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A MORPHOLOGICAL SURVEY OF BAR, LENS, AND RING COMPONENTS IN GALAXIES: SECULAR EVOLUTION IN GALAXY STRUCTURE

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ABSTRACT

A morphological survey of barred galaxies is made to investigate the frequency of occurrence, nature, and size distributions of bars, lenses, inner and outer rings, and global spiral structure. The 121 brightest available barred galaxies are examined on Sky Survey copy plates, and on deeper and larger-scale plates, with the following main results.

1. Lenses and inner rings are components of major importance in barred galaxies, occurring, respectively, in 54% of SB0–SBa, and 76% of SBab–SBc galaxies. Few early-type galaxies have rings; almost no late-type ones have lenses.
2. There is an intimate connection between bars and lenses: in 17 of 20 galaxies with both components, the bar exactly fills the lens in one dimension.
3. We suggest that lenses originate as bars, through an unknown process which makes some bars evolve away to a nearly axisymmetric state. Several properties of the proposed process are deduced. We emphasize the possible importance of internal processes of secular evolution in galaxy structure.
4. Several galaxies, notably NGC 3945, seem to have strongly triaxial bulge components.
5. Inner rings are round. Lenses tend to be slightly triaxial, flattened ellipsoids, with a preferred equatorial axis ratio of $\sim 0.9 \pm 0.05$. Most outer rings are prolate, the shortest dimension being the one filled by the bar.
6. The sizes of bars, rings, and lenses are well correlated with the absolute magnitude of the galaxy, such that the mean surface brightness is constant for each morphological type. The form of the correlation $M_B + 5 \log D = \text{constant}$ is such that these diameters cannot be used as distance indicators. We show that the galaxy mass determines the bar size uniquely.
7. Spiral structure in SB galaxies is distorted to resemble inner and outer rings, showing that the arms feel the potential of the bar. Also, of 61 survey galaxies with spiral structure, 55 have global patterns usually interpreted as density waves. No survey galaxy had purely NGC 2841-type filamentary arms, though six transition cases were found. This supports the well-known suggestion that bars help to drive spiral density waves.

The morphological approach of studying distinct components in galaxy brightness distributions is described, and the seven components identified to date are listed.

Subject headings: galaxies: structure — galaxies: evolution

I. INTRODUCTION

In this paper, we continue a recent study (Kormendy 1977*a*, hereafter Paper I) of the distinct components in galaxy brightness distributions. The aim of this program is to identify such components, investigate their structure, and make deductions about their dynamics and origin. The ultimate goal is a better understanding of the features that define Hubble types (Hubble 1926, 1936; Sandage 1961, hereafter Hubble Atlas; and the extension of de Vaucouleurs 1959).

Our approach differs from classical morphology in the following way. In past classification schemes (see Sandage 1975), the aim was to divide galaxies into a small number of groups or cells, each described by a list of characteristics. Since galaxy structure is complicated, many cells are required. In fact, the revised morphological types of de Vaucouleurs require "about one hundred cells" (de Vaucouleurs 1963). As explicit recognition becomes needed for more and more distinct features, the number of cells becomes disturbingly large. In contrast, we do not assign a separate cell to each list of characteristics. Rather, we consider galaxies to be composed of a small number of building blocks, the distinct components. Some of these seem to form separately and are largely independent of the rest of the galaxy. We will conclude in §§ IV and VIII that others may form from the primary components by interactions. All components can have secondary behavior, such as density waves in disks. (Note that the dividing line between new components produced by interactions and old ones disturbed by interactions is somewhat arbitrary. For instance, we have chosen to call inner rings a distinct component,

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but spiral structure an aspect of disk behavior.) The large number of component combinations (cells in classical morphology) is not disturbing, because the focus is on a small number of building blocks. This procedure breaks up problems of galaxy structure into smaller and more manageable pieces, to which it is much easier to attach physical interpretations.

The most fundamental components—spheroids, disks, and bars—are well known. However, we emphasized in Paper I that galaxies show a much greater variety of features than just these three (see also de Vaucouleurs 1959). In particular, we discussed features which were called lenses by Sandage (Hubble Atlas). A lens is defined as an elliptical (as opposed to bar-shaped) feature occurring between the spheroid and disk, and clearly differentiated from them, which has a very shallow brightness gradient interior to a sharp outer edge, and a steep gradient thereafter. Examples are shown in the Hubble Atlas, de Vaucouleurs (1959), Freeman (1975), and Figure 1 and Figure 2*a* (Plates 13–14). We concluded in Paper I that lenses are a distinct component in galaxies, and that they are morphologically intermediate between spheroids and disks.

