

BLUE AND NEAR-INFRARED SURFACE PHOTOMETRY OF SPIRAL STRUCTURE IN 34 NONBARRED GRAND DESIGN AND FLOCCULENT GALAXIES

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ABSTRACT

Thirty-four nonbarred spiral galaxies have been analyzed with blue and near-infrared surface photometry in order to examine radial disk profiles and spiral arm structure. Radial profiles indicate that the blue and near-infrared scale lengths are similar within each galaxy. Azimuthal profiles reveal several important differences between grand design and flocculent galaxies. To study the azimuthal variations systematically, arm-interarm contrast ratios were derived in both colors for all of the prominent features in the azimuthal profiles at 10 radial positions in each galaxy. These data were displayed on plots of the ratio of blue to near-infrared arm/interarm contrast versus the near-infrared arm/interarm contrast. The distribution of spiral arm features on such a color-amplitude plot was found to change systematically with spiral arm morphology. This correlation is discussed in terms of a model for color evolution in star systems. The model determines the relative contributions of star formation and stellar density enhancements to the colors and amplitudes of spiral arm features. From the data and models we conclude the following: (1) Extreme flocculent galaxies (e.g., NGC 7793) have very little structure in their old stellar population disks. Most of the structure seen in blue photographs of these galaxies is from star formation or from very weak stellar density ripples. (2) Extreme grand design galaxies (e.g., M51) have smooth stellar density variations with amplitudes often exceeding 60% and occasional evidence for nonlinearity in the corresponding wave structure. Infrared photographs reveal density wave structure of these galaxies. (3) Intermediate-type spiral galaxies (e.g., M33, M101) can have both prominent blue star-formation features and strong stellar density arms at the same time. Images in both blue and near-infrared passbands are required to reveal the differences between these two types of features. In the grand design and intermediate-type galaxies, the blueness of the arms is independent of the arm amplitude, indicating either that the rate of star formation saturates to a constant value in a stellar density wave or material arm, or that star formation is independent of these density variations.

Subject headings: galaxies: photometry — galaxies: structure — stars: formation

1. INTRODUCTION

Photographic surface photometry in B and I passbands was used to determine disk scale lengths and spiral arm intensity profiles in 34 face-on spiral galaxies without prominent bars. The I band was used because it is virtually free of radiation from H II regions and OB stars, and it suffers little extinction from dust. Strong spiral patterns visible in the I band are therefore candidates for stellar density waves or material arms. The B band was chosen for comparison because arm-interarm variations of the $B - I$ color can reveal variations in the mean stellar ages, which may result from star formation in spiral arms.

A distinction is made here between grand design galaxies, which have long and continuous spiral arms, of which at least one pair is symmetric around the galactic center, and flocculent galaxies, which have short, chaotic-looking arms and no apparent symmetry (Elmegreen 1981). Many of the grand design galaxies in our sample were found to have strong

near-infrared arms and little arm-interarm color variation; these infrared arms are almost pure density variations in the background stellar disks. Such variations have been predicted by theories of spiral density waves (see reviews by Toomre 1977 and Lin and Lau 1979), and, for a few galaxies, modeled to observations of H I streaming motions (Rots 1975; Visser 1980). Stellar density arms have also been recognized previously from galactic surface photometry (Strom, Jensen, and Strom 1976; Schweizer 1976; Jensen 1977); ours is the first quantitative study of galactic spiral structure in the I band for a large number of galaxies with different spiral arm structures.

Many of the spiral arms in flocculent galaxies are very blue compared to the interarm regions. These blue arms appear to be caused by star formation; the underlying mass density variations in the galactic disks are very small. We show here that the color age of a blue arm or feature is approximately equal to the time scale for shear to give the corresponding star-formation patch its observed shape. Thus, flocculent arms may be transient bursts of star formation, or regions of

self-propagating star formation, that have been swept back by differential rotation. Such arms are illustrated in the computer simulations reviewed by Seiden and Gerola (1982).

Arm classifications from 1 through 12 (Elmegreen and Elmegreen 1982) were made for each of the galaxies in this study. (No class 10 galaxies, which have strong bars and a grand design spiral structure in the outer parts, are studied here.) Galaxies with arm classes 5–12 were previously designated as grand design, and galaxies with arm classes 1–4 were designated as flocculent. This division primarily distinguished between galaxies with and without symmetric arms, respectively, and it was based entirely on spiral morphology. The present study uses a quantitative method, in addition to the morphological one, to examine the intrinsic properties of spiral arms from their relative color and intensity variations. This technique demonstrates that the extreme grand design classes, 11 and 12, are caused by strong stellar density enhancements or waves in the stellar disks, and that, in many cases, the extreme flocculent classes, 1–3, owe their structure almost entirely to star formation. Galaxies with arm classes 4–9 appear to be transition cases, in which both spiral density waves or material arms, and bright, isolated patches of star formation can coexist. The distinction between stellar density patches and pure star-formation patches cannot generally be made for intermediate-type galaxies simply from the morphology of the spirals in a single passband. The differences between these two types of features become evident after a comparison is made between blue and near-infrared images.

The observational material and data reduction methods used for this analysis are discussed in § II. Radial profiles and scale lengths are presented in § III; azimuthal profiles and color-amplitude plots of spiral arms are in § IV. Color evolution models are discussed in § V. These models are used to determine the amplitude of the underlying stellar density spirals and the relative enhancement of star formation in the arms, based on the observed arm amplitudes and color variations. A summary of the results is in § VI.

II. PLATE MATERIAL AND CALIBRATION

The 34 galaxies listed in Table 1 were observed in blue ($\lambda_{\text{eff}} \approx 4360 \text{ \AA}$) and near-infrared ($\lambda_{\text{eff}} \approx 8250 \text{ \AA}$) passbands, using baked 103a-O emulsions behind GG 385 filters (*B*) and AgNO₃ hypersensitized IV-N emulsions behind Wr 88A filters (*I*), respectively (see Elmegreen 1981). All galaxies were observed with the Palomar 1.2 m Schmidt telescope except NGC 628, 7424, and 7793, which were photographed with the CTIO 4 and 1.5 m telescopes. Exposure times of 1.5–2 hr were usually made for the near-infrared plates, in order to highlight the outer spiral arms. Blue plates on the 1.2 m telescope required 10–12 minute exposures. All plates have sensitometer wedges photographed in the same passband as the galaxies and recorded on a clear section of each plate immediately after the galaxy exposure (the CTIO plates have sensitometer spots recorded during the galaxy exposure). The angular resolution of the plates is $\sim 2''$.

The galaxies were selected on the basis of their large angular sizes and low inclinations to the line of sight. Table 1 lists the Hubble types (de Vaucouleurs, de Vaucouleurs, and Corwin

1976), arm classifications (Elmegreen and Elmegreen 1982), distances, radii, and position angles for each galaxy.

The plates were scanned with a microdensitometer at the IBM Thomas J. Watson Research Center (see Angilello *et al.* 1983). Each galaxy image was digitized into 512×512 pixels with a raster scan; the scanning apertures ranged from 20 to $80 \mu\text{m}$. Table 1 lists the spatial resolution per pixel for each digitized galaxy, using the assumed distances.

Photographic densities were converted to relative intensities using the calibration wedges on each plate. These relative calibrations are sufficient for the determinations of radial scale lengths, arm-interarm contrasts, and relative color gradients. As a check on the photometric accuracy of the microdensitometer, absolute intensities were obtained from the relative intensities using published photoelectric photometry for seven galaxies. The published photoelectric data consist of observations with $15''$ – $20''$ diameter apertures, positioned along the east-west or major-minor axes. To calibrate a plate on an absolute scale, we integrated the relative intensities from our plates over the areas in the galaxies that correspond to the regions covered by the photoelectric apertures, and the zero-point magnitudes were determined from the average of the photoelectric minus photographic surface brightnesses. The galactic nuclei were avoided because they were often overexposed on the plates. Table 2 lists the rms deviations between the calibrated absolute photographic magnitudes and the photoelectric magnitudes obtained from the literature. The deviations are ~ 0.1 mag, which is typical when comparing photographic surface photometry of galaxies with photoelectric values; no systematic deviations were observed (see also Angilello *et al.* 1983).

III. GALACTIC RADIAL PROFILES

Figure 1 shows radial profiles of the galaxies in the near-infrared and blue passbands. They were derived from inclination-corrected, azimuthally averaged surface brightnesses at 10 regularly spaced galactocentric radii (inclinations were obtained from de Vaucouleurs, de Vaucouleurs, and Corwin 1976). This method reduces the irregularities in single radial strips introduced by spiral arms (see Boroson 1981).

Many spiral galaxy disks have approximately exponential light distributions with scale lengths, α^{-1} , defined by the relation

$$I = I_0 \exp(-\alpha R) \quad (1)$$

for intensity *I* (de Vaucouleurs 1959; Freeman 1970). The exponential scale lengths for our galaxies, listed in Table 3, were determined from least-squares fits to the radial profiles, avoiding the nuclear bulges. Also listed are the ratios of *B* and *I* scale lengths, α_B^{-1} and α_I^{-1} , to R_{25} , the radius of the galaxy where the surface brightness equals $25 \text{ mag arcsec}^{-2}$ (from de Vaucouleurs, de Vaucouleurs, and Corwin 1976). One standard deviation errors in the fits to the exponential scale lengths are given. In almost all cases, the blue and near-infrared disk scale lengths are comparable to one another for a particular galaxy. No systematic variations between *B* and *I* scale lengths as a function of either Hubble type or arm class have been found.

TABLE 1
GALAXY PARAMETERS

Galaxy	Hubble Type	Arm Class ^a	Distance ^b (Mpc)	R_{25} (kpc)	Pixel Resolution (pc)	P.A.
NGC 157	SAB(rs)bc	12	15.1 (1)	9.4	92	25°
309	SAB(r)c	12	57.9 (2)	25.9	353	340
598 (M33)	SA(s)cd	5	0.72 (1)	6.5	19	22
628 (M74)	SA(s)c	9	7.8 (3)	11.6	55	0
1232	SAB(rs)c	9	17.3 (4)	19.5	106	90
1637	SAB(rs)c	6	5.6 (1)	2.7	34	26
1961	SAB(rs)c	2	40.6 (4)	25.1	247	90
2403	SAB(s)cd	4	3.3 (1)	8.5	22	140
2715	SAB(rs)c	4	13.0 (4)	9.4	79	16
2841	SA(r)b:	3	6.0 (1)	7.1	39	155
2903	SAB(rs)bc	7	7.0 (1)	12.8	64	13
3031 (M81)	SA(s)ab	12	3.2 (5)	12.1	53	330
3344	RSAB(r)bc	9	7.9 (1)	7.9	72	346
3486	SAB(r)c	9	6.7 (4)	6.8	41	70
3675	SA(s)b	3	7.4 (4)	6.3	45	0
4254	SA(s)c	9	20.0 (5)	15.6	122	58
4298	SA(rs)c	1	10.4 (4)	4.8	63	131
4321 (M100)	SAB(s)bc	12	20.0 (5)	20.1	130	110
4414	SA(rs)c	3	7.2 (4)	3.8	44	160
5005	SAB(rs)bc	3	8.7 (1)	6.8	53	66
5033	SA(s)c	9	10.5 (1)	15.9	64	345
5055	SA(rs)bc	3	4.6 (1)	8.2	30	105
5194 (M51)	SA(s)bcp	11	9.6 (5)	15.3	94	340
5248	SAB(rs)bc	12	10.5 (1)	9.9	103	113
5457 (M101)	SAB(rs)cd	9	7.2 (5)	28.2	117	30
6015	SA(s)cd	3	9.8 (1)	7.6	60	27
6181	SAB(rs)c	12	25.1 (4)	9.4	153	352
6384	SAB(r)bc	9	18.0 (4)	15.7	164	51
6643	SA(rs)c	4	16.5 (1)	9.3	100	40
6946	SAB(rs)cd	9	10.0 (6)	15.9	98	245
6951	SAB(rs)bc	12	16.3 (4)	9.0	99	86
7424	SAB(rs)cd	9	8.5 (4)	9.4	61	270
7793	SA(s)d	2	2.4 (7)	3.2	17	0
IC 342	SAB(rs)cd	9	4.5 (4)	11.6	73	35

^a“Arm Class” refers to the symmetry and continuity of spiral arms. AC 1–4 galaxies are flocculent, AC 5–12 galaxies are grand design.

^bDistance references, in parentheses, are (1) Roberts 1969, and references therein; (2) From Sandage and Tammann 1981, using $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$; (3) Roberts, Roberts, and Shu 1975; (4) From de Vaucouleurs, de Vaucouleurs, and Corwin 1976, using $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$; (5) Sandage and Tammann 1974; (6) Bosma 1981; (7) Davoust and de Vaucouleurs 1980.

TABLE 2
MAGNITUDE CALIBRATION ERRORS

Galaxy	Passband	Standard Deviation	Number of Determinations	Number of Points per Determination	Reference
NGC 628	<i>B</i>	0.08	1	5	1
		0.19	1	5	1
2841	<i>B</i>	0.13	1	12	2
3031	<i>B</i>	0.05	1	5	3
	<i>I</i>	0.09	1	5	3
4321	<i>B</i>	0.11	3	5,27,24	3,2
	<i>I</i>	0.12	1	5	3
5055	<i>B</i>	0.12	2	18,17	4
5194	<i>B</i>	0.11	1	9	3
	<i>I</i>	0.10	1	10	3
5457	<i>B</i>	0.15	2	10,34	3,2
	<i>I</i>	0.18	1	10	3

REFERENCES.—(1) Elmegreen 1980; (2) Whitmore and Kirshner 1982; (3) Schweizer 1976; (4) Fish 1961.

