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EVIDENCE FOR NONAXISYMMETRIC NUCLEAR BULGES IN SPIRAL GALAXIES

DENNIS ZARITSKY AND K. Y. LO
Department of Astronomy and Palomar Observatory, California Institute of Technology
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ABSTRACT

The $\lambda = 0.8$ μm surface brightness distribution of the nuclear region of 11 galaxies was analyzed to look for evidence of deviation from axisymmetry. Nuclear bulges are clearly present in all the galaxies, including the Sc galaxies. Variation of the position angle and ellipticity with semimajor axis length of the elliptical isophotes of the nuclear region was found in all the galaxies. This suggests that nonaxisymmetric nuclear bulges could be very common in ordinary spiral galaxies. As a result, the presence of noncircular gas motion in the central regions of spiral galaxies should be generally anticipated. Other implications are also discussed.

Subject headings: galaxies: photometry — galaxies: structure

I. INTRODUCTION

Spiral galaxies are generally divided into the ordinary and the barred families (cf. Sandage 1961). Of the galaxies in the revised Shapley-Ames catalog (Sandage and Tammann 1981), about one-third are classified as barred. However, among the ordinary galaxies, whether the light (and therefore mass) distribution in the nuclear bulge is axisymmetric has not been systematically studied. The form of the light (mass) distribution has an important bearing on the gas dynamics in the central region of galaxies.

Recent aperture synthesis observations of CO emission from the nucleus of the galaxy IC 342 have shown that the spatial distribution and kinematics of the molecular gas there are best explained as the gas response to an oval gravitational potential (Lo *et al.* 1984). An oval distortion in the light distribution in the nucleus of IC 342 is seen in the 2.2 μm distribution (Becklin *et al.* 1980; Kinney *et al.* 1985). As demonstrated in numerical studies (e.g., Roberts, Huntley, and van Albada 1979; Sanders and Huntley 1976; Huntley, Sanders, and Roberts 1978), a small deviation from axisymmetry in the nuclear mass distribution can lead to substantial noncircular motion of the gas. Such noncircular motion in the gas can cause enhanced cloud collisions and growth of molecular clouds (Scoville and Hersh 1979), as well as radial transport of gas toward the galactic center. This may be an underlying mechanism for enhancing the surface density of gas in the nuclei of some galaxies, as well as for triggering star formation there. Simkin, Su, and Schwarz (1980) have suggested that Seyfert galaxies are fueled by inward flow of gas caused by a barlike potential.

IC 342 is not obviously a barred galaxy (even though it has been classified as SAB(rs)cd by de Vaucouleurs, de Voucouleurs, and Corwin 1976). Yet, the distribution and kinematics of the gas show such significant deviation from axisymmetry that it raises the question of how common oval distortions are in the mass distribution in the nuclear regions of ordinary spirals. If such oval distortions are indeed common, then their effects on the gas dynamics have to be taken into serious consideration.

In order to assess the frequency of occurrence of such oval distortion, we obtained CCD pictures of a sample of 11 galaxies (Table 1) and analysed the surface brightness distribution. The galaxies used in the study were chosen to have large angular extent and to include various Hubble types. To identify deviations from axisymmetry we examined the position angle and ellipticity of isophotal contours as a function of the semimajor axis length. Similar analysis of position angle and ellipticity variations has been done for elliptical galaxies in search of triaxiality (e.g., Williams and Schwarschild 1979). An extensive study of surface brightness profiles for spiral galaxies by Kent (1984) includes position angle and ellipticity data, but there was no discussion of nonaxisymmetry in the nuclear bulge of the galaxies studied. Hackwell and Schweizer (1983) showed the existence of an infrared bar in the center of NGC 1566, an ScI galaxy. We report here our study of 11 spiral galaxies and our findings.

II. OBSERVATIONS AND DATA REDUCTION

Pictures of the galaxies were taken with the RCA CCD camera on the 60 inch (1.5 m) telescope at the Palomar Observatory during runs in 1984 May and August. The CCD is a 320 × 512 pixel back-illuminated thin chip. It has a scale of $0\farcs46$ pixel^{-1} without the reimaging lens, and $1\farcs29$ pixel^{-1} with the lens. The Gunn *i* filter, centered at approximately 8250 Å, and the Gunn *z* filter, centered at approximately 9500 Å were used. Filters at these relatively long wavelengths were used in order to emphasize in the pictures the older stars in the nuclear bulge and to minimize the effects of dust. Despite its shorter wavelength, the *i* filter was used more extensively because of the higher sensitivity of the camera in this band.

The exposure time was mostly in the 1–2 minute range, but was sometimes up to 5 minutes. Flat-field exposures were done by exposing the CCD to an illuminated area at the top of the dome, at the beginning and the end of each night. The seeing was between 1″ and 2″, quite adequate for the purposes of our study.

Each frame contains an erase line in the header. The erase line was subtracted from the images when they were read off the tape, and then each image was divided by the average of the two flat fields taken that night. The images were then analyzed with the Galaxy Aperture Surface Photometry (GASP) computer package developed by Mike Cawson of Steward Observatory.