An examination of Hubble Atlas and Sky Survey prints shows that there is a very fundamental relationship between lenses and bars. Galaxies very often contain both a lens and a bar which exactly fills the lens in one dimension (e.g., NGC 1291 and NGC 3945 [Figs. 2*b*, 2*c*]). This motivates the present survey of SB galaxies, to better determine the frequency and properties of this coincidence.

Many other features also show a close relationship to bars (e.g., de Vaucouleurs 1959). These include inner rings, such as the one in NGC 2523 (Fig. 2*e*), and outer rings (e.g., NGC 3945 [Figs. 2*c*, 9]). Possibly even the form of the spiral structure is correlated with the presence of the bar, since the suggestion has been made that bars help to drive density waves (Toomre 1969; Sanders and Huntley 1976; and references therein). If this is so, then barred galaxies should show global spiral patterns, and not have NGC 2841–type disks (Fig. 2*f*), with many short spiral filaments but no coherent pattern.

The purpose of this paper is to make a morphological survey of a reasonably complete sample of barred galaxies, to investigate the frequency of occurrence and properties of components associated with bars, and to investigate possible interactions between them. We will also measure the features' size and axial ratio distributions. Since a bar creates a large, nonaxisymmetric distortion in the gravitational potential field, with which other stars can interact, a not surprising conclusion will be that secular evolution plays a major role in changing galaxy structure.

It is important to note some properties of a morphological study that strongly effect its results. The advantage of morphology is that it is very efficient in suggesting the presence and explanation of new phenomena in an undeveloped field. It also provides definite results on basic component properties such as frequency of occurrence and intrinsic shape. The disadvantage is that it rarely provides concrete proofs

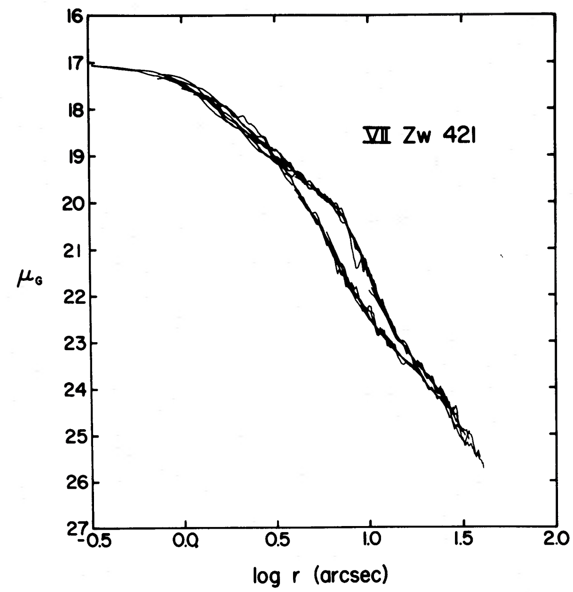

FIG. 1.—Brightness profiles of VII Zw 421 along the major and minor axes, in G mag arcsec^{-2} (4600–5400 Å). Each line is one measurement of one plate, from Paper I. The lens dominates the major axis profile from $\log r = 0.7$ to $\log r = 1.1$.

of theoretical interpretations. Thus further quantitative work is required. For example, a detailed surface photometry program on many of the objects discussed is now under way.

The survey is described in § II. Following sections discuss the properties of lenses and inner rings: frequency of incidence (§ III), origin (§ IV), intrinsic shapes (§ V), and diameter distributions (§ VI). Outer rings are discussed in § VII. Section VIII describes two special galaxies with outer rings. A correlation of spiral structure type with the presence of bars is discussed in § IX. Finally, § X gives a list of components identified to date, and a summary of conclusions.