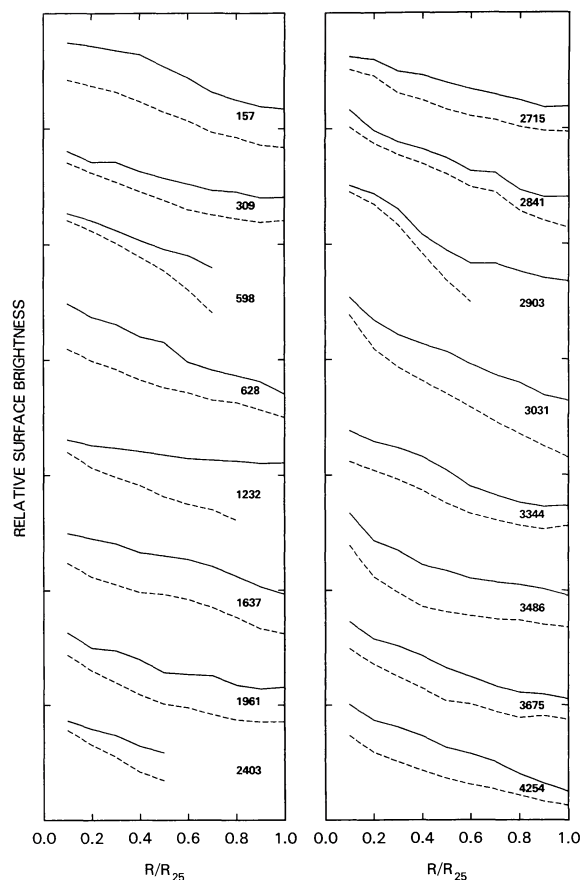


FIG. 1a

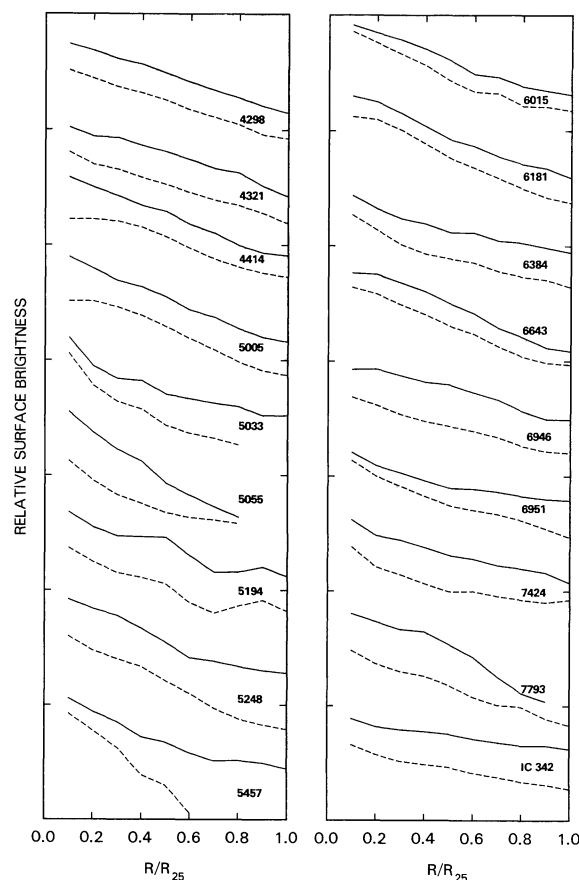


FIG. 1b

FIG. 1.—Radial profiles are shown for the indicated spiral galaxies. Solid lines correspond to the B passband; dashed lines to the I passband. Abscissa is the radial distance, measured in units of the radius at which the surface brightness equals $25 \text{ mag arcsec}^{-2}$. Ordinate is the surface brightness in mag arcsec^{-2} , with arbitrary zero point; fiducial marks indicate intervals $5 \text{ mag arcsec}^{-2}$.

Bosma (1981) determined the radial profiles of mass surface density in eight of the galaxies listed in Table 1 using H I rotation curves and a model for the disk-to-bulge mass ratio. The relative mass scale lengths, $1/\alpha_M R_{25}$, derived from his profiles, are listed in Table 3. Again no systematic correlations are evident.

Some of the program galaxies have previous measurements of scale lengths, as listed in Table 3. These other measurements include scale lengths in B and I passbands determined from photoelectric photometry, in B and O passbands determined from photographic surface photometry, in nonthermal radio continuum at 21.2 and 49.2 cm wavelengths, and in carbon monoxide emission at 2.6 mm. In most cases, the scale lengths (normalized to R_{25}) are similar to those derived in this paper. The published scale lengths do not necessarily correspond precisely to the measurements determined in this paper; e.g., Schweizer (1976) used the interarm light only, and Boroson (1981) subtracted the bulge component first.

IV. SPIRAL ARM PROFILES

a) Azimuthal Scans

Azimuthal profiles for each galaxy were obtained at various radii by measuring the intensity as a function of inclination-

corrected azimuthal angle. Adjacent pixels were subdivided or averaged in such a way that each azimuthal profile consists of 200 points. Figure 2 shows azimuthal profiles at selected radii for all of the galaxies studied here. The radii in units of R_{25} are given to the left of each pair of scans. The 0° azimuthal angle corresponds to the major axis in the direction given by the galaxy position angle (see Table 1). The azimuthal angle increases counterclockwise around the galactic center.

The reality of the features may be ascertained by noting their presence in both blue and near-infrared passbands. Strong features that are not present in both colors are often blue clusters or sharp dust patches that can be seen on direct photographs of the galaxies, or they are foreground blue stars in our own Galaxy, also visible on photographs. The common occurrence of star spikes on both the B and I scans assures us that the two colors are properly aligned. The highest spatial frequencies are dominated by photographic plate noise (i.e., granularity); the relative amplitude of the plate noise increases with radius in a galaxy because the outer regions become faint compared with the sky. Since the sky brightness depends on the position and phase of the Moon at the time of the exposure, the pixel-to-pixel noise level at fixed values of R/R_{25} varies from galaxy to galaxy.

Figure 2 indicates that galactic spiral structure is often complex. Only a small fraction of the galaxies in this sample

TABLE 3
DISK SCALE LENGTHS

Galaxy	$\frac{1}{\alpha_B}$ (kpc)	$\frac{1}{\alpha_I}$ (kpc)	$\frac{1}{\alpha_B R_{25}}$	$\frac{1}{\alpha_I R_{25}}$	$\frac{1}{\alpha_M R_{25}}$	$\frac{1}{\alpha_B R_{25}}$	$\frac{1}{\alpha_0 R_{25}}$	$\frac{1}{\alpha_I R_{25}}$	$\frac{1}{\alpha_{\text{Radio}} R_{25}}$	Reference
NGC 157.....	2.1	2.6	0.22 ± 0.02	0.27 ± 0.02	...	...	...	...	...	
309.....	10.4	7.0	0.40 ± 0.06	0.27 ± 0.01	...	...	...	...	...	
598.....	1.8	1.0	0.28 ± 0.02	0.16 ± 0.13	0.24	{ 0.25 0.17	...	...	...	1, 2 3 3, 4
628.....	2.9	4.0	0.25 ± 0.03	0.35 ± 0.03	...	0.18, 0.28	...	0.15	...	
1232.....	16.1	5.4	0.82 ± 0.10	0.27 ± 0.03	...	...	...	...	...	
1637.....	1.0	1.0	0.37 ± 0.05	0.36 ± 0.04	...	...	...	...	...	
1961.....	6.9	5.2	0.28 ± 0.06	0.21 ± 0.02	...	...	...	...	...	
2403.....	3.1	1.8	0.36 ± 0.07	0.21 ± 0.04	0.53	...	...	...	...	1
2715.....	3.9	3.7	0.41 ± 0.02	0.39 ± 0.04	...	...	...	...	...	
2841.....	1.9	1.6	0.26 ± 0.04	0.22 ± 0.01	0.53	0.30	...	...	...	4
2903.....	1.8	1.3	0.14 ± 0.03	0.10 ± 0.01	...	...	...	...	...	
3031.....	3.0	2.2	0.23 ± 0.03	0.17 ± 0.12	0.27	0.36	0.25	0.31	...	1, 3, 5, 3
3344.....	1.9	1.9	0.24 ± 0.03	0.24 ± 0.01	...	...	...	...	...	
3486.....	3.5	5.3	0.52 ± 0.07	0.78 ± 0.07	...	...	...	...	...	
3675.....	1.7	1.8	0.27 ± 0.02	0.29 ± 0.05	...	...	...	...	...	
4254.....	4.4	6.1	0.28 ± 0.01	0.39 ± 0.04	...	...	0.26	...	...	
4298.....	1.6	1.6	0.33 ± 0.02	0.33 ± 0.02	...	...	...	...	...	
4321.....	6.9	6.7	0.34 ± 0.05	0.33 ± 0.03	...	...	0.32	...	...	5
4414.....	1.8	1.8	0.25 ± 0.03	0.25 ± 0.01	...	...	...	...	...	
5005.....	1.8	3.3	0.27 ± 0.02	0.48 ± 0.06	...	0.32	...	...	...	2
5033.....	6.0	4.1	0.38 ± 0.08	0.26 ± 0.04	...	...	...	...	...	
5055.....	1.4	2.4	0.17 ± 0.15	0.29 ± 0.12	0.91	...	...	...	...	1
5194.....	5.2	5.3	0.34 ± 0.07	0.35 ± 0.11	0.14	...	0.33	0.26	...	1, 5, 6
5248.....	2.9	2.2	0.29 ± 0.07	0.22 ± 0.04	...	...	...	...	...	
5457.....	9.1	4.7	0.32 ± 0.09	0.17 ± 0.08	0.15	...	0.19	...	...	1, 5
6015.....	2.1	1.8	0.28 ± 0.02	0.24 ± 0.02	...	...	...	...	...	
6181.....	2.2	2.2	0.23 ± 0.02	0.24 ± 0.05	...	...	...	...	...	
6384.....	8.3	6.8	0.53 ± 0.06	0.43 ± 0.03	...	...	...	...	...	
6643.....	2.2	2.3	0.24 ± 0.02	0.24 ± 0.01	...	...	...	...	...	
6946.....	6.3	6.3	0.40 ± 0.07	0.39 ± 0.04	...	0.29	...	...	{ 0.28 0.30	7, 8 9
6951.....	3.0	2.3	0.34 ± 0.01	0.26 ± 0.01	...	...	...	...	...	
7424.....	4.3	4.8	0.46 ± 0.04	0.51 ± 0.10	...	0.42	...	...	...	2
7793.....	0.6	1.0	0.19 ± 0.03	0.32 ± 0.06	...	0.21	...	...	...	2
IC 342.....	9.2	6.4	0.79 ± 0.15	0.55 ± 0.08	0.83	0.46	...	...	0.35	1, 8

REFERENCES.—(1) Bosma 1981; (2) Freeman 1970; (3) Guidoni, Messi, and Natali 1981; (4) Boroson 1981; (5) Schweizer 1976; (6) Scoville and Young 1983; (7) Ables 1971; (8) Young and Scoville 1982; (9) van der Kruit, Allen, and Rots 1977.

have arm-interarm profiles with a simple sinusoidal pattern (e.g., NGC 3031, 4321, 5194, and 5248). The flocculent galaxies have very chaotic-looking azimuthal scans (e.g., NGC 5055, 7793), as do three-armed galaxies (NGC 309, 4254) and other multiple-armed galaxies of the M101-type (arm class 9: e.g., NGC 1232, 3486, 5457, 6946, 7424, IC 342). One galaxy, NGC 1637, has a single dominant arm in the outer part, and some of its azimuthal profiles are indeed strongly asymmetric. Even galaxies with long symmetric spirals often have interarm spiral pieces, spiral spurs, and multiple long arms in the outer parts.

Several of the azimuthal profiles reveal prominent interarm star formation. NGC 598 has an infrared arm at $0.5 R_{25}$ that is much stronger than the corresponding blue arm. This peculiar situation arises because both the interarm and arm regions are filled with blue radiation from star formation, and so they appear almost equally bright in the blue band. The near-infrared passband, however, exposes primarily the un-

derlying spiral density pattern in the old stellar disk (see § V), which does have a strong azimuthal variation. Thus, NGC 598 (M33) has a comparatively strong underlying arm, even though the arm structure in the blue image has low contrast. The azimuthal scan of NGC 4321 (M100) at $R = 0.5 R_{25}$ also shows interarm star formation, at $\theta = 140^\circ$ and 300° , where there are large blue patches with no corresponding infrared patches.

The azimuthal profiles of NGC 5248 may reveal nonlinear structure in a spiral density wave. The near-infrared arms are very narrow, and the interarm regions are broad (as expected for nonlinear waves—Haas, private communication). Our near-infrared data reveal such peaked waves in some regions of other strong-armed galaxies as well (NGC 3031, NGC 5194). The near-infrared passband appears to be useful for the identification of nonlinearities because profiles of spiral arms at shorter wavelengths may be peaked entirely as a result of intense star formation.

