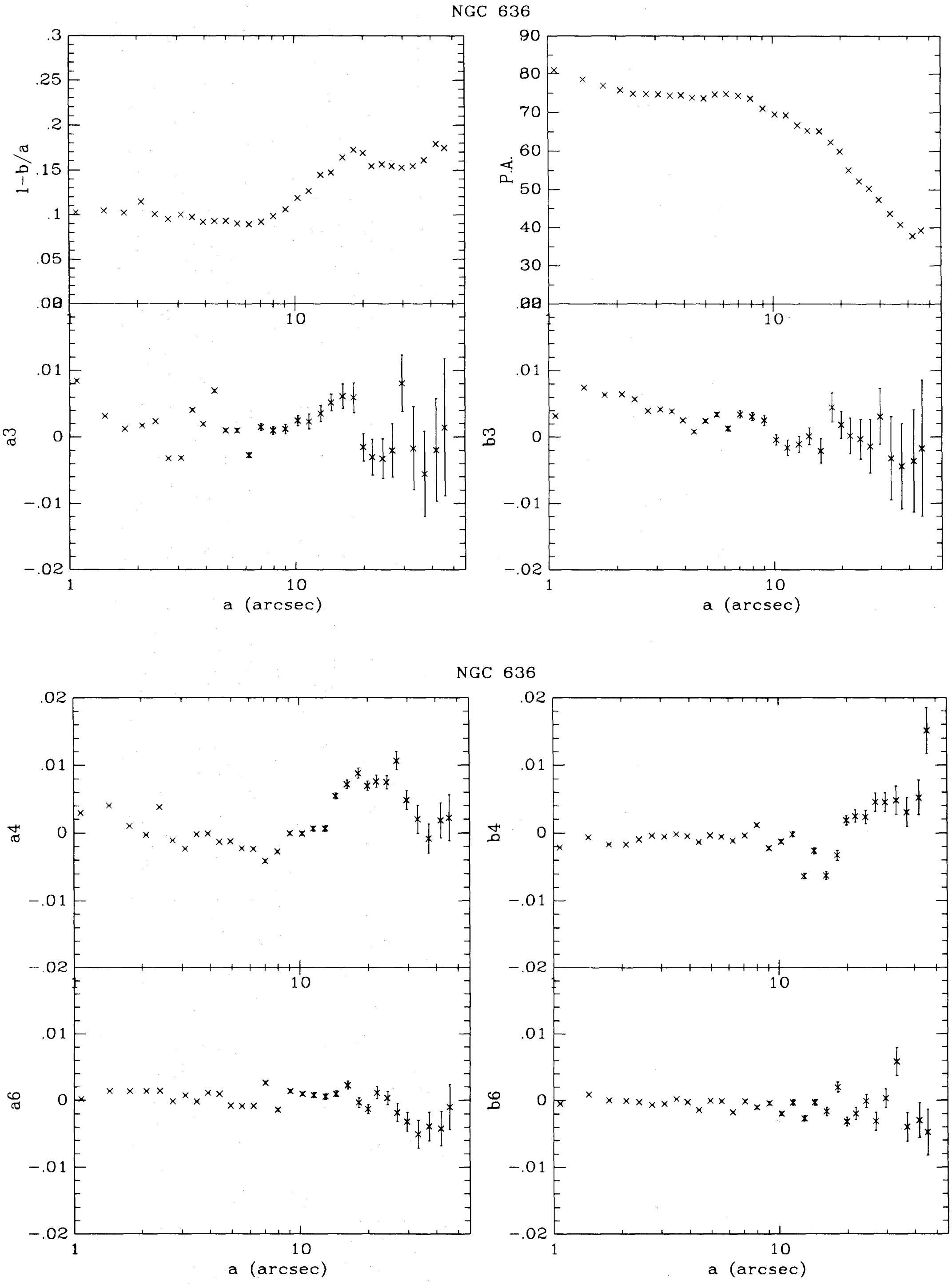

Fig. 3b

galaxy appears where a change of sign in the a_4 occurs: see, for instance, the cases of NGC 227, NGC 543, NGC 558 (?), NGC 1052, IC 312, NGC 7034, NGC 7052, NGC 7785.