The background, typically on the order of 100 counts, has a gradient across the image of on the order of 1% after flat-fielding. The background used in GASP was measured by averaging counts along a border of the image typically 40

TABLE 1

PARAMETERS OF SAMPLE GALAXIES

Name	Type	Scale of Observation (pixel^{-1})	Distance[a] (Mpc)	i[b]	P.A. of disk	References
NGC 488	Sab(rs)I	0".46	30.8	24°	15°	1, 2, 3, 4, 5
NGC 628	Sc(s)I	0.46	10.6	22	115	2, 4, 5, 6
NGC 3810......	Sc(s)II	1.29	15.5	50	28	1, 2, 4, 5, 6
NGC 4254......	Sc(s)I/3	1.29	31.5	25	85	2, 4, 5
NGC 5194......	Sbc(s)I-II	1.29	6.0	20	170	4, 5, 7
NGC 6814......	Sbc(rs)I-II	1.29	22.4	19	55	2, 4, 5, 6
NGC 6946......	Sc(s)III	1.29	4.7	30	62	2, 4, 5, 8
NGC 6951......	Sb/SBb(rs)I.3	1.29	22.4	30	55	2, 4, 5, 6
NGC 7177......	Sab(r)II.2	0.46	16.0	60	90	1, 2, 4, 5, 9
NGC 7217......	Sb(r)I-III	0.46	16.3	35	86	2, 3, 4, 5
NGC 7331......	Sb(rs)I-II	0.46	14.6	71	171	1, 2, 4, 5, 6

[a] $H_0 = 75$ km s^{-1} Mpc^{-1}.

[b] Inclination angle (0° = face on).

REFERENCES.—(1) Nilson 1973. (2) Palumbo *et al.* 1983. (3) Rood and Dickel 1976. (4) Sandage 1961. (5) Sandage 1981. (6) Shostak 1978. (7) Tully 1972. (8) Rogstad *et al.* 1973. (9) Bottinelli *et al.* 1970.

pixels wide, so that the deviation of this value from either edge should be less than 1%. Therefore, the gradient has a negligible effect on the galaxies.

The program was used to fit ellipses to the isophotes of the galaxy, yielding the position angle (P.A.) of the major axis; the ellipticity $\epsilon = 1 - b/a$, where a and b are respectively the semimajor and semiminor axis length of the fitted ellipse, and the average intensity along the contour at designated semimajor axis lengths. The fitting is done by applying a least-squares fit on the coefficients of a Fourier expansion of the pixel intensity variation along the trial ellipses. The fitting procedure in GASP gives the residuals, a measure of the convergence, of the Fourier coefficients of the series used to fit the ellipses.

The errors associated with the fitted parameters, P.A. and ϵ, are due to errors in fitting the ellipses to the isophotes and to errors in the isophotes. To estimate the error due to the fitting procedure, the fitting process was stopped after various numbers of iterations, to derive the curve of P.A. and ϵ error versus residual. From these curves, we determine that the errors from the fit are less than $\pm 1°$ and 0.005 for P.A. and ϵ respectively, even for comparatively large residuals. When the isophotes are very round, the P.A. may be less well defined. However, only NGC 628 and NGC 7217 may have this problem ($\epsilon < 0.1$) for a significant number of their data points, and even for these galaxies the fitted P.A.'s compare well between the i and z images. It should also be noted that even for $a = 3''$ there are still about 12 data points available to fit the ellipse in the 1".29 pixel^{-1} scale, so that the fit for the smaller ellipses should also be reliable.

Aside from the fitting errors there is also the question of whether the isophotes faithfully represent the distribution of stars in the galaxy. Sources of error here include seeing, statistical, and background effects, and readout noise. The readout noise has been measured to be typically between 5 and 6 counts. Statistical errors become more important with the larger isophotes; however, even for the larger isophotes the counts per pixel exceed 400: the statistical error including readout noise is at worst 3%; also, the larger isophotes consist of more data points (over 300 points for the largest isophotes), thereby compensating for the larger statistical error in the counts. Seeing makes isophotes rounder and flattens the gradient of intensity variation with radius. Its effects tend to mask the P.A. and ϵ variations if present.

To assess the overall error in P.A. and ϵ, i- and z-band images of the same galaxy were compared. Figure 1 includes i and z images of NGC 628, but we also used NGC 6814, NGC 7177, and NGC 7331 in this procedure. The images for NGC 6814 were taken on different observing runs and with different image scales. From the agreements of the P.A. determined from comparing these different images, we arrived at a *conservative* P.A. error of $\pm 2°$ and ϵ error of ± 0.02; we adopted this error for all the points. To avoid large errors from seeing we do not use data from isophotes with $a < 3''$. To allow for a larger P.A. error for rounder isophotes, we adopted an error of $\pm 5°$ for NGC 628 and NGC 7217, consistent with the comparison of the i and z images in the region of interest. The z-band images are less affected by dust (see below), so that the error estimates from comparing i- and z-band results should incorporate the effects of dust.

The presence of dust lanes can obviously affect the shape of the isophotes of the underlying red stars. There are basically two types of effects. First, if a dust lane is nearly parallel to an isophotal contour, it will change the shape and orientation of the isophote, which would give a different position angle and ellipticity than those of the underlying red stars. Second, if the dust lane is nearly perpendicular to the contours, it will result in a dent in the isophote, which would not significantly affect the P.A. and ϵ of the fitted ellipse, although it would increase the error in the fit and introduce scatter into the data.