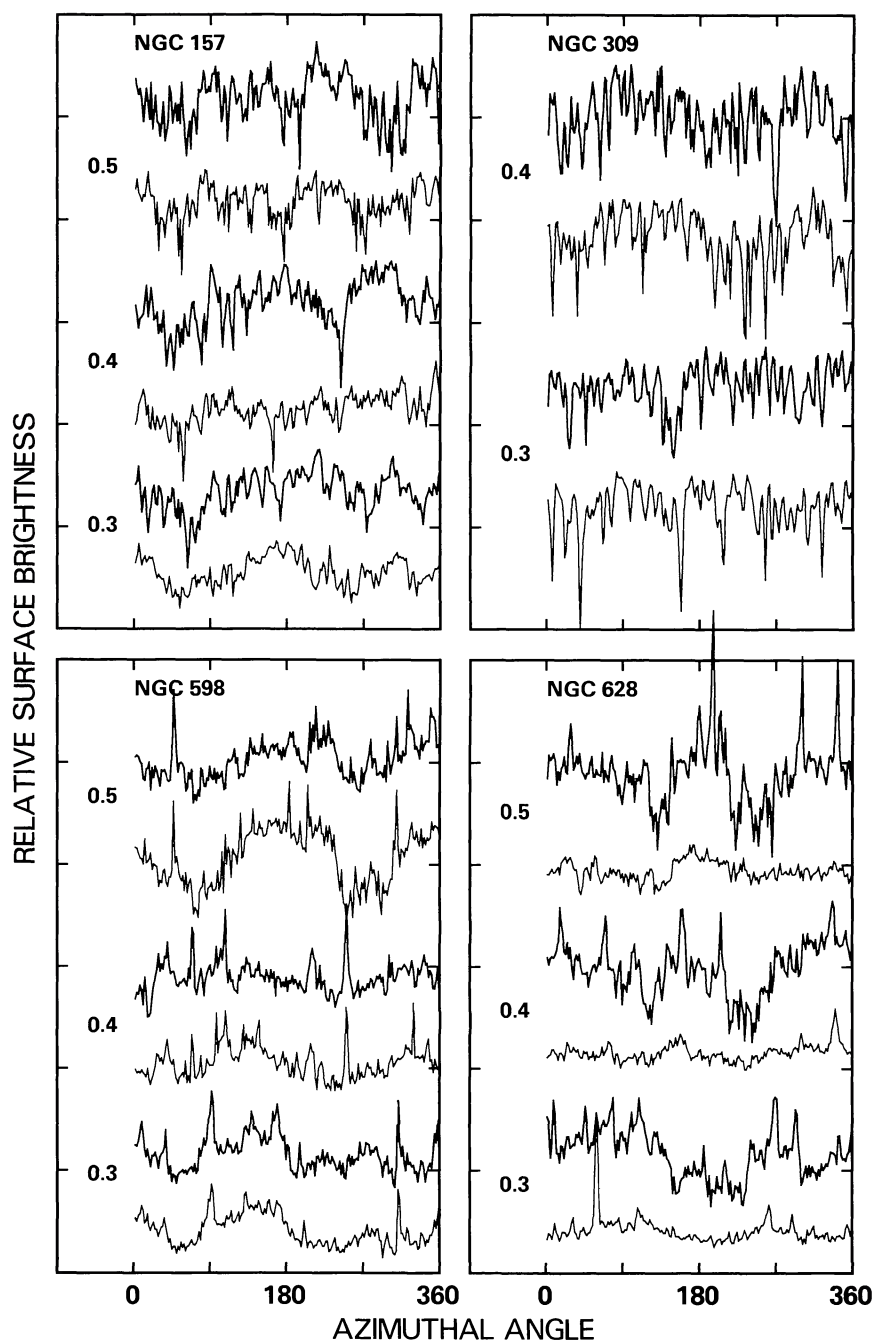


FIG. 2.—Typical azimuthal profiles are shown for each galaxy. Upper (*heavy*) and lower (*light*) lines correspond to *B* and *I* passbands, respectively. The number next to each pair of lines indicates the radial position at which the azimuthal scan was made, in units of R_{25} . Abscissa is the azimuthal angle, θ , measured in degrees counterclockwise from the galaxy position angle. Ordinate is the relative surface brightness, in mag arcsec^{-2} , with fiducial marks at 2 mag intervals. The galaxies are arranged according to NGC number.

b) Color-Amplitude Plots

The color and intensity variations caused by spirals and patches of star formation in a galactic disk were studied quantitatively by measuring the magnitudes of prominent bright features on azimuthal profiles of *B* and *I* band images. The intensity contrast for each feature in a galaxy was determined by subtracting the average relative surface brightness

at the peak of a bright patch on an azimuthal intensity profile from the average of the relative surface brightnesses of the two immediately adjacent intensity minima. The minima were measured on each side of a bright feature at the same galactocentric radius. A typical azimuthal profile may contain two, three, or more intensity peaks, and for each, an average interpeak minimum. The resulting surface brightness differences, Δm , were converted to linear intensity ratios by the

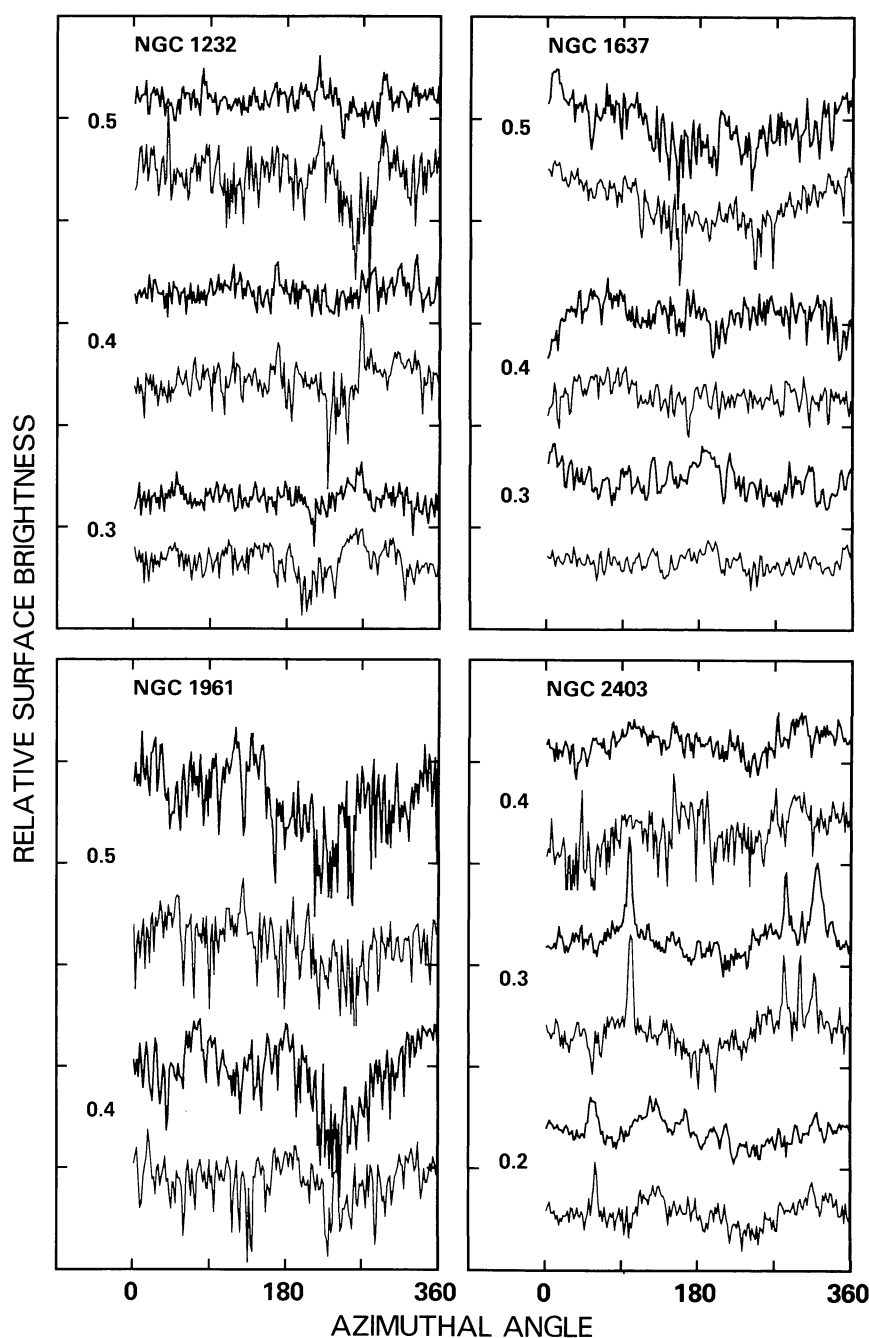


FIG. 2.—Continued

equations

$$A_I = 10^{0.4\Delta m_I}, \quad \text{and} \quad A_B = 10^{0.4\Delta m_B}; \quad (2)$$

A_I is therefore the I band arm-interarm contrast ratio for a particular spiral arm feature, and A_B is the B band arm-interarm contrast ratio for the same feature, at the same radius. Errors in Δm , resulting primarily from the intrinsic irregularity of spiral arms and from plate granularity, are estimated to be a few tenths of a magnitude.

Values of A_I and A_B were determined for all of the prominent emission features in azimuthal scans at radial positions from $0.1 R_{25}$ to R_{25} in units of $0.1 R_{25}$. The relative colors and amplitudes of these features are illustrated here by plotting A_B/A_I versus A_I for each feature. Each feature on such a *color-amplitude* plot is designated by an integer which indicates the radial positions of the corresponding azimuthal scan, measured in units of $0.1 R_{25}$.

Figure 3 illustrates the procedure, applied to NGC 157. A near-infrared photograph of this galaxy has the three indi-

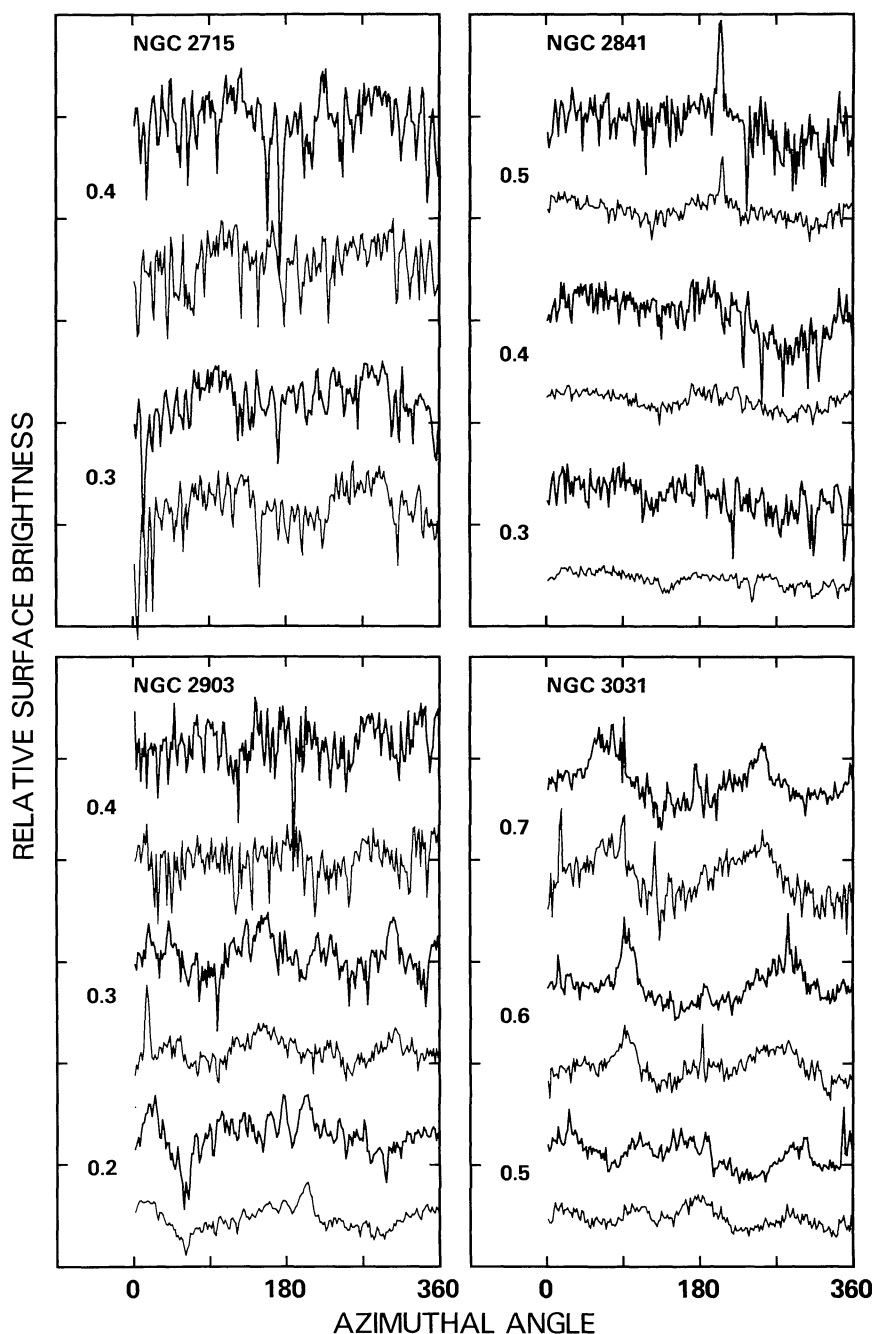


FIG. 2.—Continued

cated patches at $R/R_{25} = 0.3$. These patches are marked in the azimuthal profiles in Figure 3b and shown in a color-amplitude plot in Figure 3c.