II. THE SURVEY

We have surveyed all 121 galaxies listed in the *Second Reference Catalogue of Bright Galaxies* (de Vaucouleurs, de Vaucouleurs, and Corwin 1976, hereafter RC2) with the following properties: (i) morphological type SB; (ii) types SB0$^-$ to SBd, inclusive; (iii) B_T (or m_c, if B_T is not available) ≤ 12.5; (iv) declination $\delta > -30°$; and (v) not edge-on (i.e., not "/"). The distribution of these objects with absolute magnitude and morphological type is shown in Figure 3. Most distances are based on a Hubble constant of $H_0 = 50$ km s^{-1} Mpc^{-1} and individual galaxy redshifts from the RC2, or unpublished redshifts kindly communicated by Dr. A. Sandage. Galaxies listed by de Vaucouleurs (1961) as being in the Virgo cluster are assumed to be 22.2 Mpc away, from the cluster's mean velocity (Sandage and Tammann 1974). Redshifts are unavailable for only four galaxies. However,

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TABLE 1
DATA ON SB GALAXIES SURVEYED*

NGC (1)	Type (2)	(·) Type (3)	D major (arcsec) (4)	D minor (arcsec) (5)	Bar Diameter (arcsec) (6)	Bar Pos. ∠ (deg) (7)	Bar fills lens? (8)	S Type$^+$ (9)	Notes (10)	NGC (1)	Type (2)	(·) Type (3)	D major (arcsec) (4)	D minor (arcsec) (5)	Bar Diameter (arcsec) (6)	Bar Pos. ∠ (deg) (7)	Bar fills lens? (8)	S Type$^+$ (9)	Notes (10)
150	SB(rs)b:	r	101	35	39	81	-	2	-	3359	SB(rs)c	-	-	-	73	-	-	2	-
151	SB(r)bc	r	64	33	36	77	-	m	-	3384	SB(s)0$^-$?	-	-	-	-	-	-	-	2
337	SB(s)d	-	-	-	-	-	-	-	1	3412	SB(s)0	1	153	75	36:	61	-	S0	-
521	SB(r)bc	r	45	45	37	-	-	m/(2481)	-	3513	SB(rs)c	-	-	-	43	-	-	2	-
613	SB(rs)bc	r'	144	72	139	3	-	m	-	3516	(R)SB(s)0:	-	-	-	31	76	-	(R)	-
660	SB(s)aP	-	-	-	-	-	-	-	2	3583	SB(s)b	-	-	-	-	-	-	2	6
672	SB(s)cd	-	-	-	74	-	-	2	-	3673	SB(rs)b	r'	96	47	85	21	-	2	-
936	SB(rs)0$^+$	(r)1	209	162	84	72	<<	S0	3	3686	SB(s)bc	-	-	-	37	85	-	2	-
1022	(R')SB(s)a	r	55	44	34:	76	-	2	-	3718	SB(s)aP	-	-	-	-	-	-	2	4
1023	SB(rs)0$^-$	-	-	-	90:	26:	-	S0	2	3729	SB(r)aP	r	76	32	47:	44	-	S0	-
1073	SB(rs)c	r	97	94	59	28	-	m	-	3887	SB(r)bc	r'	70	49	55	30	-	m	-