To check on the effect of dust, pictures of all the galaxies except NGC 3810, NGC 4254, and M51 were taken in both i and z bands. The z-band pictures are less sensitive to dust and represent the distribution of the underlying red stars better. This difference between the i- and z-band pictures is illustrated for the case of NGC 628 in Figure 1. However, because the sensitivity of the CCD camera falls off rapidly at z band, requiring substantially longer exposure times, z-band pictures were taken only as checks for dust contamination of the i-band pictures.

The i- and z-band pictures of NGC 628 in Figure 1 illustrate that the dust lanes are much less visible in the z band. Results from fitting both the i and z images of NGC 488 and NGC 628 are shown in Figure 2. They show that there is good agreement between the two bands, especially between $a = 2''$ and $10''$, where the bulge light dominates. Agreement between i- and z-band fits is good to within the errors quoted above, *in the*

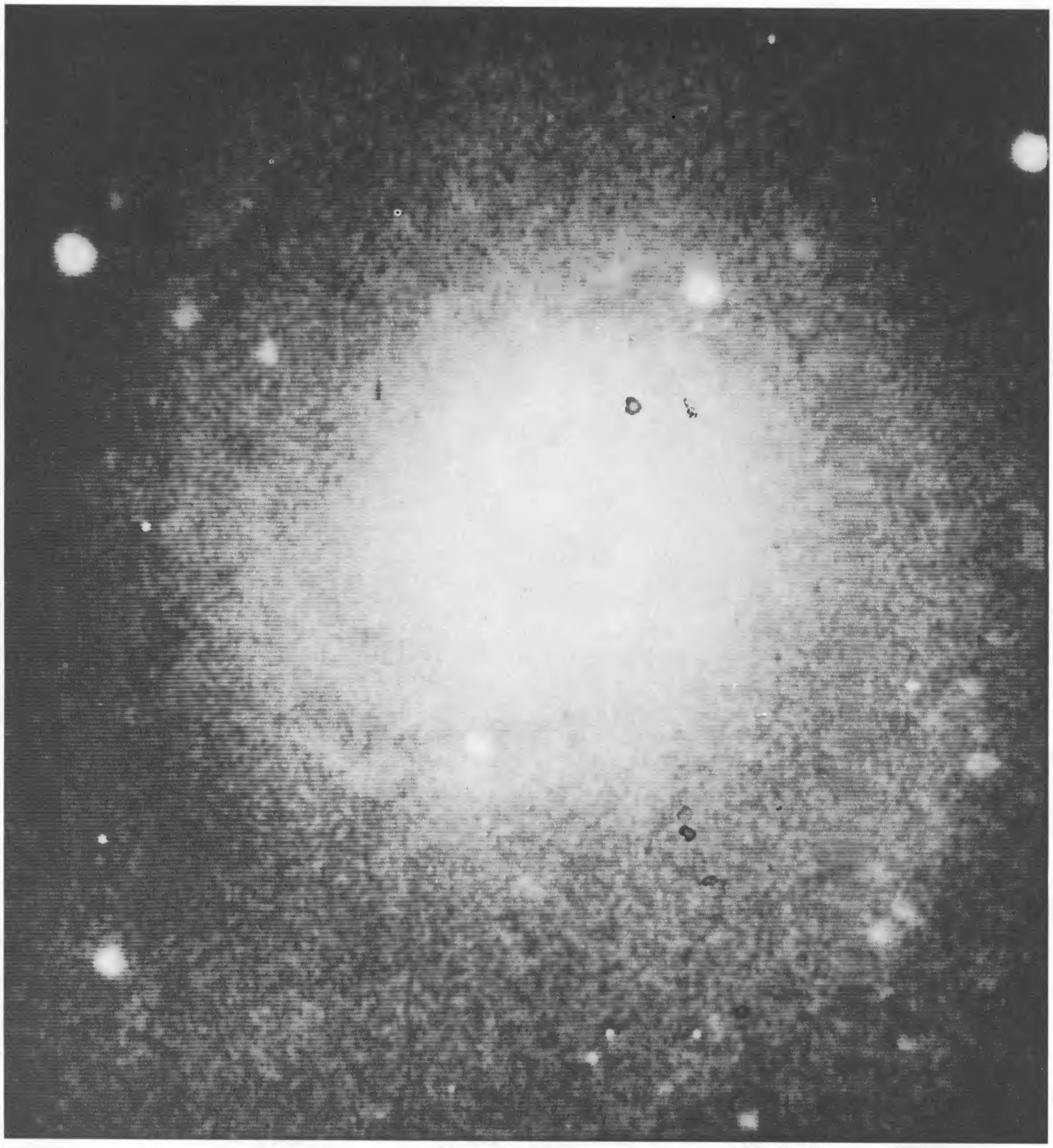

FIG. 1.—(a) The i-band picture of the central region of NGC 628; (b) the z-band picture. Note the absence of dust lanes in the z-band image.

area of interst, in all the galaxies for which comparisons can be made. This suggests that the bulge-dominated part of the i-band images can be reliably used to derive the parameters needed for our purposes.

III. RESULTS

The results of the fits to the i-band isophotes of the remaining nine galaxies studied are presented in Figure 3, which shows the data for the inner parts of the galaxies only. The most noticeable feature of all the surface brightness profiles is the clear demarcation between the exponential disk component and a prominent nuclear bulge, even for the Sc galaxies. This is remarkable because the late-type galaxies tend to have weak spheroidal components in the blue, e.g., M33 (Freeman 1970; de Vaucouleurs 1959).