Figure 4 shows a color-amplitude plot for each galaxy. These plots are ordered by spiral arm class, as indicated by the AC number below the galaxy name. Extreme flocculent galaxies have arm classes 1–3, intermediate or mixed spiral types have arm classes 4–9, and extreme grand design galaxies have arm classes 11 and 12.

Color-amplitude plots conveniently display the range of color and intensity variations in a galaxy. Features to the left or right on this plot are weak or strong in the near-infrared,

respectively, and features in the upper part of the plot are very blue compared to the color of the average galactic disk at the same radius. Figure 4 indicates that the distribution of points on a color-amplitude plot varies significantly with the spiral arm class. Flocculent galaxies have all of their arm features to the left in the plot (small A_I), whereas grand design galaxies have arm features covering a wide range of A_I . Both types of galaxies span about the same range of spiral arm color, A_B/A_I .

Only the intermediate type and extreme grand design galaxies have arm features with large values of A_I . These arm features usually correspond to the large and continuous spirals

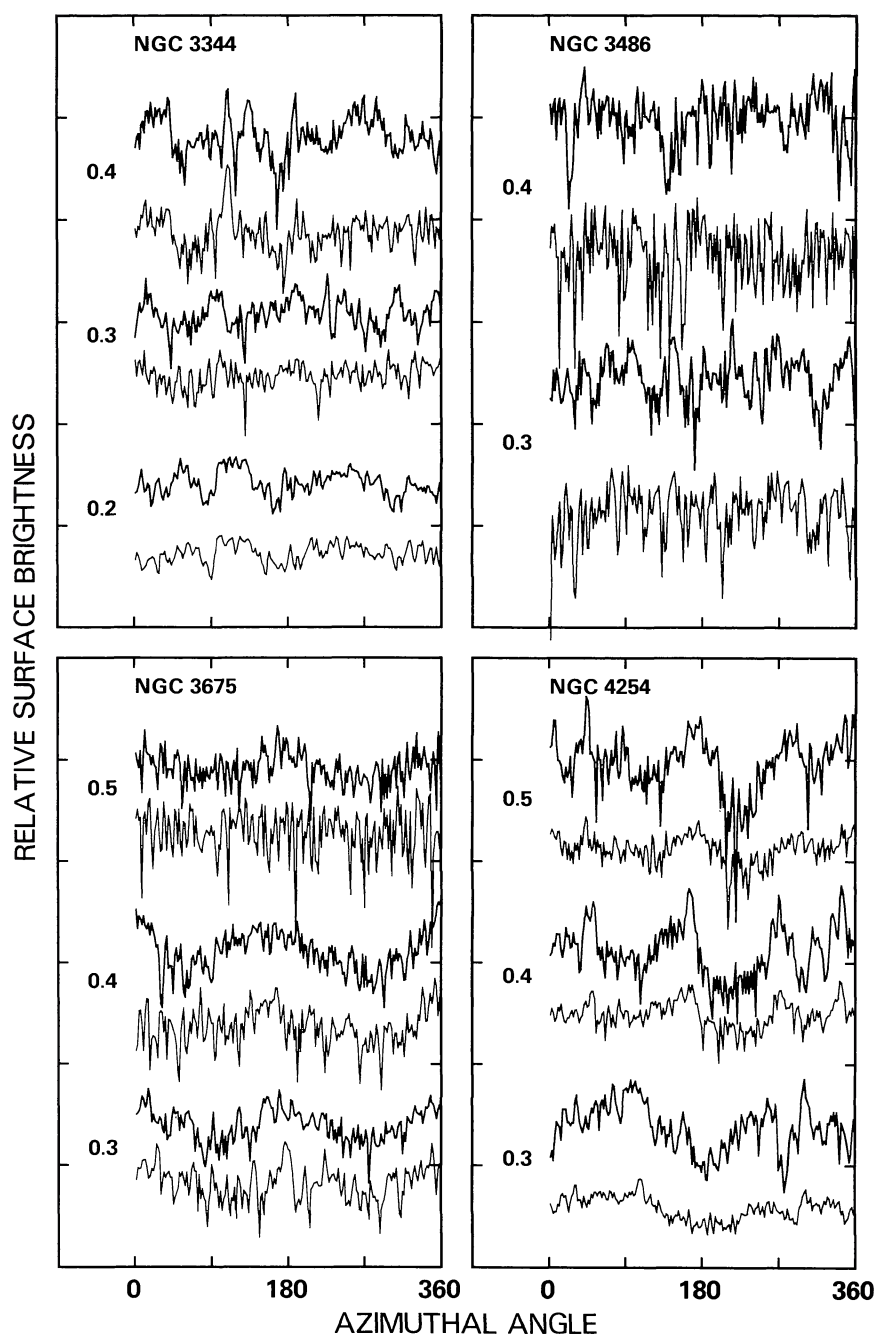


FIG. 2.—Continued

that define this range of arm classes. Such spirals often have values of A_B/A_I close to 1 (i.e., the arms have about the same colors as the interarms), which implies that the arms must be nearly pure stellar density enhancements. Star formation also contributes to the arm/interarm contrast in some cases ($A_B/A_I > 1$), but if A_I is large, then even in these cases the largest contribution to the near-infrared amplitude must be from a stellar density enhancement or density wave. Model fits to the density wave amplitudes will be made in § V.

Extreme flocculent galaxies have smaller I band amplitudes than grand design galaxies. Such flocculent galaxies have relatively little stellar density structure. Galaxies such as NGC

2403, NGC 2841, NGC 3675, and NGC 5005, which have $A_B/A_I \approx 1$, may contain weak stellar density waves or ripples, but galaxies such as NGC 1961, NGC 4414, NGC 5055, NGC 6643, and NGC 7793, which have $A_B/A_I > 1$, get most of their structure from bright patches of star formation and young star clusters. The duration of star formation in such bright blue patches will be estimated in § V.

Galaxies with intermediate arm classes have emission features that cover a large area from top to bottom and from left to right on a color-amplitude plot. These galaxies can have both star-formation patches, which are bright and blue, and stellar density arms, which have the same colors as the inter-

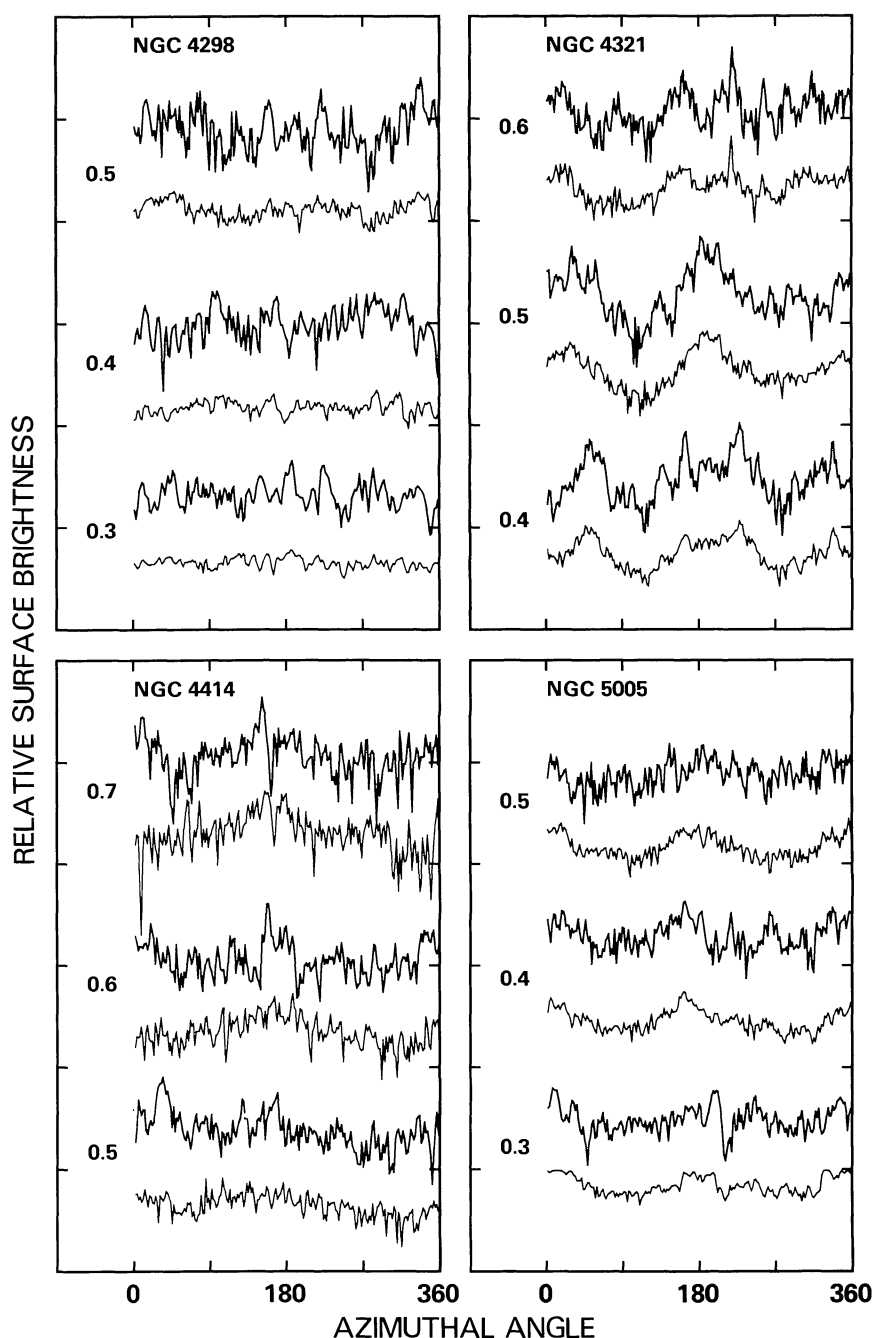


FIG. 2.—Continued

arms. An examination of the galaxy images reveals that some of the star-formation patches are within the density arms and some are isolated. Many of the density arms are also found to be small and irregularly positioned in the galaxy, having no symmetric counterparts. Such a mixture of arm features may imply that density waves or material arms in intermediate-type galaxies are either just appearing or disappearing from otherwise flocculent disks, or that these density arms are continuously present in the disks, but never strong enough to destroy or organize the large star-formation patches that form separately.

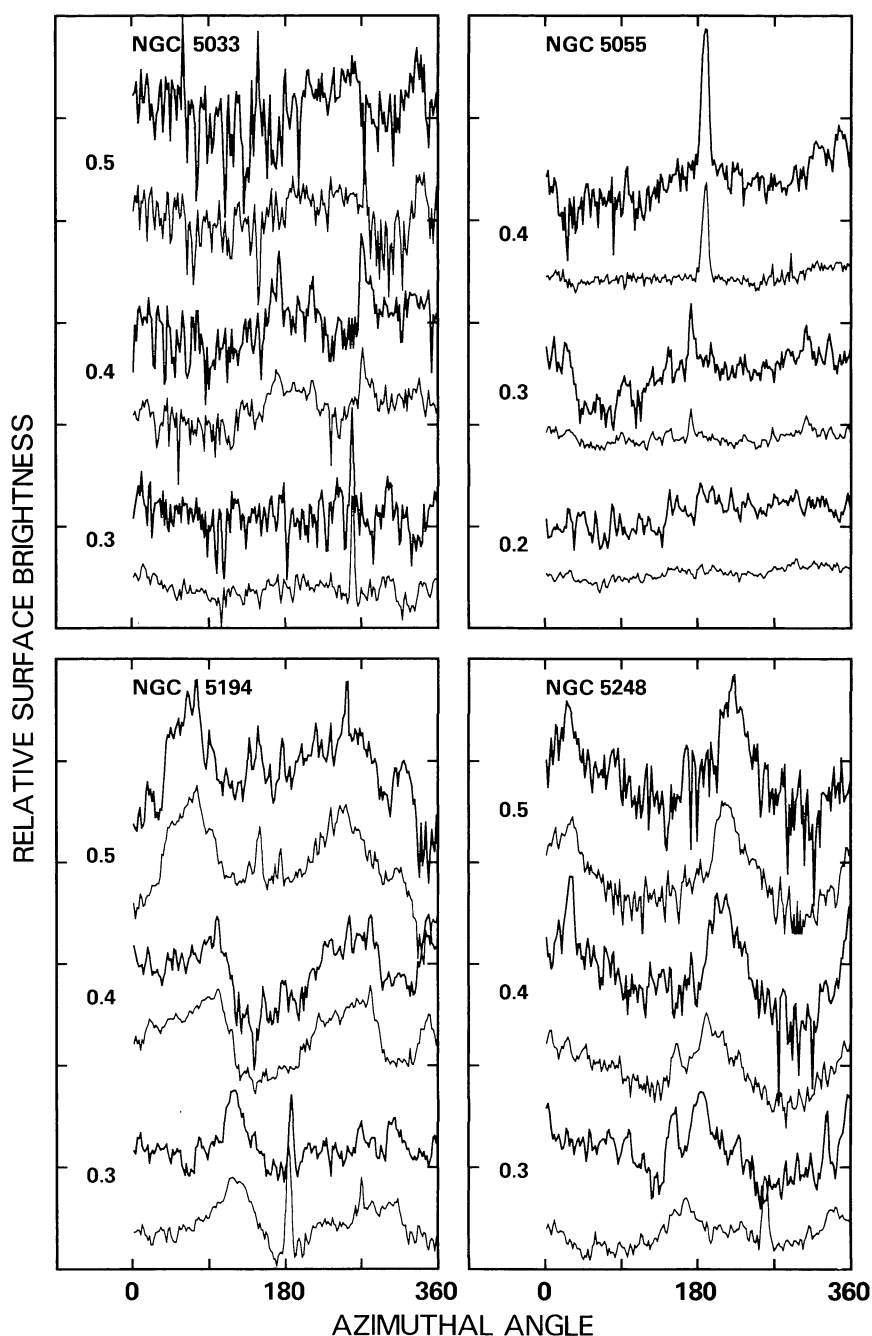
Figure 4 also shows a slight tendency for A_I and A_B to increase with galactocentric distance in intermediate and grand

design-type galaxies (i.e., larger radial positions are toward the right in the plots), as discussed by Schweizer (1976). Such radial variations are not generally evident in flocculent spirals.