In other words, only orientation would be responsible for differentiating the observable properties of these SB0s containing very imbricated substructures and that are called E's: a) disks are recognised in E's when the systems are seen edge-on (with no isophotal twists, but slight bar-like deviations in 1/3 of them), while b) strong isophotal twist (but no disk) would be detectable when the system is seen face-on.

5.4. *Kinematics of SB0-like systems*

Let us assume that all E galaxies with large isophotal twists discussed above, except NGC 3415 (spiral like) and the five having no significant deviations, are two-component systems,

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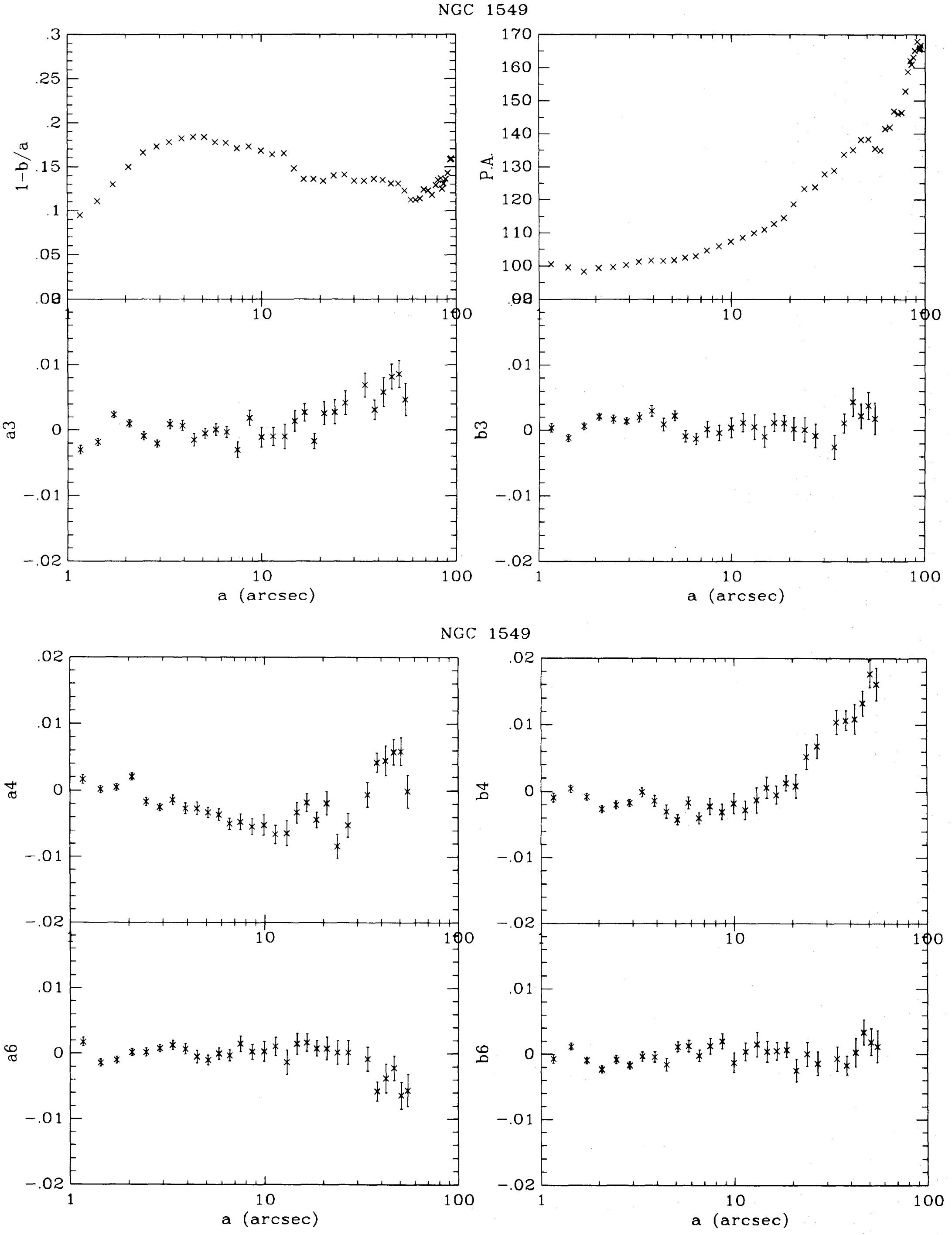