1097	SB(s)b	-	-	-	184	0	-	2	-	3892	SB(rs)0$^+$	1	79	61:	79	0	yes	(R)	-
1187	SB(r)c	r	85	41	84	9	-	m	-	3941	SB(s)0	1	97	61	49:	21	<<	S0	-
1300	SB(rs)bc	-	-	-	163	0:	-	2	-	3945	SB(rs)0$^+$	1	104	77	68	88	yes	(R)	7
1302	(R)SB(s)0/a	1	68	68	65	24	yes	Sa	-	3953	SB(r)bc	r	80	42	46	50	-	m	-
1353	SB(rs)b:	r'	155:	53:	33:	29	-	2	-	3992	SB(rs)bc	r	143	88	104	34	-	2	-
IC1953	SB(rs)d	r	42	42	41	-	-	m	-	4050	SB(r)ab	r	101	72	89	10	-	2	-
1385	SB(s)cd	-	-	-	-	-	-	-	1	4064	SB(s)a:P	-	-	-	-	-	-	-	2
1398	(R')SB(r)ab	r1	101	83	78	87	yes	2	-	4106	SB(s)0$^+$	-	-	-	76:	-	-	2	-
1640	SB(r)b	r1	61	47	55	0	yes	2	-	4123	SB(r)c	r	88	63	91:	3	-	2	-
1744	SB(s)d	-	-	-	87	-	-	2	-	4245	SB(r)0/a:	(r)1	84	62	80	14	yes	S0	-
1784	SB(r)c	r1	59	55	65	0	yes	m	-	4262	SB(s)0$^-$?	1	56	46	30	50	<<	S0	-
1832	SB(r)bc	r(1)	36	24	36	0	-	2	-	4267	SB(s)0$^-$?	-	-	-	≤23	-	-	S0	-
2146	SB(s)abP	-	-	-	-	-	-	-	4	4273	SB(s)c	-	-	-	24:	-	-	2	-
2217	(R)SB(rs)0$^+$	1	86	73	85	0	yes	(R)	-	4274	(R)SB(r)ab	r	151	48	51:	70:	-	(R)	-
2500	SB(rs)d	-	-	-	39	0	-	(m)/2841	-	4293	(R)SB(s)0/a	-	-	-	-	-	-	-	2
2525	SB(s)c	-	-	-	38	-	-	2	-	4314	SB(rs)a	1	149	115	140	13	yes	2	-
2685	(R)SB0P	-	-	-	-	-	-	-	2,4	4340	SB(r)0$^+$	r(1)	121	74	81	56	-	-	7
2811	SB(rs)a	-	-	-	-	-	-	-	2	4371	SB(r)0$^+$	r(1)	125	74	77	-	-	S0	7
2787	SB(r)0$^+$	(r)1	113	61	61	62	yes	S0	-	4394	(R)SB(r)b	r	86	76	74	0	-	(R)	-
2835	SB(rs)c	r	71	31:	25	87	-	m	-	4424	SB(s)a:	-	-	-	135	0	-	2	-
2859	(R)SB(r)0$^+$	1	91	84	76	56	yes	(R)	7	4435	SB(s)0	-	-	-	-	-	-	-	2
2950	(R)SB(r)0	1	71	48	52	34	yes	S0	-	4442	SB(s)0	-	-	-	58:	30:	-	S0	-
3027	SB(rs)d:	-	-	-	39:	-	-	2	-	4448	SB(r)ab	r	76	30	-	-	-	S0	2
3145	SB(rs)bc	r	45:	22:	21	64	-	2	-	4461	SB(r)0$^+$:	-	-	-	-	-	-	-	4
3198	SB(rs)c	r	107	24	-	-	-	2	2	4477	SB(s)0:?	-	-	-	61	90	-	S0	8
3301	(R')SB(rs)0/a	r(1)	55	16	-	-	-	S0	2	4490	SB(s)dP	-	-	-	-	-	-	-	1
3319	SB(rs)cd	-	-	-	65	0	-	2	-	4503	SB0$^-$:	1	108	47	-	-	-	S0	4
3346	SB(rs)cd	-	-	-	26	0	-	2/(2841)	5	4519	SB(rs)d	-	-	-	26:	-	-	2	-
3351	SB(r)b	r(1)	130	113	97	80	-	2	-	4546	SB(s)0$^-$:	-	-	-	-	-	-	-	4