V. A DERIVATION OF THE AMPLITUDES OF STELLAR DENSITY ARMS FROM B AND I BAND ARM/INTERARM CONTRASTS

a) A Model with No Extinction

The amplitude of the underlying stellar density peak in a spiral arm can be estimated from the color and intensity variations through the arm. To determine the relative contri-

FIG. 2.— *Continued*

bution to B and I band radiation from star formation, we use a general model for the spiral arm intensities that includes the color evolution of aging star clusters. This model is applied to our observations in §§ Vb, c. The results are not sensitive to dust extinction. Correction factors for extinction are derived in the Appendix.

Consider the mass surface density of old disk stars to be $K\sigma_o$ and σ_o in the arm and interarm regions, respectively (subscript o for old); the factor K is the amplitude of a stellar density enhancement that may be present in the arm ($K=1$ means no density enhancement). The mass surface density of newly formed stars in the arm is $K\sigma_y$ (subscript y for young). The theory of stellar evolution gives the luminosity-to-mass

ratio of a stellar system as a function of time. This luminosity-to-mass ratio is taken to be $(L/M)_o$ for the old disk population and $(L/M)_y$ for the young stars in the arm. Thus, the blue (B) and near-infrared (I) intensities of the arm and interarm regions (subscripts a and i) in the absence of extinction are

$$\begin{aligned}
 B_a &= [(L_B/M)_o \sigma_o + (L_B/M)_y \sigma_y] K, \\
 B_i &= (L_B/M)_o \sigma_o, \\
 I_a &= [(L_I/M)_o \sigma_o + (L_I/M)_y \sigma_y] K, \\
 I_i &= (L_I/M)_o \sigma_o.
 \end{aligned} \tag{3}$$

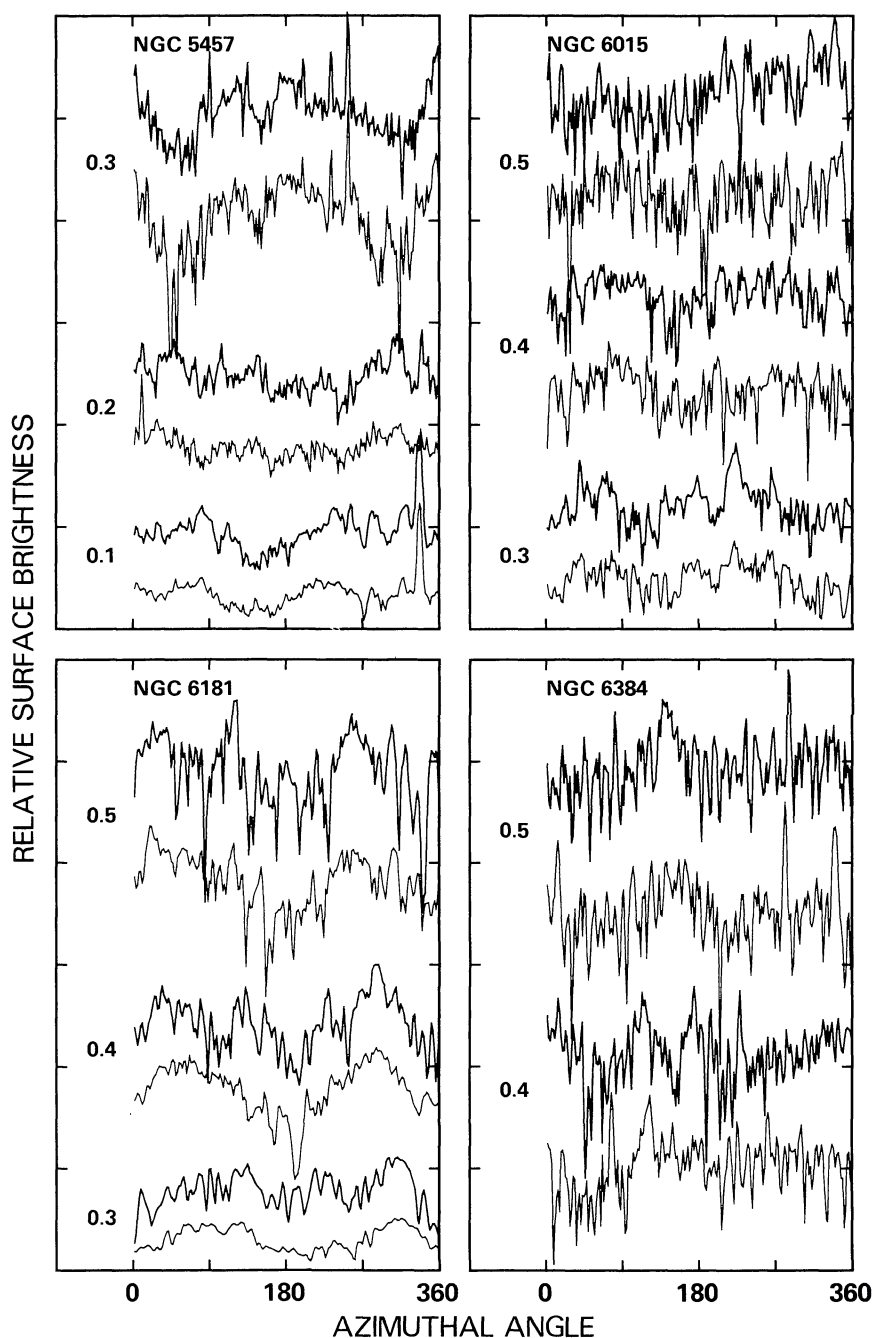


FIG. 2.—Continued

The arm/interarm intensity ratios for these two passbands are therefore

$$A_B = B_a/B_i = K [1 + (\sigma_y/\sigma_o) p_B], \quad (4)$$

and

$$A_I = I_a/I_i = K [1 + (\sigma_y/\sigma_o) p_I], \quad (5)$$

where $p = (L/M)_y/(L/M)_o$, and the subscript on p designates the passband.

Dividing equation (4) by (5) and simplifying, we obtain

$$A_B/A_I = K/A_I + (1 - K/A_I) X, \quad (6)$$

where

$$X = (L_I/L_B)_o/(L_I/L_B)_y \quad (7)$$

is the ratio of the I to B luminosities from old population stars in the arm and interarm regions, divided by the same I -to- B ratio for the young component of stars in the arms.

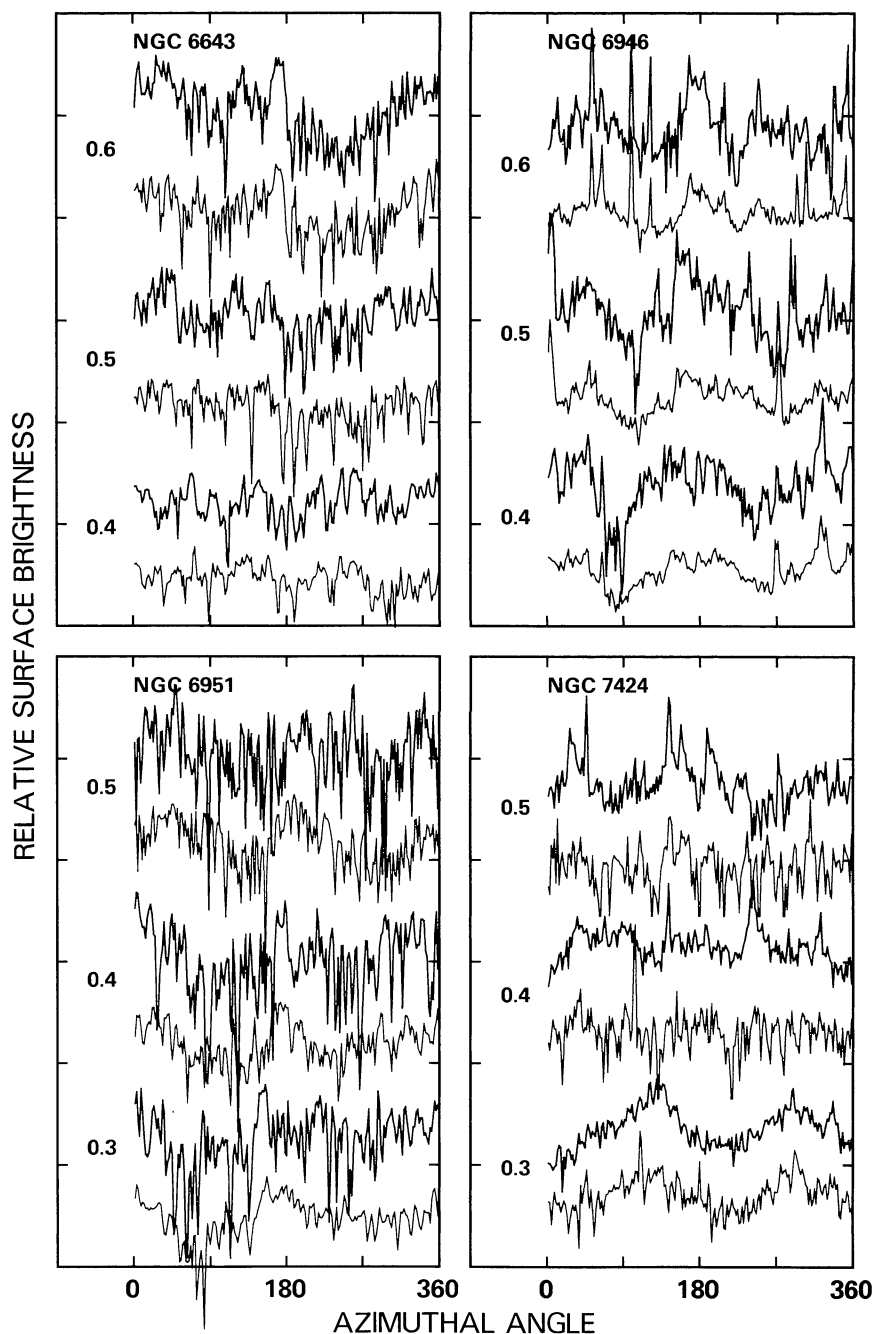


FIG. 2.—Continued

The ratio L_I/L_B of a group of stars increases with time as the stars evolve. The value of X depends on the luminosity-weighted mean age of the young stars in the arms compared to the luminosity-weighted mean age of all the older stars in the galaxy. Figure 5 shows L_I/M and L_I/L_B versus time for the model of continuous star formation studied by Struck-Marcell and Tinsley (1978; $V-I$ colors were obtained from Struck-Marcell, private communication). This color evolution model assumes that stars have been forming at a constant average rate for the time t . Figure 5 suggests that $L_I/L_B \propto$

$(t/10^{10} \text{ yr})^{0.3}$, in which case,

$$X \approx (t_i/t_a)^{0.3}. \quad (8)$$

For the old population of stars in both the arm and interarm regions, $t (\equiv t_i)$ probably equals the age of the galactic disk, $\sim 10^{10}$ yr. For the young component of stars in a spiral arm, $t (\equiv t_a)$ should equal the age of the arm, or, in the case of a density wave arm, the time during which the arm moves over its own width. Theories of stochastic (Seiden and Gerola

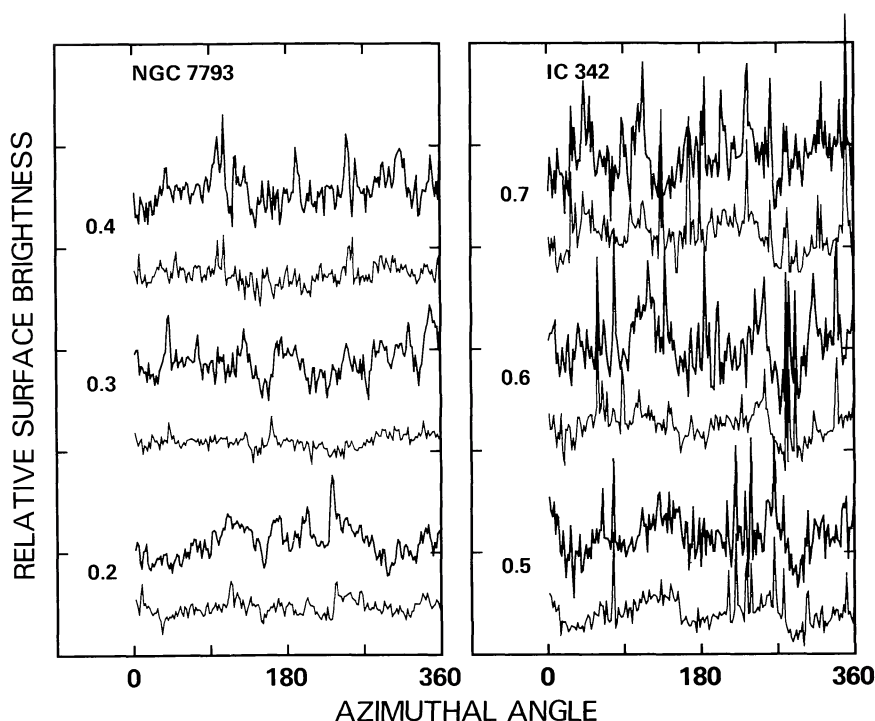


FIG. 2.—Continued

1982), shear-instability (Goldreich and Lynden-Bell 1965), and density-wave arms (Lin and Shu 1964) all imply that t_a should be $\sim 10^8$ yr, in which case $X \approx 4$. The value of X does not depend sensitively on t_a .

b) Model Fits to the Amplitudes of Stellar Density Variations

Figure 6a shows A_B/A_I versus A_I from equation (6) for $K = (1, 2, 4, 8)$ and $X = 4$. The asymptotic value of each curve for $A_I \rightarrow \infty$ equals X ; thus, differences between the durations of star formation in the arms will cause the curve asymptotes to shift up (younger arms) or down (older arms). Curves with different K are all identical except for a different horizontal position. The rightward displacement of each curve from the $K=1$ curve (as measured by the units on the A_I axis) equals the K value of the shifted curve.