Fig. 3c

namely SB0s with overlapping substructures. In this case, long-slit spectroscopy along average directions should reflect, in spite of the angle offset, the kinematics of the stellar bar (streaming motions, cf. Bettoni 1989, and little rotation) and that of the disk (fast rotation).

In their kinematical study of 22 E's, Franx et al. (1989b) observed three galaxies showing large isophotal twists: NGC 636, NGC 1549, and NGC 7145. The "major" axis that they adopted was the mean of the PA between 10 and 30″ (from Franx et al. 1989a). They noticed minor axis rotation in these three galaxies and note even that NGC 1549 and NGC 7145 have $v_{\rm min} \simeq v_{\rm maj}$. In NGC 636, only "major-axis" rotation has been observed.

NGC 636 (Figs. 3b and 4a): The adopted kinematical major axis is that of $r \simeq 20''$, namely PA $=60°$; at this distance to the center,

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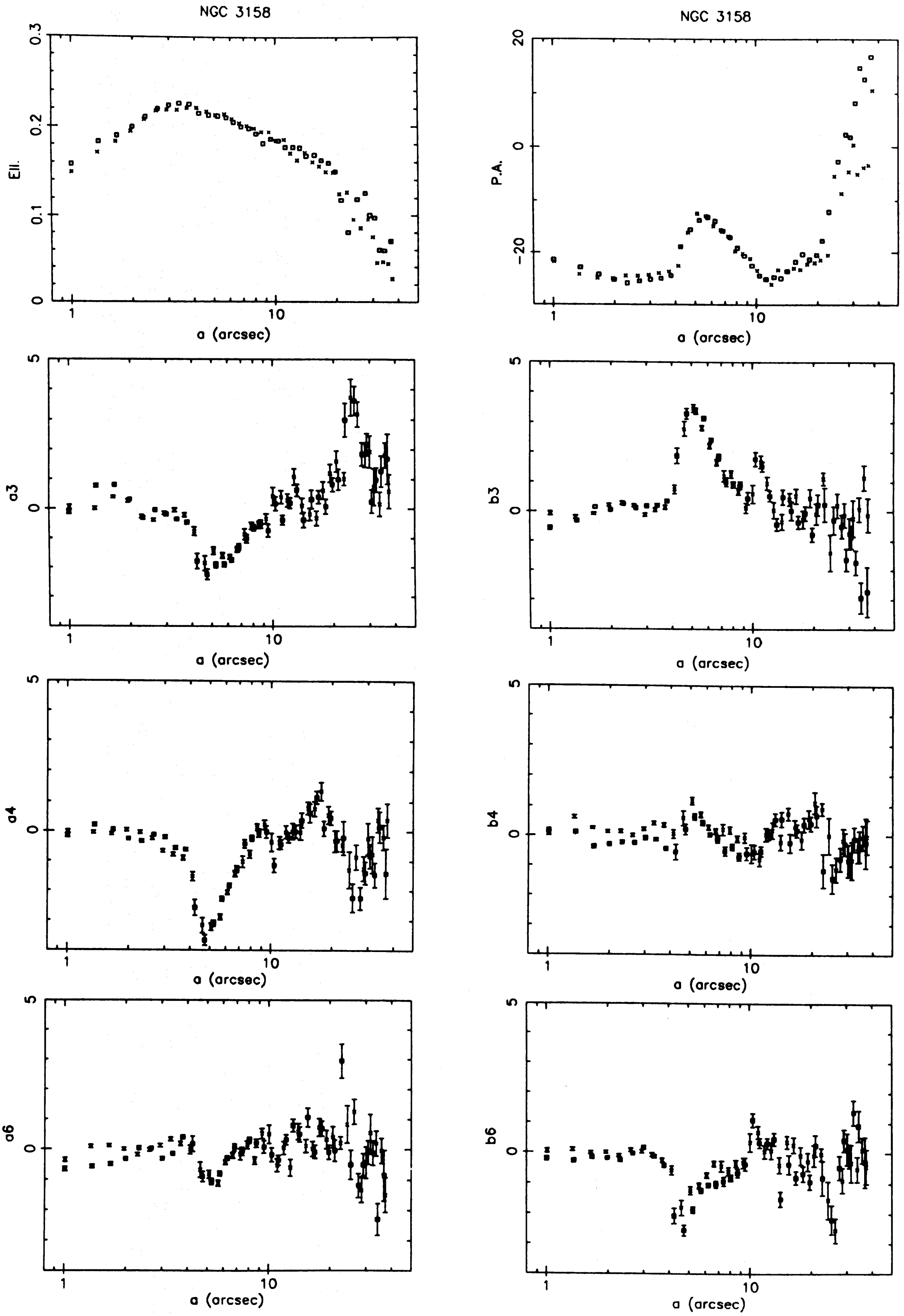