Variation of P.A. and ϵ with a is also apparent in all the galaxies. Twists within the bulge probably indicate that the bulge is triaxial. The twists could be due to spiral arms; however, the effect of this is small, since the twists are seen inside the bulge-dominated region of the galaxies. While it has been argued above that dust lanes do not significantly affect the analysis of the i-band images, we will still concentrate on the central regions of the galaxies where dust lanes are absent or do not dominate. For all the galaxies except M51, NGC 3810, and NGC 6946, the range of a between $\lesssim 2''$ and $20''$ is free of any major dust contamination. For the three exceptions, the dust-free region is confined to $a < 10''$. For larger a, there is increased scatter seen in the P.A. plots for several of the galaxies, e.g., NGC 628 and M51. Increase in the scatter is also seen in the ellipticity plots for several of the galaxies, e.g., NGC 6946, at larger semimajor axis values.

The P.A. of the major axis of the galactic disk is given in Table 1, and it is usually at a different P.A. from that in the central region. All the galaxies in this study, except perhaps NGC 7217, show P.A. or ϵ variations or bulge-disk misalignment. For galaxies whose change in position angle is on the

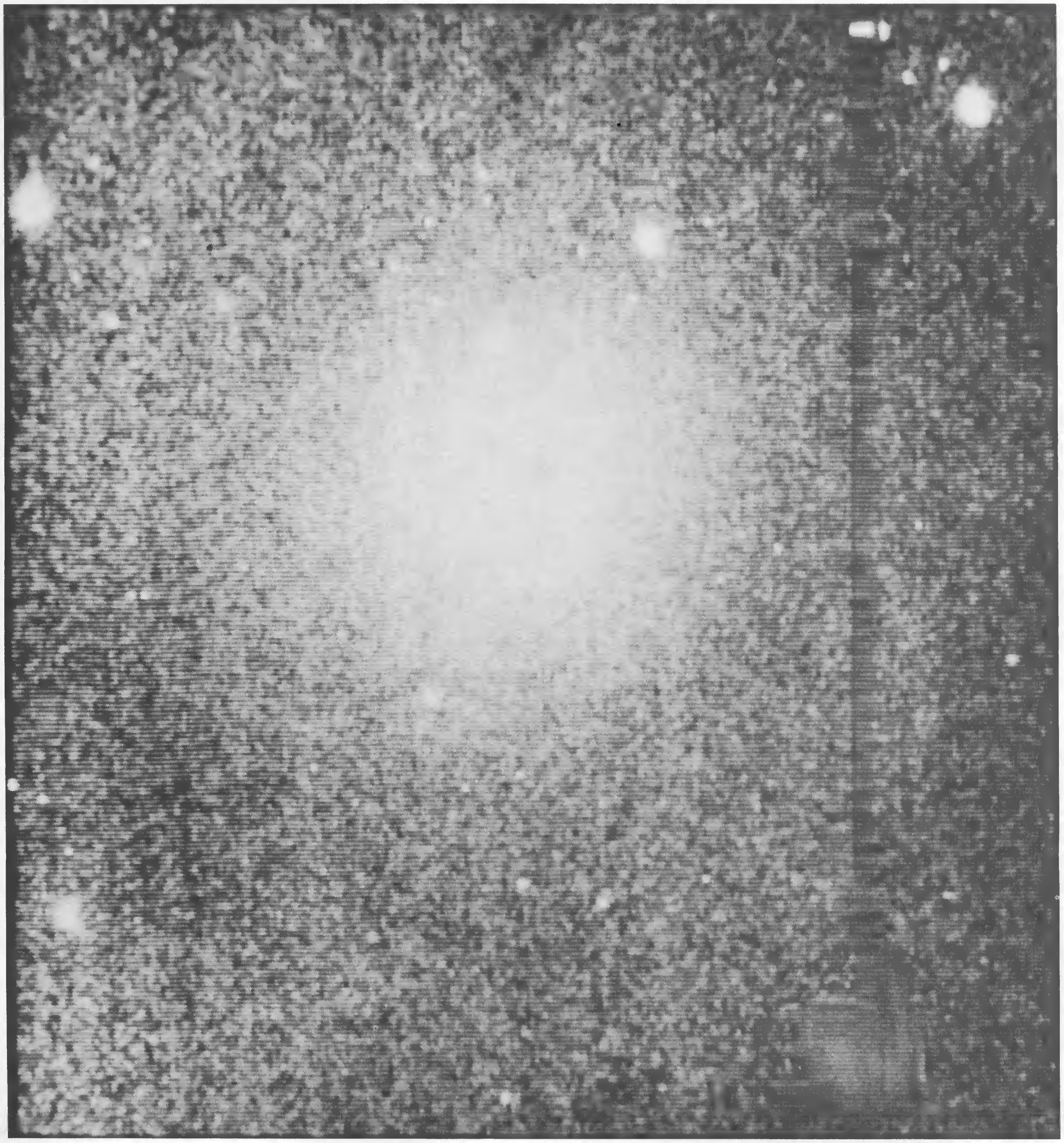

FIG. 1*b*

order of 10°, such as NGC 488 and NGC 7331, the *z*-band pictures show good confirmation, indicating that the variations in position angle and ellipticity are real.