In Figures 6b and 6c, the theoretical curves are superposed on color-amplitude plots for two representative galaxies, NGC 5055 (flocculent, AC 3) and NGC 5248 (grand design, AC 12). All of the features in NGC 5055 lie near the theoretical curve for $K=1$. Thus, in NGC 5055 (and in other extreme flocculent galaxies), the flocculent spiral arms are probably pure star-formation patches superposed on a uniform disk. The features in NGC 5248 (and in other extreme grand design galaxies) lie on theoretical curves with $K \gg 1$. These grand design features must contain an enhancement in the density of disk stars and probably result from a strong spiral density wave.

The amplitude of the disk density enhancement, K , may be determined easily for each feature in Figure 4 because the rightward displacement of a galaxy feature from the $K=1$ curve equals the K value of the feature. For example, in Figure

6c, the feature numbered 5 in NGC 5248 at $(A_B/A_I, A_I) = (1.6, 4)$ is shifted to the right of the $K=1$ curve by a distance that corresponds to a factor of 3 on the A_I axis. Thus, $K=3$ for this feature. Corrections for internal dust extinction do not change K by more than $\sim 10\%$ (see Appendix).

The value of K can also be obtained directly from equation (6):

$$K = A_I (X - A_B/A_I) / (X - 1). \quad (9)$$

For typical values of A_B/A_I between 1 and 1.5, and for $X=4$, K is between 0.83 and 1.0 A_I . Thus, the arm/interarm intensity contrast measured in the I band is usually within $\sim 20\%$ of the intrinsic stellar density contrast in the galaxy. I band photographs therefore illustrate the underlying stellar density patterns of grand design galaxies (see Elmegreen 1981).

Figure 4 demonstrates that the amplitude (K) of an underlying disk density variation can be very large in some of the arms of grand design galaxies. The outer regions of NGC 309, 5033, 5194, 5248, 5457, and 6181, for example, have stellar density enhancements exceeding a factor of 4. Such large amplitudes are also evident directly from the azimuthal profiles in Figure 2. The arm/interarm contrast ratio used here (K) corresponds to a relative deviation from the mean density in the disk that equals $(K-1)/(K+1)$. Thus, $K > 4$ spiral arms have relative stellar density variations that exceed 60%.

For flocculent galaxies with $A_B/A_I > 1$, the amplitude of the stellar disk density variation, K , can be equal to 1. Arms with $K=1$ are composed entirely of young star clusters and patches of star formation. According to the $X=4$ curves in

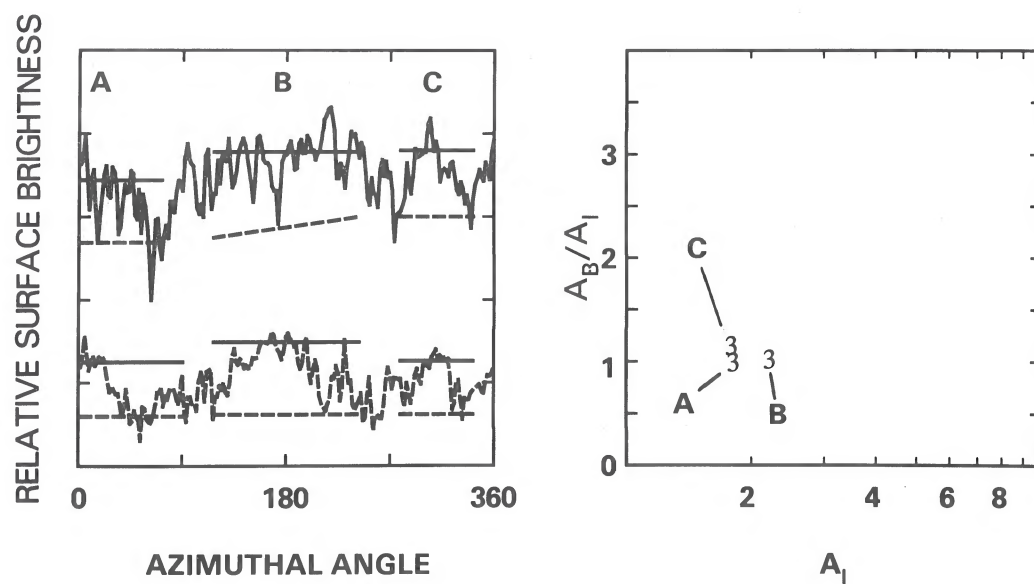
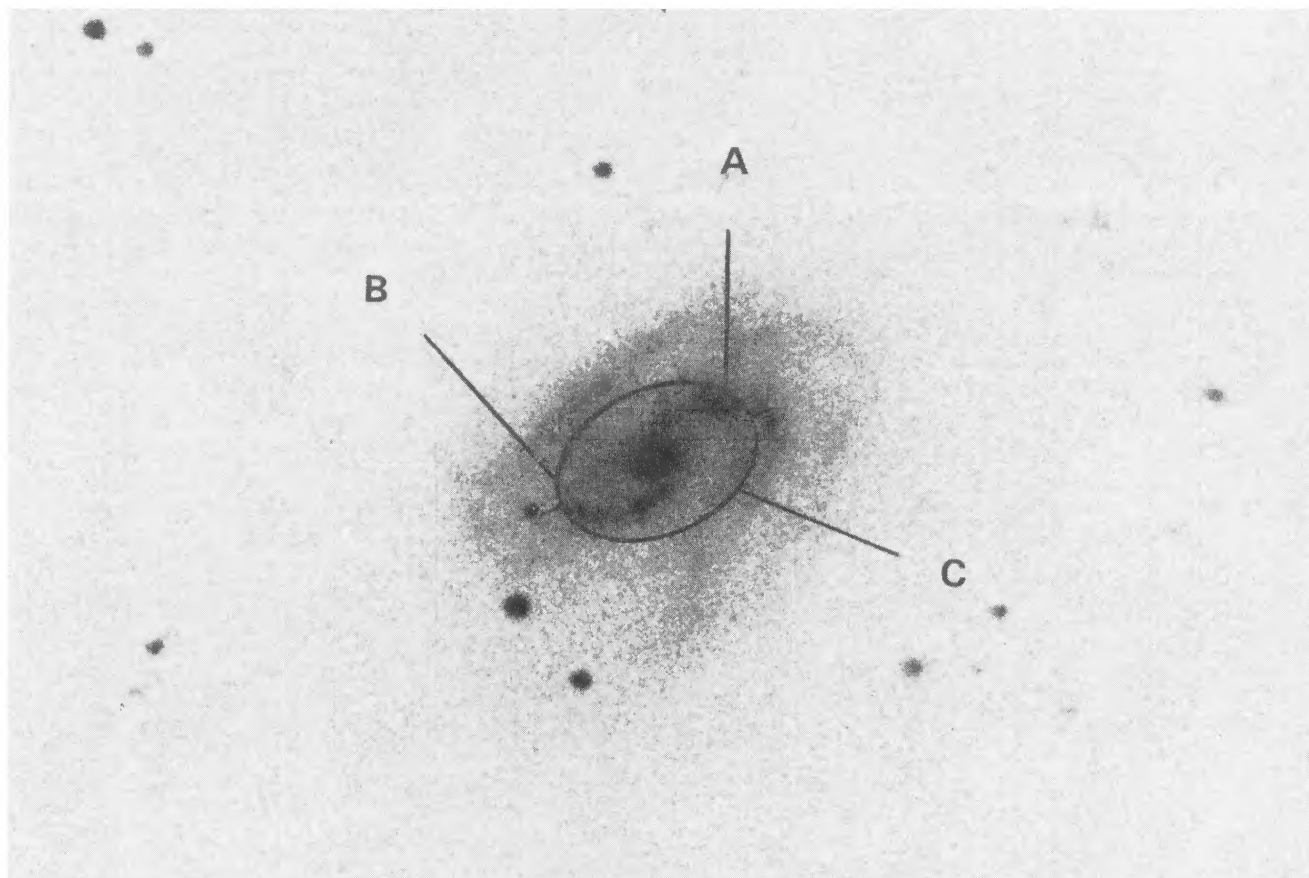


FIG. 3.—This figure illustrates the method described in the text for determining arm-interarm contrast ratios. (a) Three regions are marked at $0.3 R_{25}$ (indicated by an ellipse with an eccentricity corresponding to the inclination of the galaxy to the line of sight) in this infrared photograph of NGC 157. Azimuthal profiles (b) and color-amplitude plot (c) for the marked features are shown.

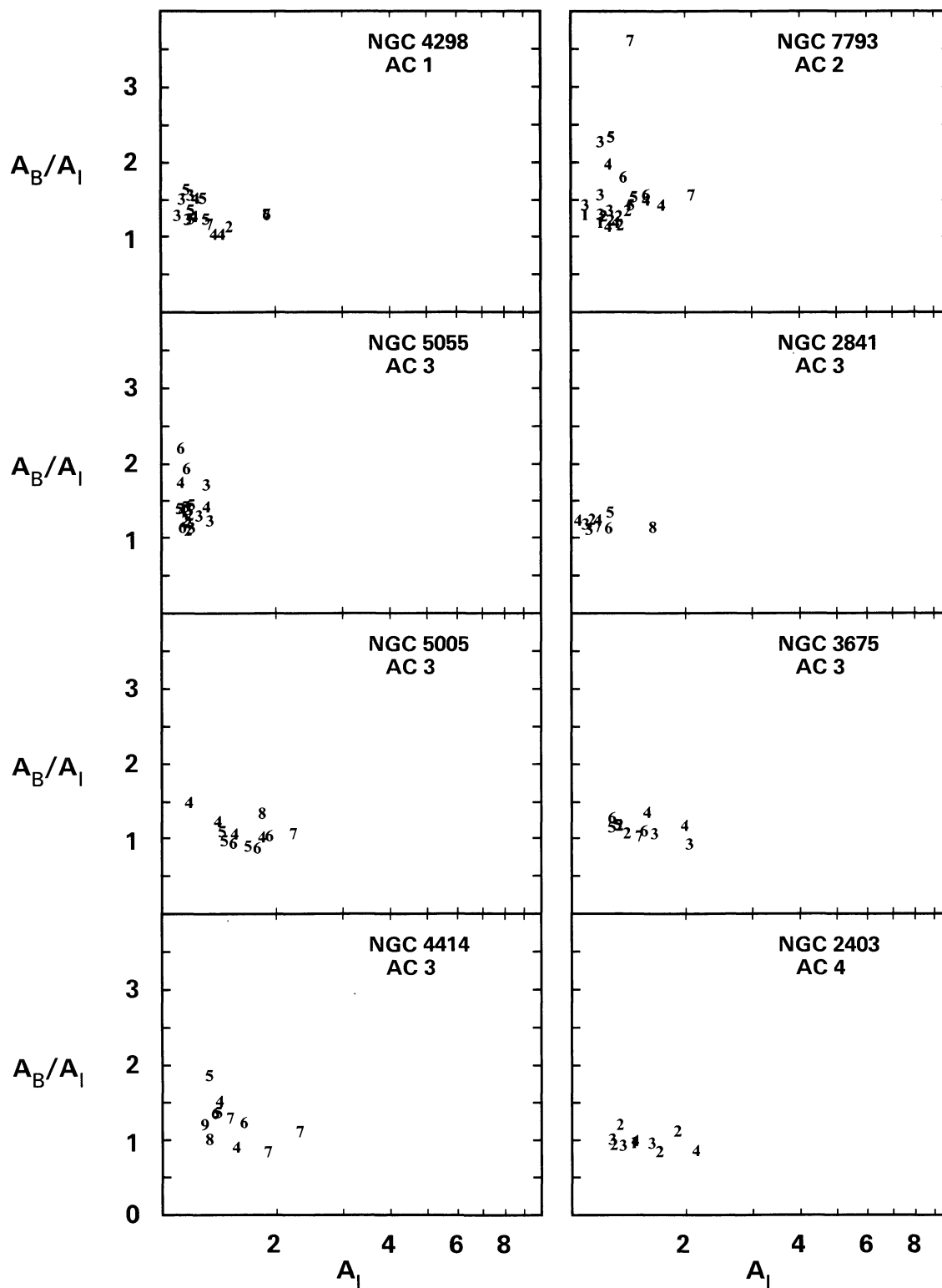


FIG. 4.—Color-amplitude plots are shown for each of the galaxies. Ordinate is the ratio of the blue arm-interarm intensity ratio to the near-infrared arm-interarm intensity ratio; abscissa is the near-infrared arm-interarm intensity ratio. Integers represent galaxy features at radial positions equal to the integer value times $0.1 R_{25}$ (a value of 0 represents $1.0 R_{25}$). The galaxies are arranged in order of increasing arm class, which is the AC number below each galaxy name. Flocculent galaxies have AC 1–4, grand design galaxies have AC 5–12.