Fig. 3d

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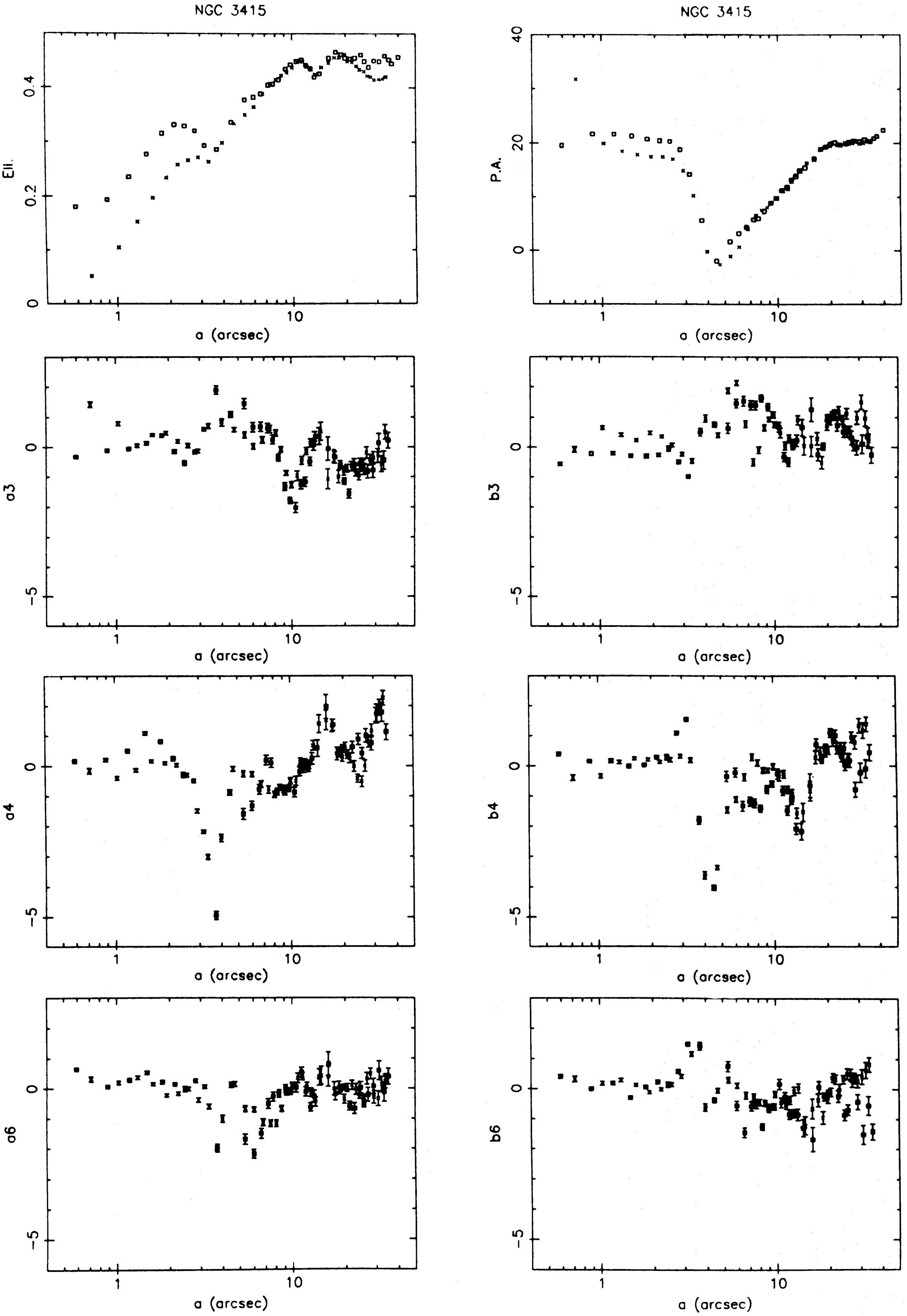