If the isophotes in the central region are tipped, i.e., differ in position angle, from those of the disk, then this can be further interpreted as a bar (Lindblad 1956; Stark 1977). NGC 6951 is classified as a barred galaxy and was included as a control. The level area in the position angle plot of NGC 6951 differs by $\sim 50°$ from the position angle of the disk, estimated at roughly 145°, thus confirming a bar. Similar disk-bulge misalignment is also seen in NGC 4254, NGC 5194, NGC, 6814, and NGC 6951.

IV. DISCUSSION

The technique of studying isophotal twists has been applied to elliptical galaxies (e.g., Williams and Schwarzchild 1979). The isophotal twists are taken to suggest strongly that the elliptical galaxies observed do not possess an axis of rotational symmetry and that the dynamically acceptable models of the figures are triaxial (Mihalas and Binney 1981). Similar isophotal twists are observed in the central region of our entire sample of spiral galaxies. Furthermore, slightly under 87% of the ordinary spiral galaxies in Kent's (1984) extensive study have P.A. variations of more than 5° for $a = 2''$–$20''$. Thus, there is strong evidence that nonaxisymmetric nuclear bulges are very common among ordinary spiral galaxies. Given that a small distortion in the mass distribution is sufficient to significantly affect the gas dynamics, the presence of noncircular motion in nuclear regions should thus be generally anticipated.

To assess more quantitatively the effect of the nonaxisymmetric nuclear bulge on gas dynamics, we have made estimates of F_q, the ratio of tangential force to radial force, for M51, the only galaxy in our sample with all the necessary parameters well determined. We assume that inside the last isophote that is tipped with respect to the isophotes of the disk the nuclear bulge consists of similar concentric ellipsoids with

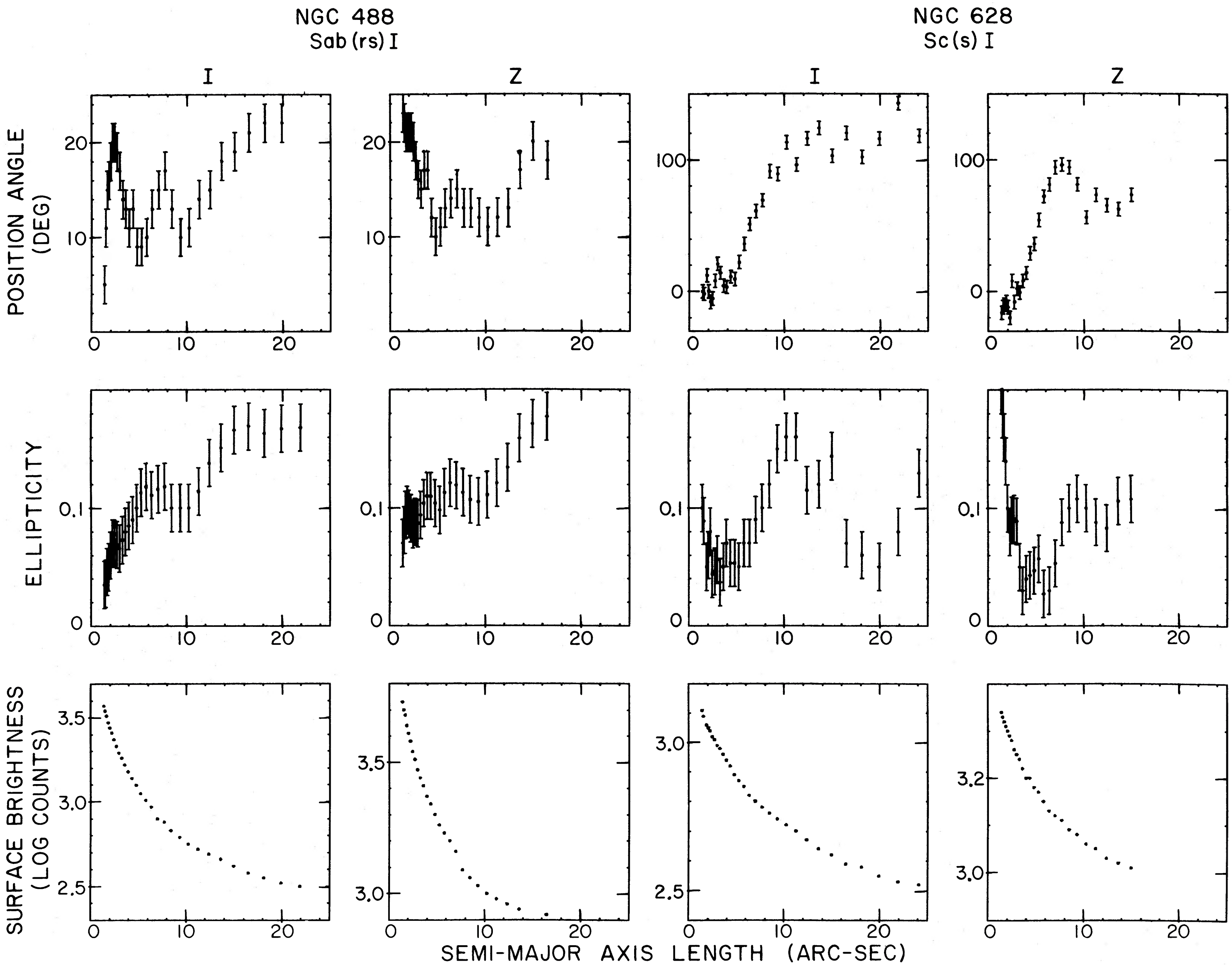

FIG. 2—P.A., ϵ, and surface brightness (log counts) vs. semimajor axis length plots for *i*- and *z*-band images of NGC 488 and NGC 628. P.A. is measured in degrees from north through east. The surface brightness plot is the logarithm of the average value of the counts for the isophote with the given semimajor axis length.