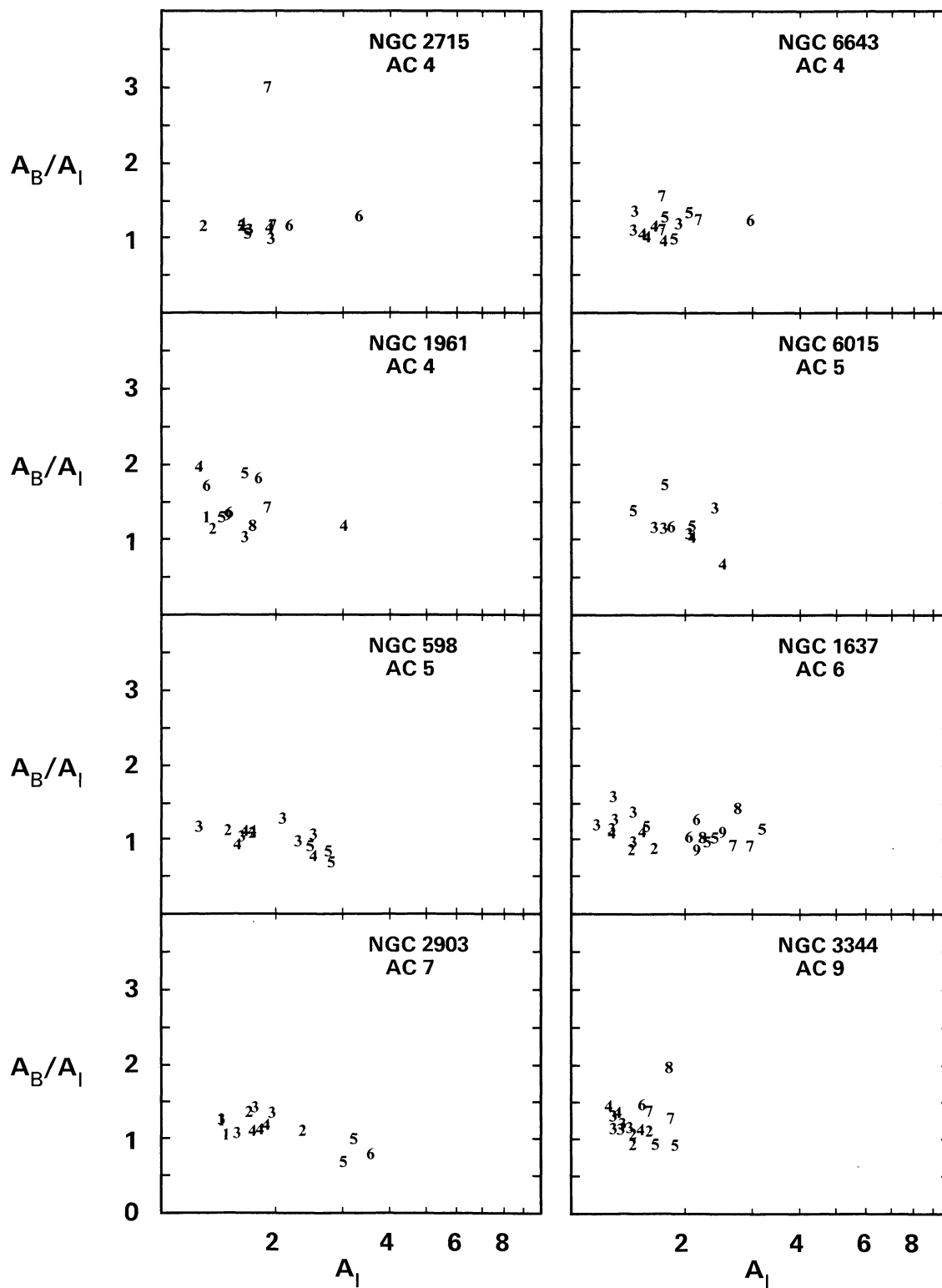
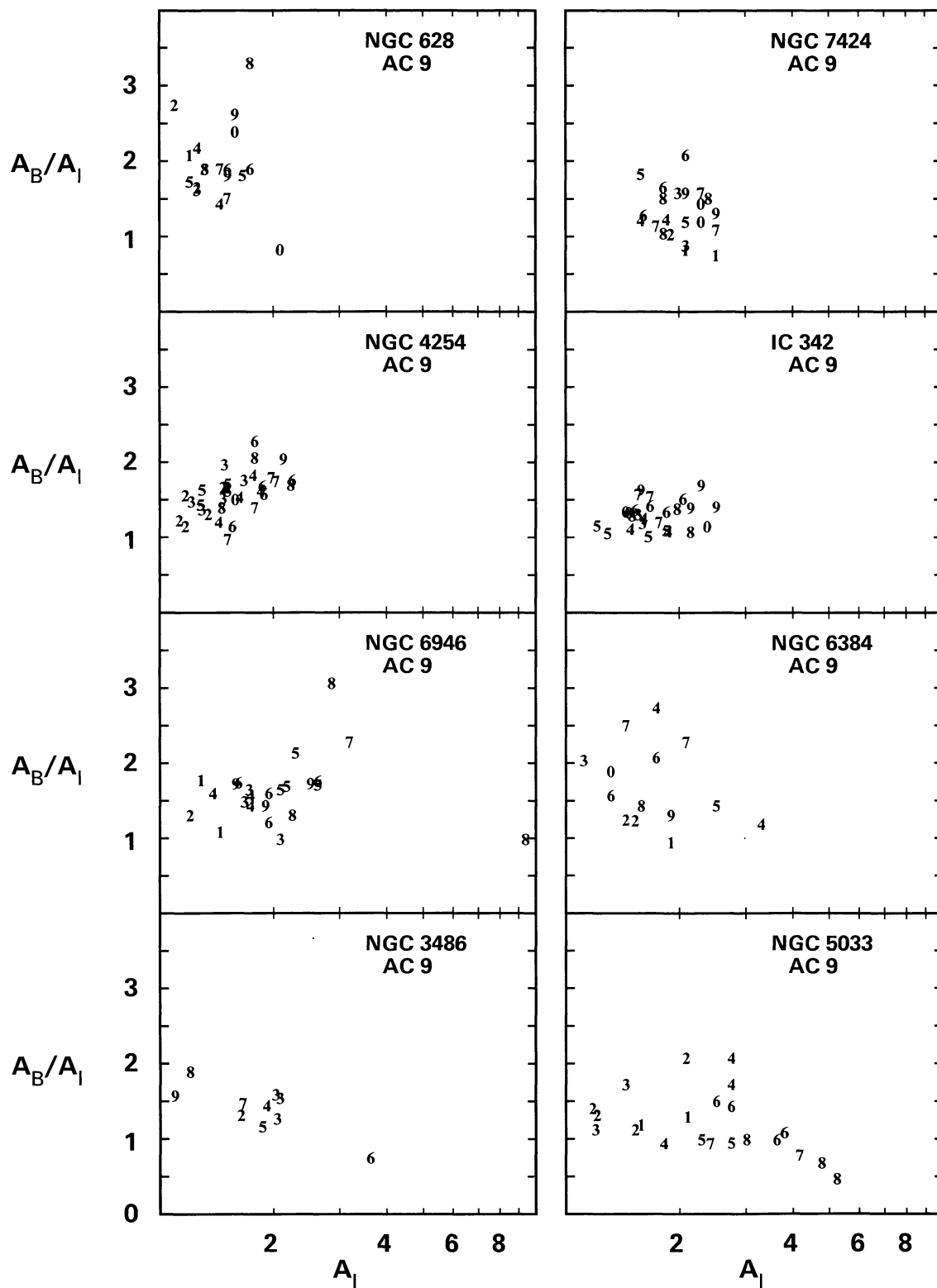