Fig. 3e

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the disk deviations of the central bulge (oriented at PA = 75°) are maximum. Beyond 30″, the bar tends to protrude, oriented toward 0°, but, unfortunately, no kinematical measurement is available at these distances. Since the directions of both the inner (rotating) bulge and the adopted kinematical major axis are close, the rotation is indeed found only along the major axis, and little, if any, is found along the minor axis.

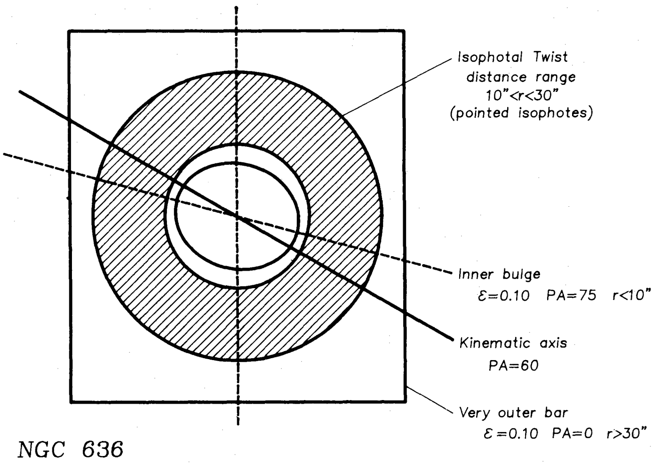
NGC 1549 (Figs. 3c and 4b): This case is extremely interesting since the kinematical data (reaching $r \simeq 40''$) almost cover the two sub-systems. The bar, however, seems to dominate up to 30″. The adopted kinematical PA is ≃127°, close to that of the isophotal contour at a distance ($r \simeq 25''$) where the bar deviations are maximum. Beyond, the outer disk (lens) starts to protrude, oriented at PA = 140°, while the bar itself (clearly showing at 25″) is at PA = 120–130°. The kinematical measurements show weak (25 km s^{-1}) minor- and major-axis rotation up to 25″, very consistent with a inner bar at this distance range, and a large major axis rotation outside (due to the presence of a disk whose major axis is 20° away). This major-axis rotation outside is, in turn, of large amplitude as that along minor axis (which is evidently not zero). This is to be expected if the kinematic axis is closer to the real major axis of the lens than to the minor axis. The minor-axis rotation at $r = 40''$ may indicate that the bar component still contributes at this distance. The kinematic axis is ≃30° away from the major axis of the very central bulge, which easily explains the almost equivalent minor- and major-axis rotation. Measurements further out are obviously crucial to define better the relative contribution of these different structures.

NGC 7145: The adopted kinematical axis is 132°. The central bulge extends up to 30″, slightly over the limit of the kinematical measurements. The situation is slightly more complicated than in the two other cases, since there is, in addition, an inner isophotal twist. However, the minor-axis rotation can be well explained by the fact that the slit axis does not go through the major axis of the system.