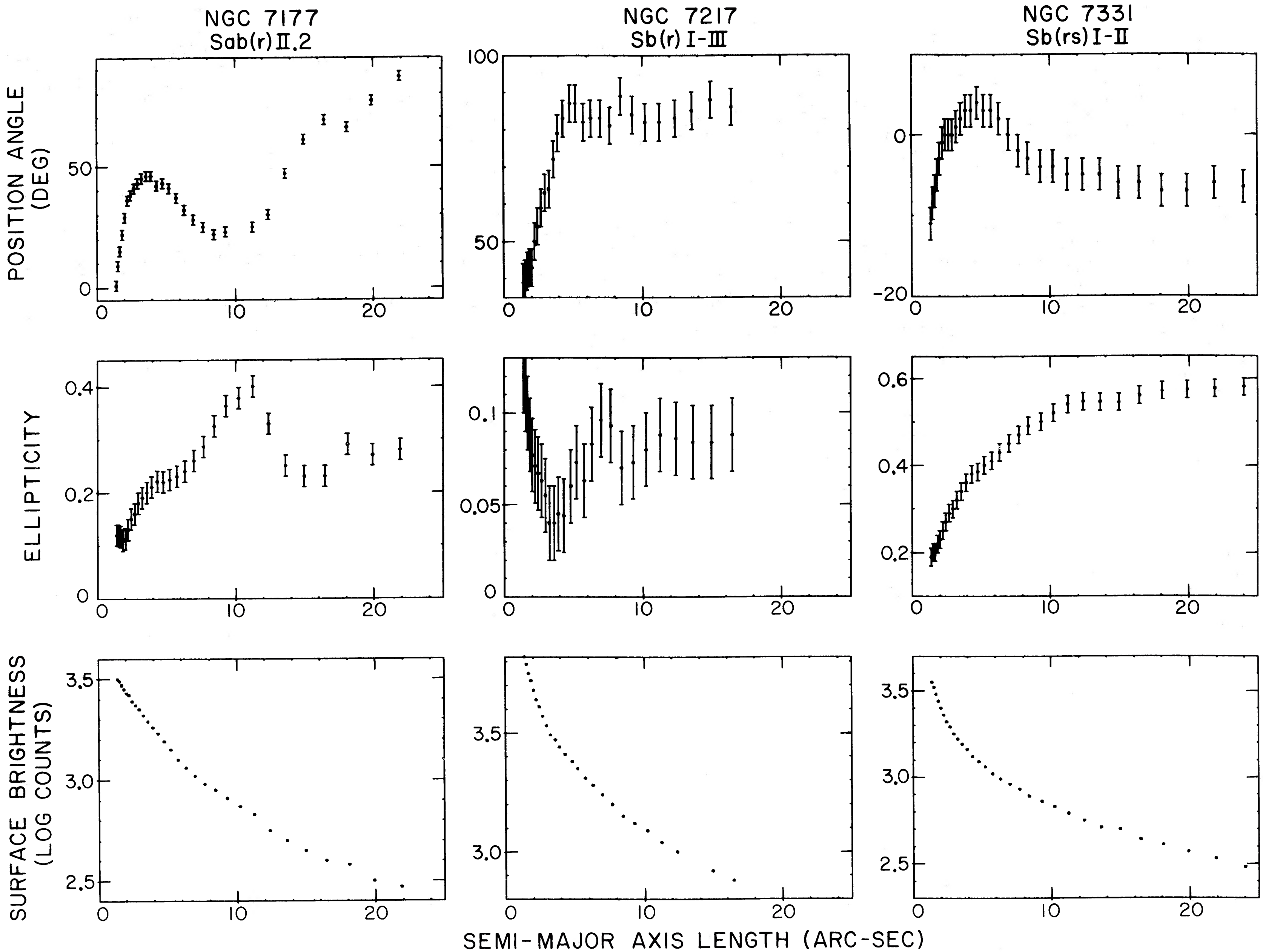

FIG. 3.—P.A., ϵ, and surface brightness (log counts) vs. semimajor axis length plots for the *i*- band images