TABLE 1—*Continued*

NGC	Type	(·) Type	D major (arcsec)	D minor (arcsec)	Bar Diameter (arcsec)	Bar Pos. ∠ (deg)	Bar fills lens?	S Type+	Notes
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
4548	SB(rs)b	-	-	-	99	-	-	2	-
4593	(R)SB(rs)b	r(1)	114	81	86	35	-	(R)	-
4596	SB(r)0$^+$	1	139	81	108	-	yes	(R)	8
4605	SB(s)cP	-	-	-	-	-	-	-	2
4608	SB(r)0	r	93:	84	87	89	-	S0	-
4643	SB(rs)0/a	1	111	98	103	49	yes	S0	-
4665	SB(s)0/a	-	-	-	105	90	-	S0	-
4684	SB(r)0$^+$	-	-	-	-	-	-	-	2
4688	SB(s)cd	-	-	-	42	-	-	2	-
4691	(R)SB(s)0/aP	1	110	79	110	8	yes	(R)	-
4694	SBOP	-	-	-	-	-	-	-	2
4731	SB(s)cd	-	-	-	88	-	-	2	-
4754	SB(r)0$^-$:	1	57	49	57	45	yes	S0	7?
4781	SB(rs)d	-	-	-	40:	37	-	2/(2841)	-
4856	SB(s)0/a	-	-	-	-	-	-	-	2
4900	SB(rs)c	-	-	-	41	0	0	?	-
4902	SB(r)b	r	51	51	44	-	-	m	-
5101	(R)SB(rs)0/a	1	107	95	107	0	yes	(R)	8
5112	SB(rs)cd	-	-	-	33	-	-	2	-
5334	SB(rs)c:	-	-	-	39	-	-	(2)/2841	-
5350	SB(r)b	r	42	31	30	73	-	2	-
5377	(R)SB(s)a	-	-	-	-	-	-	(R)	2
5383	SB(rs)b:P	r(1)	122	108	107	62	-	-	-
5566	SB(r)ab	r(1)	78	43	50	54	-	2	-
5701	(R)SB(rs)0/a	1	86	80	86	0	yes	(R)	-
5750	SB(r)0/a	r	69	35	34	57	-	S0	-
5792	SB(rs)b	r	140	45	-	-	-	2	2
5850	SB(r)b	r	119	106	128	7	-	2	-
5905	SB(r)b	r'	51:	52:	45	-	-	2	-
5921	SB(r)bc	r	62	51	72	4	-	2	-
5970	SB(r)c	r(1)	51	25	32:	20	-	2/(2841)	-
6217	(R)SB(rs)bc	-	-	-	66	-	-	2	-
6654	(R')SB(s)0/a	-	-	-	56	21	-	Sa	8,9
6907	SB(s)bc	-	-	-	19:	-	-	2	-
7184	SB(r)c	r	99	25	-	-	-	-	2
7479	SB(s)c	-	-	-	112	-	-	2	-
7541	SB(rs)bc:P	-	-	-	-	-	-	-	2
7640	SB(s)c	-	-	-	-	-	-	-	2
7723	SB(r)b	r	39	38	41	0	-	2	-
7741	SB(s)cd	-	-	-	59	-	-	2	-
7743	(R)SB(s)0$^+$	-	-	-	81	0	-	(R)	7,8
210	SAB(s)b	1	70	39	70	5	yes	2	10
A0209+1543	-	1	30	26	30	0	yes	(R)	7,10
1291	(R)SB(s)0/a	1	203	162:	203	0	yes	(R)	10
1343	-	1	129	81	116	9	yes	-	10
2273	SAB(rs)0/a:	(r)1	49	39	30	38	yes	2	10
2365	-	1	86	35	47	22	yes	(R)	10
3081	(R)SAB(r)0$^+$	r(1)	64	43	58	53	yes	(R)	10
3504	(R)SAB(s)ab	1	81	45	68:	10:	yes	(R)	10
3637	(R)SB(r)0	1	36	36	36	-	yes	S0	10
4454	(R)SB(r)0/a	(r)1	62	45	58	16	yes	(R)	10
4612	(R)SABO	1	62:	52:	41	55	yes	(R)?	10

*Colons indicate uncertainty.

+Disk structure types: two-armed (2), multi-armed global pattern (m), S0, Sa, and all types of outer rings (R). For transition objects, the less-well-developed feature is in parentheses.

NOTES TO TABLE 1

1. Chaotic spiral. Could not identify bar.

2. Too edge-on.

3. Spheroid + bar + partial ring at ends of bar + uniform outer disk much larger than the bar. May be outer lens (L); see §§VII, VIII*b*.

4. No bar.

5. Good example of a 2-arm/(NGC 2841-type) transition case. The bar is weak. Close to the bar, the spiral structure is two-armed; at large radii it is filamentary-armed.

6. Discarded: surface brightness too high to distinguish bar.

7. The spheroid is distorted into a secondary bar; i.e., is prolate. The prototype example is NGC 3945.

8. Outer lens (L). The prototype example is NGC 4596.

9. VII Zw 793; see Paper I.

Note 10 identifies galaxies which are not properly part of the survey sample, generally because they are too faint or too far south, but which were previously known to contain lenses.