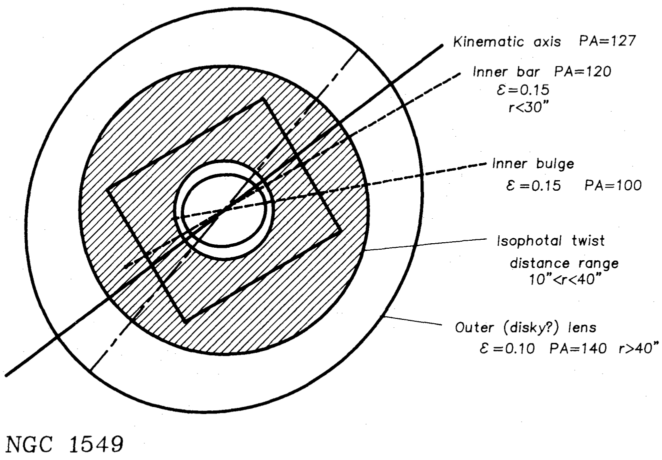
Similarly, in NGC 596, the steepest gradient is measured at PA = 120° (Williams 1981), namely the PA of the major axis of the galaxy in its central region. This is in agreement with the assumption that the very central region ($r < 10''$) is the central bulge of an SB0 galaxy. (A similar argument applies for NGC 584.)

Another extremely interesting case is that of NGC 4278 which can be described morphologically as being very much like NGC 636: an inner bulge with dust, oriented at PA ≃ 20° and an outer bar oriented at PA ≃ 40°, that contain pointed isophotes at $r \simeq 30''$, like in NGC 636). Detailed kinematical measurements by Davies & Birkinshaw (1988; see also Schechter & Gunn 1979) show a central rotating body with $v_{max} \simeq 50$ km s^{-1} at PA = 0 and 45, little rotation at PA = 135, and no rotation at all at PA = 90. These results are quite consistent with the assumption of a central bulge elongated in the PA = 20° direction. The possible "reversal" of the rotation velocity emphasized by Illingworth & Franx (1988) coincides with the appearance of the outer bar-like system and may simply reflect its different kinematical behavior.

Data on the other galaxies are scarce: most of them suffer from the limitations of single-axis spectroscopy, or and of photography. Because of the isophotal twists, all systems from our sample are expected to present either low "major-axis rotation" or some "minor-axis" rotation: this is the case for NGC 5831 (Davies et al. 1983) for instance. All kinematical data thus quite nicely support the idea of E's being SB0s or, more generally, two-component systems.



a



b

Fig. 4a and b. Schematic representation of the geometry of two E galaxies with isophotal twists for which major- and minor-axis kinematics are available: **a** NGC 636, **b**: NGC 1549. The shaded areas define the angular distance range where the isophotal twists take place

5.5. *Isophotal shape correlations*

A corollary of this recognition of E's with isophotal twists being SB0-like systems is the following: in the same way as disks in E's have been recognised in E's from small $a_4 > 0$ deviations, bars in E's are now recognised (i) from small $a_4 < 0$ deviations AND (ii) as producing (but not necessarily) strong isophotal twists. Formerly classified as "irregular", E's with strong isophotal twists can be now clearly understood as being bar or bar-like systems, are probably must be physically related to the "boxy-lemons" family discussed by Nieto & Bender (1989), from which they differ probably only because of orientation effects. Even if these SB0-like E's introduce a further refinement in the disky/boxy dichotomy, these considerations do not basically

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change the overall picture outlined by Bender et al. (1989), since several of them, as irregular systems, were not included in the two main classes.

6. Consequences and conclusions

The present study shows that, in most cases (the exceptions being essentially some round E's where *no* deviation can be detected, or E's where isophotal twists are produced by barely detectable spiral structure), E's with large isophotal twists are systems physically similar to SB0s, but harboring substructures more overlapping with each other than standard SB0s *at the same distance range* would. This very likely applies also to a large percentage of E's showing smaller isophotal twists, but the data are more difficult to interpret univocally. These SB0-like E's may be either disk-dominated outside (NGC 584, 596, 1549) or bar-dominated (NGC 5831, 1395, 3872). Consequently, in the same way as isophotal analysis has permitted us to uncover unambiguously faint disks in E's, and to recognize the physical similarities of disky E's and S0s, it also permits us to uncover imbricated bars in E's and to relate these barred E's to SB0s. This suggests *a strong continuity in morphological properties between S0/SB0s and these E's where disks and bars have been unambiguously uncovered*. This result has interesting consequences on the Hubble sequence and all the correlations that are attached to it (Tremaine 1987). Indeed, it was previously believed that the tuning fork diagram and the parallel sequences of barred/unbarred systems stop at the S0 stage. It appears now that the tuning fork diagram continues through much earlier types, with substructures so imbricated that orientation effects are an extremely crucial factor for determining the global structure of these systems[1]