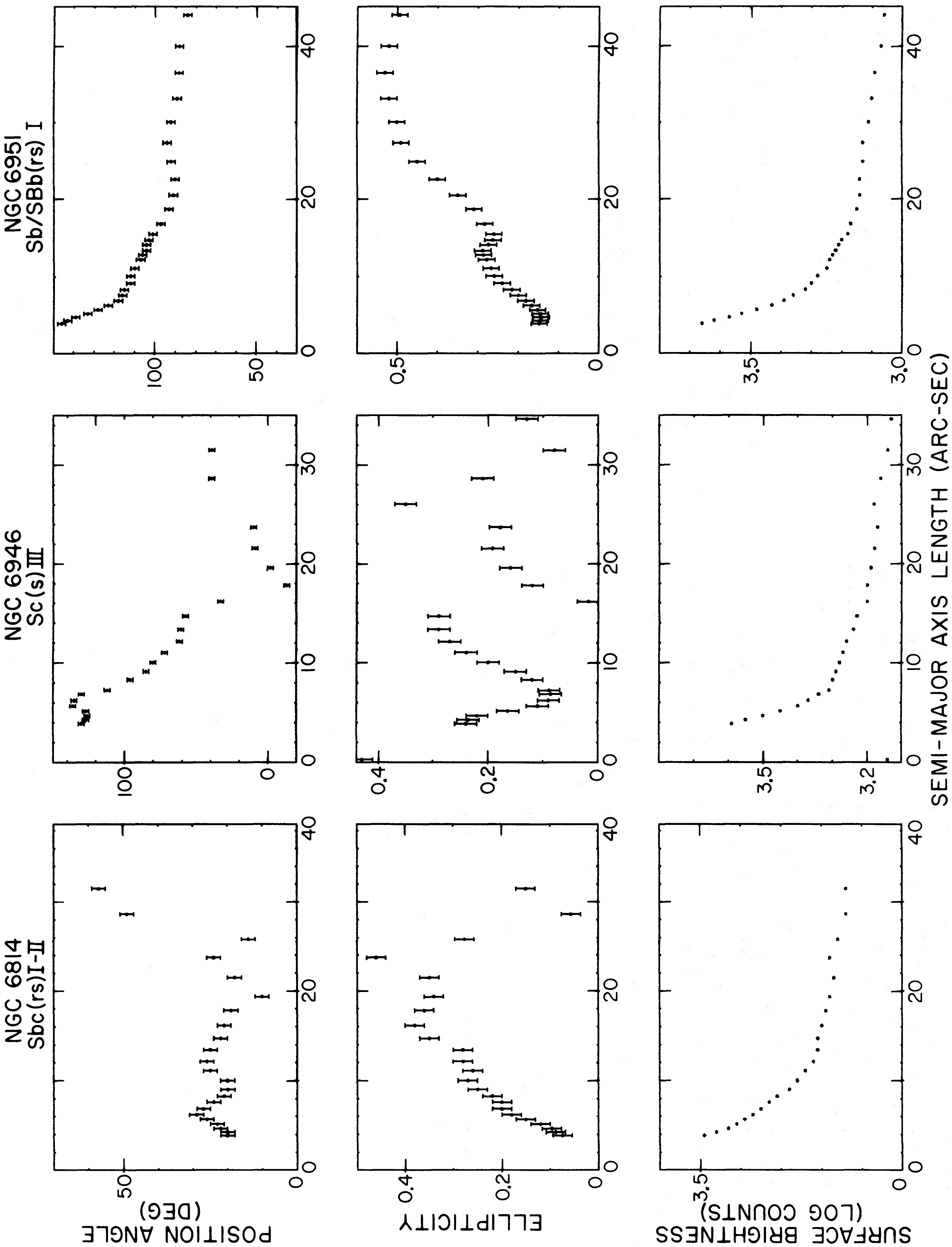

Fig. 3.—*Continued*

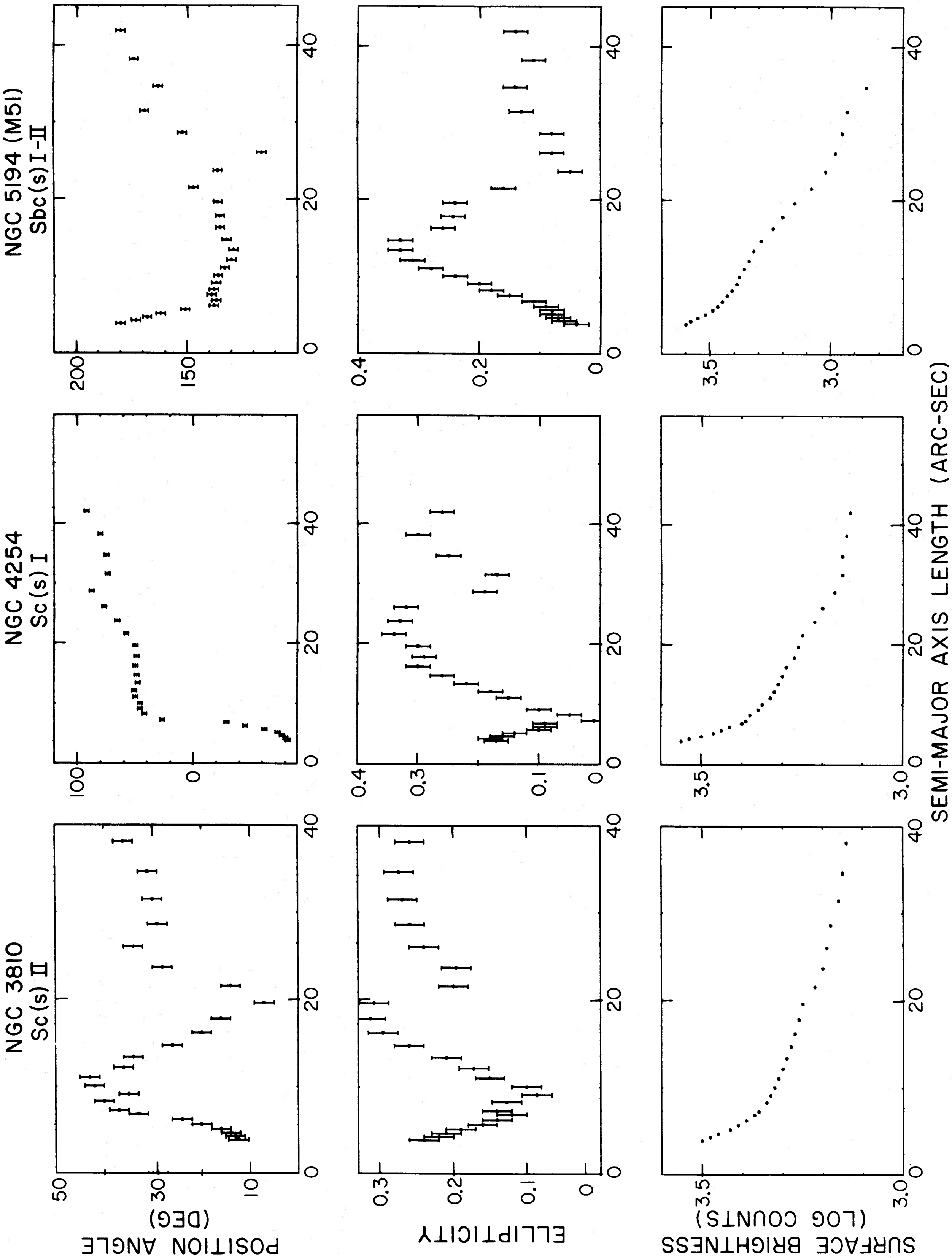

FIG. 3.—*Continued*

three unequal axes, and with one of the symmetry axes aligned perpendicular to the plane of the disk. Under this assumption, a family of models, parameterized by an angle ϕ, of the volume brightness distribution can be derived from the observed surface brightness distribution (Stark 1977). Then by adopting a mass to light ratio, the volume brightness distribution can be transformed into a mass distribution from which the second moments and the quadrupole moments can be calculated. The gravitational potential Ψ due to the quadrupole moments is then calculated, and from that we arrive at $F_q = \langle -\text{grad } \Psi \rangle / (v^2/r)$.

The procedure described was applied to M51, with the last tipped isophote taken to be at 15" and $M/L = 2.4$ for the i band, which corresponds to $M/L = 20$ in the B band and a $B - i$ color index of 3. After subtracting the disk component, the luminosity, mass distribution, and mass moments of the nuclear bulge were evaluated. The F_q was found to be 0.11 at $r = 1$ kpc using $v = 220$ km s^{-1} (Tully 1972). This agrees fairly well with the value of F_q of 15%–20% at 1.2 kpc Tully arrived at using kinematical methods.

The F_q estimate is a lower limit because we have chosen the ϕ solution which was the least barlike. Furthermore, the true extent of the oval distortion was not measured. The last tipped isophote simply sets a lower bound on the size of the triaxial feature. In addition, as pointed out by Stark (1977), there may be other nonradial forces due to the mass distribution in the disk and halo.

Noncircular gas motion is often observed in the central region of galaxies, including our Galaxy (e.g., Oort 1977), M31 (e.g., Morton and Thuan 1973; Brinks 1982), M81 (Goad 1974), M51 (Tully 1972), and M83 (Allen *et al.* 1982), as well as a sample of galaxies studied by Bosma (1978). In view of the present results, the effects of an oval gravitational potential would be an important mechanism to consider. In the case of our Galaxy, the effects of a bar have already been discussed (e.g., Simonson and Mader 1973; Liszt and Burton 1978).