FIG. 4.—Continued

FIG. 4.— *Continued*

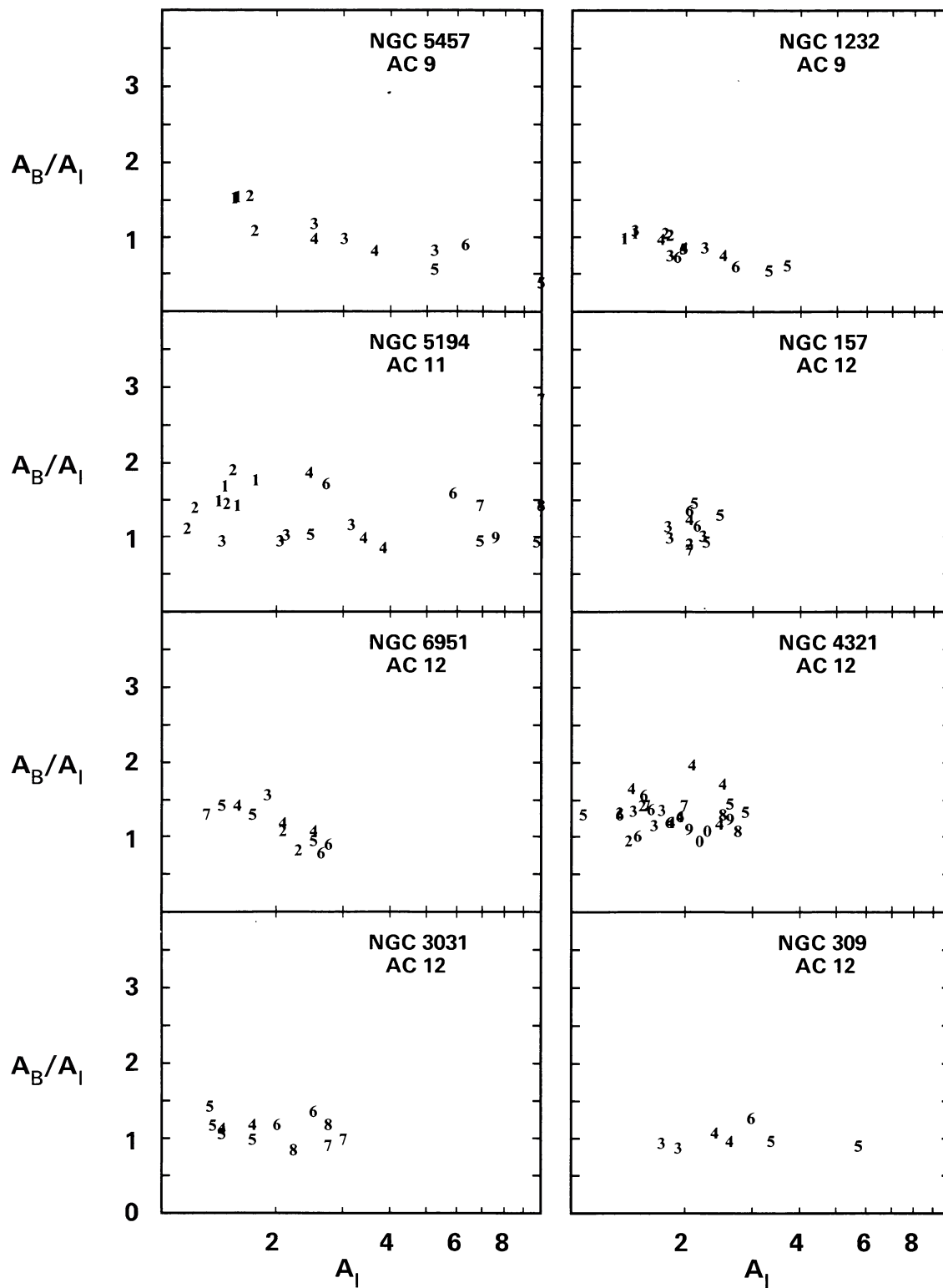


FIG. 4.—Continued

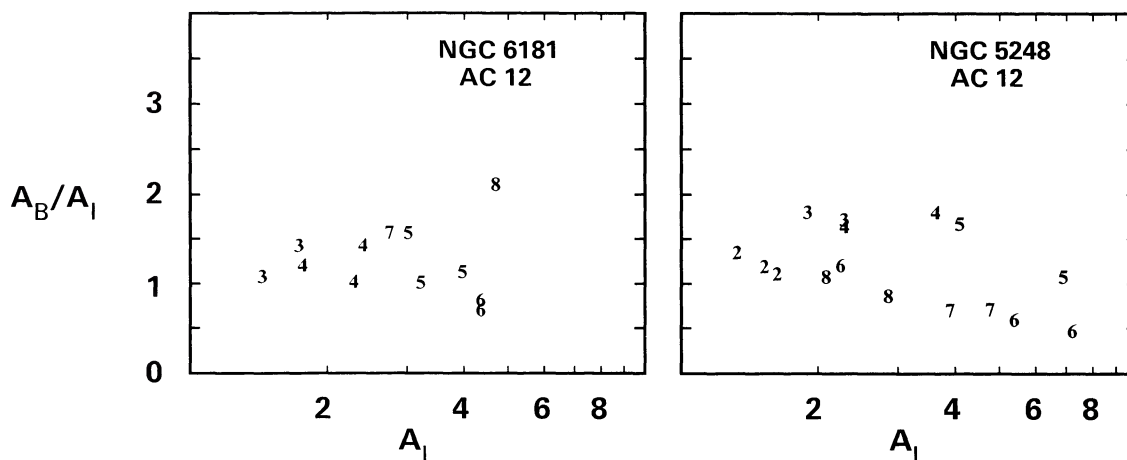


FIG. 4.—Continued

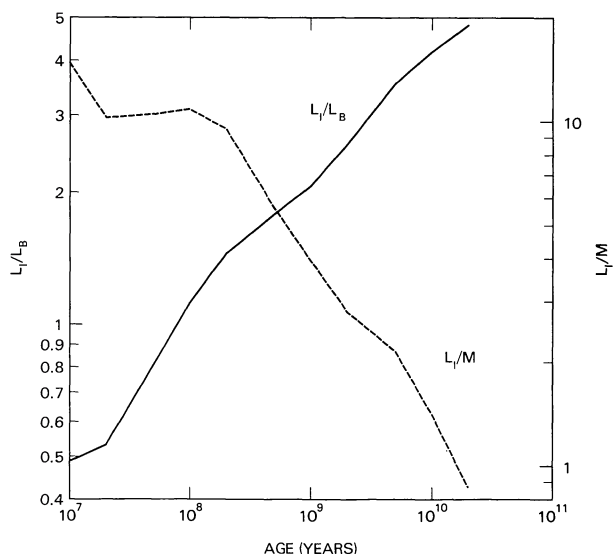


FIG. 5.—The color evolution model for continuous star formation from Struck-Marcell and Tinsley (1976) is shown. For the solid line, the left-hand ordinate is the ratio of near-infrared to blue luminosity, and the abscissa is the age in years. For the dashed line, the right-hand ordinate is the luminosity-to-mass ratio (in solar units) in the near-infrared.

Figure 6b (and considering how these curves scale with X), the ages of these patches are within a factor of ~ 3 of 10^8 yr. This time scale is consistent with the observed pitch angles of the flocculent arms if such arms are sheared patches of star formation. The pitch angle, i , of an initially circular patch varies with time t approximately as

$$i = \arccot[t(V/R - dV/dR)] \quad (10)$$

for rotation velocity V and galactocentric distance R . For constant $V \approx 200 \text{ km s}^{-1}$, $R \approx 5 \text{ kpc}$, and t between 3×10^7 and 3×10^8 yr, i ranges between 5° and 40° , which is typical for flocculent spirals.

c) Model Fits to the Star-Formation Rates in Spiral Arms

The ratio of the mass density of young stars to that of old stars in an arm is obtained from equations (5) and (9):

$$\sigma_y/\sigma_o = (L_I/M)_o (L_I/M)_y^{-1} (A_B/A_I - 1)(X - A_B/A_I)^{-1}. \quad (11)$$

This ratio may be determined for each data point in Figure 4 using L_I/M from Figure 5. The value of $(L_I/M)_o/(L_I/M)_y$ equals ~ 0.15 for $t_i = 10^{10}$ yr and for t_a between 3×10^7 and 3×10^8 yr. Thus, the ratio σ_y/σ_o equals ~ 0.15 times the vertical displacement of a data point on Figure 4 from the $A_B/A_I = 1$ line, divided by the vertical displacement of the value X (≈ 4) from the data point. For a typical value of $A_B/A_I \approx 1.5$, σ_y/σ_o equals ~ 0.03 . If the star-formation rate in these galaxies has been relatively constant with time, then such a value of σ_y/σ_o is consistent with the formation of most of the disk stars in spiral arms. This conclusion follows because the number of times the gas has been subject to star-formation processes in an arm is ~ 30 (approximately once per rotation for a two-armed spiral). Thus, the mass density of new stars per star-formation burst, σ_y , multiplied by the number of bursts, 30, equals approximately the mass density of all stars, σ_o .

Figure 4 also indicates that, except for NGC 4254, A_B/A_I does not systematically increase with A_I , so the relative star-formation rate in a spiral arm does not depend sensitively on the arm strength. This observation would seem to contradict theories that predict a dependence of the star-formation rate on the interstellar shock strength in a density wave, since the shock strength depends on the arm amplitude (Shu, Milione, and Roberts 1973). Actually, the strongest spiral arms occur in the outer parts of the galaxies where the spiral mass enhancement may be only a small fraction of the total enclosed galaxy mass. There, the gas streaming motions and shocks may not be particularly strong, even though the stellar arm contrast is

large (Lin, private communication). Furthermore, the rate of star formation may easily saturate to a maximum value when the gas enters a weak spiral wave arm. Then the rate will not increase to a higher value when the gas enters a stronger arm. For example, even the weakest spiral density waves could trigger the nearly complete conversion of ambient gas into superclouds (Elmegreen and Elmegreen 1983*b*), which then form molecular clouds and giant star complexes as a result of processes that are entirely independent of the wave. Generalized models of stochastic self-propagating star formation also have the property that the rate of star formation is independent of the strength of any underlying stellar waves (Gerola and Seiden 1980; Seiden and Gerola 1982).

VI. SUMMARY

Blue and near-infrared surface photometry was used to measure disk scale lengths, spiral arm amplitudes, and spiral

arm color variations in 34 spiral galaxies. The following results were obtained:

1. Blue and near-infrared disk scale lengths are similar within each galaxy.

2. The color and amplitude variations in azimuthal profiles of galaxies correlate with the morphology of the spiral structure. Flocculent galaxies have very weak arms in the near-infrared. When these flocculent arms are strong in the blue, then most of the structure in these galaxies is from star formation. When the blue arms are also weak, then flocculent structure arises from weak stellar density ripples. Extreme grand design galaxies have strong near-infrared arms with about the same $B - I$ colors as the interarms. These arms must be nearly pure stellar density enhancements. The stellar variations often exceed 60%, and nonlinear wave structure is evident in some cases. Very blue patches of star formation can also be present in the arms or between the arms of grand design galaxies. Intermediate-type galaxies, having patchy or multiple arms, can have either or both of the blue, chaotic-looking arm features that result from star formation, and the long, relatively smooth, near-infrared arms that result from stellar density enhancements. These galaxies may have density arms that are just appearing or disappearing from otherwise flocculent disks, or the stellar density features may be continuously present, or continuously generated and destroyed, but unable to organize the star formation into a regular structure.

3. The blueness of a spiral arm compared to the interarm region in a grand design or intermediate-type galaxy appears to be independent of the amplitude of the arm. This result implies that the star-formation rate in such a galaxy is relatively insensitive to the strength of an underlying stellar density enhancement. Star formation may be stimulated by such stellar density enhancements, but then the star-formation rate would have to saturate to the same value regardless of the stellar density amplitude. Alternatively, the star-formation mechanism may be independent of the local stellar density.

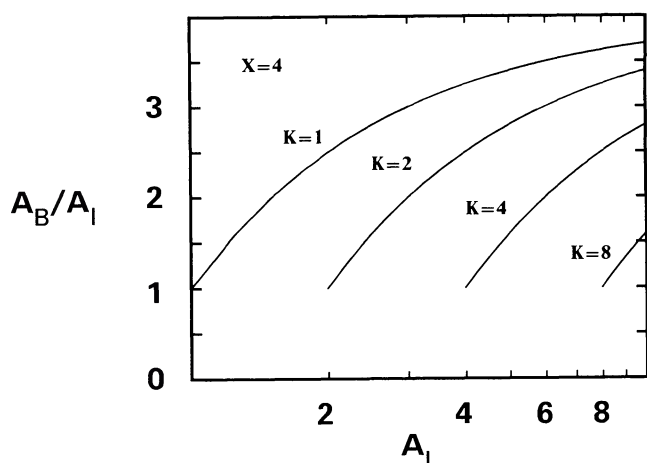


FIG. 6a

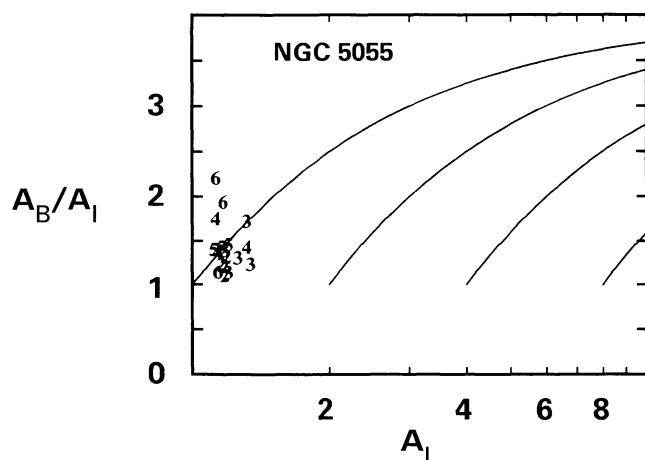


FIG. 6b

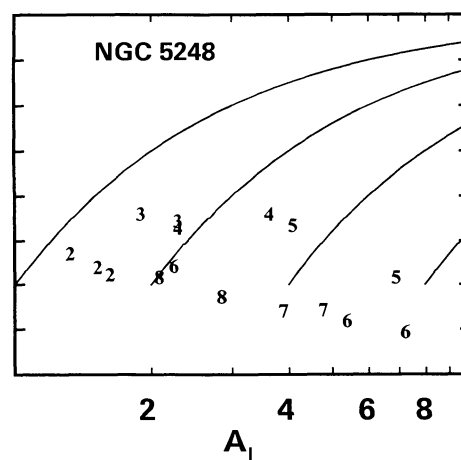


FIG. 6c

FIG. 6.—(a) Theoretical color-amplitude curves are shown based on equation (6). The axes are the same as in Fig. 4. The quantity X is the ratio of the I to B intensities from old population stars in the arm and interarm regions, divided by the same I to B ratio for the young component of stars in the arms (see eq. [7]); K is the amplitude of the density variation in the old population. The theoretical curve superposed on the color-amplitude plots for (b) a flocculent galaxy (NGC 5055) and (c) a grand design galaxy (NGC 5248).

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APPENDIX

THE EFFECT OF DUST EXTINCTION

Internal extinction in a galaxy can change the B band intensity more than the I band intensity, thereby altering the colors, and it can change the arm/interarm contrast in a given passband because the arms may contain more dust than the interarm regions. A simple model shows that a reasonable correction for dust can be incorporated into the present analysis, and that extinction does not change the results significantly.

Consider a disk galaxy with a thin layer of dust in the midplane and stars on either side of the layer. The intensity from each of the disk halves is represented by $I_0/2$, and the opacity of the dust layer is taken to be τ . Thus, the observed intensity is

$$I = I_0(1 + e^{-\tau})/2. \quad (\text{A1})$$

Typical values for τ are as follows: in a spiral arm near the radius $R_{25}/2$, the opacity for blue radiation, τ_{aB} , may be 1 to 2 mag. This value was obtained from an analysis of colors in several galaxies (Elmegreen 1980), and it is consistent with the gas column density in our own Galaxy at a galactocentric distance of ~ 5 kpc. The interarm regions of galaxies with density waves have smaller opacities than the arms because the gas density varies roughly in phase with the stellar density. Typical arm/interarm gas density contrasts in grand design galaxies may be 4 to 1; then the B band opacity in the interarm regions, τ_{iB} , will be ~ 0.25 – 0.5 mag. If bright patches are intermixed with dust in a more complicated way, then radiative transfer analyses such as that of Elmegreen (1980) are required.

Galaxies with spiral arms and no density waves ($K=1$) could have very little opacity contrast between the arm and interarm regions. If there is no contrast, then neither A_B/A_I nor A_I will change when dust is considered, and all of the previous results for the $K=1$ case are still valid.

The infrared opacities are proportional to the blue opacities; a conversion factor of $\tau_I = 0.4\tau_B$ from Whitford (1958) is used here. For these values of τ , corrected arm/interarm intensity ratios in the B and I bands may be written as correction factors multiplied by the observed values. For density wave galaxies with $4\tau_{iB} = \tau_{aB} = 1$ – 2 ,

$$A_{B_{\text{corr}}} = (1 + e^{-\tau_{iB}})/(1 + e^{-\tau_{aB}}) A_{B_{\text{obs}}} = 1.30\text{--}1.40 A_{B_{\text{obs}}}, \quad (\text{A2})$$

and

$$A_{I_{\text{corr}}} = (1 + e^{-\tau_{iI}})/(1 + e^{-\tau_{aI}}) A_{I_{\text{obs}}} = 1.14\text{--}1.34 A_{I_{\text{obs}}}. \quad (\text{A3})$$

Thus,

$$(A_B/A_I)_{\text{corr}} = 1.14\text{--}1.04 (A_B/A_I)_{\text{obs}}. \quad (\text{A4})$$

The primary effect that dust has on the analysis of § Va is to increase slightly the values of A_B/A_I and A_I . This causes a very slight shift in the position of a data point in Figure 4 to the upper right. Such a shift is approximately parallel to the curves of constant K , so extinction should not change K by more than $\sim 10\%$.

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