Incidentally, another consequence of the discovery of bars (+ accompanying disks) in elliptical galaxies relates to the controversial origin of the subtle large-scale disks recently discovered in E's, whether formed dissipatively at early stages in the history of the galaxy (but possibly affected at a later stage by recent merging events; Nieto 1988, Nieto & Bender 1989; Scorza & Bender 1990) or resulting from recent accretion events (Schweizer 1990; Schweizer et al. 1991). The physical similarity between E's having isophotal twists and SB0s tend to support the former view and confirms that *not* all fine structures in E's must necessarily result from mergings. Instabilities in these large-scale disks would thus be responsible for barred structures as complex as those found in later types, but in a most imbricated way.

The above considerations on the nature of E's with large isophotal twists stress once more that deviations from ellipticity, even small, represent important crucial information on the structure and formation of elliptical galaxies. What our study specifically suggests is that the boxy deviations seen in E's harboring large isophotal twists (systems close to face-on) as well as some of those seen in boxy/disky systems ("boxy lemons", close to edge-on) are indicative of the presence of a bar, but this result does not imply that *all* boxy deviations can be interpreted as being due to subtle bar structures within a galaxy: indeed, the underlying kinematics of SB0 systems and that of purely boxy systems (as opposed to that of boxy/disky systems) have been observed to be basically different (see Nieto & Bender 1989). However, a simple remark ought to be made at this stage: in at least some galaxies (notably relatively remote ones), distance effects smooth out large deviations from ellipticity in such a way that a nearby standard SB0 galaxy could appear to be a boxy/irregular E at large distances; therefore, boxy deviations from ellipticity, even small ones, may be evidence for the presence of a bar, in the same way as small disk-like deviations in some other galaxies is evidence for the presence of a disk. This cannot be applied, of course, in a systematic way (the case of a spurious boxiness due to spiral arms has been discussed here). However, using this straightforward interpretation as a first approximation may unravel interesting, admittedly speculative, clues. One of them would be to suggest that even the most irregular E's may be made up of overlayed, structurally simpler subsystems. This could explain not only isophotal twists (even small ones), but also some of the behaviors of the ellipticity profiles, as well as peculiar kinematics. Even if some evidence in favor of such an assumption already exist (of course, several alternatives are possible), further work is necessary before such this idea can be really discussed on a safe basis.

Another consequence of this study is on the three-dimensional structure of E's, and their "triaxiality". The idea of triaxiality is essentially based on: i) isophotal twists, and ii) anisotropic kinematical behavior. However: i) inner isophotal twists (we exclude the outer isophotal twists that may result from tidal effects) tells us that a large percentage of elliptical galaxies is intrinsically triaxial in the sense that they are two-component structures and that they contain bars; ii) most of the anisotropic systems show clear boxy deviations from ellipticity (Bender 1988). These two types of deviations (morphologically similar, but of very different physical origin, as inferred by, e.g. their kinematics) suggest that a large percentage of triaxial systems do not have the form of pure ellipsoids; only the systems showing no deviations, namely the very round ones, may be pure triaxial ellipsoids.

Acknowledgements. We are indebted to L. Athanassoula, F. Combes, G. Fasano and T. Davidge for comments on a first version of this paper, to J. Glaspey for his carefully reading of the manuscript and to K. Sweeney for his magical drawings.

[1] It would be very important indeed, as suggested by several colleagues, to attempt a disk/bulge/bar decomposition of the SB0-like E galaxies; however, we fear that the problem of barred E's is by far more complex than that of standard SB0s

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