Radial transport of gas in spiral galaxies has important consequences, such as the chemical evolution (Lacey and Fall 1985) and the supply of fuel for the central engine in active galaxies (Simkin, Su, and Schwarz 1980) and for enhanced star formation rate in the nuclei of some galaxies (e.g., Rieke *et al.* 1980). From the interferometric observations of CO emission from the central 1.5 kpc of IC 342 (Lo *et al.* 1984), we estimate the radial transport of molecular gas toward the center at a rate of a few $M_\odot$ yr^{-1}, sufficient to support the enhanced rate of star formation observed there (Becklin *et al.* 1980).

The *common* presence of nonaxisymmetric nuclear bulges, even in the late-type spiral galaxies, may also have important implications on stellar dynamics, such as the excitation of spiral density waves (e.g., Thielheim and Wolff 1984). To properly assess the importance of the distortions in the nuclear bulges, it is necessary to determine more quantitatively their true extent and the mass involved. As shown by Hackwell and Schweizer (1983), the best approach for such measurements requires observations in the 1–2 μm range.

V. SUMMARY

While our sample is small and no doubt incomplete, our findings of the isophotal twists, in all the galaxies we observed, as well as disk-bulge misalignments in several cases, when combined with the more extensive results of Kent (1984), indicate that nonaxisymmetric nuclear bulges in ordinary spiral galaxies must be quite common. This perhaps should not be unexpected, since numerical studies show that flat rotating stellar systems tend to develop bar instabilities (Miller, Prendergast, and Quirk 1970; Hohl 1971; see also Sellwood 1981). Estimates of the nonradial forces due to observed distortion indicate that significant effects on gas dynamics in the nuclear regions can be expected. The common occurrence of nonaxisymmetric nuclear bulges may also have relevance to galactic stellar dynamics, such as the maintenance of spiral density waves.

Much work remains on the quantitative measure of the mass distribution in nuclear bulges of spiral galaxies and their dynamical effects on gas and stars in the nuclear region as well as in the disk.

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K. Y. Lo and D. Zaritsky: Astronomy Department, Caltech, 105-24, Pasadena, CA 91125