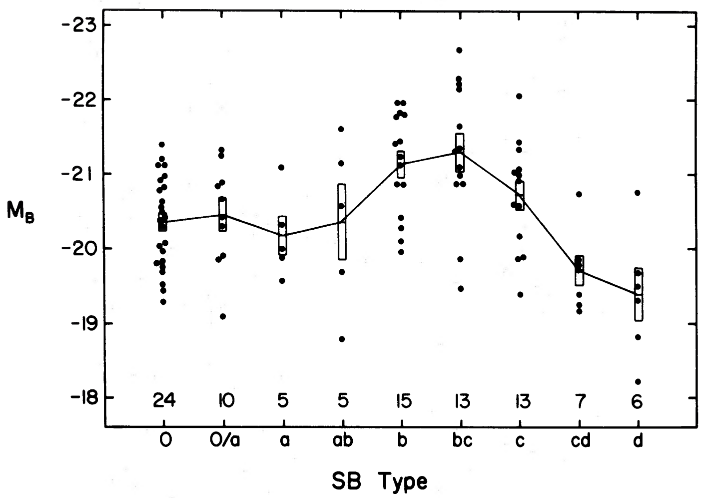

FIG. 3.—Distribution of total absolute magnitude with morphological type for the 98 Survey galaxies which were retained in the analysis (see text) and which had known distances. The number m of objects in each group is shown along the bottom. A line has been drawn connecting the average magnitudes; the $\sigma/\sqrt{m}$ errors in these averages are shown by the boxes.

only those 98 objects are shown in Figure 3 which are not too edge-on to classify, and in which bars were seen (see § III). The sample is approximately the smallest that can provide reasonable secure answers to the questions we will ask. Also, to 12.5 B_T mag, it must be nearly complete (except for the usual selection effects against large, low-surface-brightness galaxies). Most important, note that the absolute magnitudes are constant with type to SBab, and then become slightly brighter in the range SBb to SBc. Thus the correlations with type which we will discuss are *not* due to large mass changes. Only the SBcd and SBd objects are significantly fainter than average; their structure may be affected by their low mass.

The galaxies were examined on the red and blue Palomar Observatory Sky Survey (POSS) copy plates, or on original plates for objects in the Whiteoak Extension. (Whiteoak original plates are of higher quality than any of the copy plates, so that the data are not poorer for the southernmost objects.) Also, light and deep IIIa-J Schmidt plates were available for many objects, especially those in the Virgo cluster. Finally, 36 of the galaxies appear in the Hubble Atlas, and others are part of our ongoing surface photometry program, so large-scale photographs were available for nearly one-third of the galaxies.

Table 1 lists the data taken. Columns (1) and (2) give the NGC number and morphological type (RC2). Column (3) lists the classification of the inner structure, using l for lens and r for inner ring. Transition cases with, e.g., a weak inner ring and a stronger lens are denoted (r)l. A dash indicates that neither component is present. The following two columns give major and minor axis diameters of the ring or lens; rings are measured at their peak brightness points, and lenses at the sharp outer edge. Column (6) gives the bar diameter, measured in a similar way as the lens, but at a slightly different (usually higher) surface brightness. Column (7) gives the position angle of the bar with respect to the (r, l) major axis, and column (8) states whether the bar fills the lens in one dimension. Finally, morphological types of the spiral structure are given in column (9). A detailed description was also written for each object; some of this material appears in the Notes (see col. [10]). Data on outer rings will be given separately in § VII.

Morphological classification generally requires a larger scale than that of the 1.2 m Schmidt telescope ($67''.5$ mm^{-1}). Therefore, we have verified our classification on larger-scale photographs whenever possible. The resulting good agreement suggests that recognizing lenses is an easier problem than (say) distinguishing S0's from Sa's, so that our classifications are adequate. Probably a few mistakes have been made in individual cases, but these should not affect the conclusions.

Galaxies appearing in the Hubble Atlas (HA) were remeasured on Atlas prints as an accuracy check. The average deviations in arcseconds of POSS from HA measurements are given in Table 2. Column (1) is the feature measured, and column (2) the mean size difference. Column (3) gives the dispersion about this mean of the n measurements compared (col. [4]). Comparing Table 2 with Tables 1 and 4 (§ VII) shows that all features are measured with good accuracy, with no significant systematic error in the POSS data. Again, our interpretation of what feature to measure will occasionally be incorrect, especially in faint galaxies which do not often appear in the Hubble Atlas, but the size distributions should not be significantly affected.

III. FREQUENCY OF INCIDENCE OF INNER RINGS AND LENSES

Table 3 shows the percentage of galaxies of each morphological type which have various combinations of inner rings and lenses. Here r′ refers to pseudo inner

TABLE 2

Mean Deviations of Sky Survey and Hubble Atlas Diameter Measurements

Feature	δD (POSS − HA)	$\sigma(\delta D)$	n
(l, r) major........	+0″.3	2″.9	18
(l, r) minor........	−0″.9	3″.1	19
B major...........	−0″.2	3″.2	27
B position angle...	+1°.1	4°.1	14
(R) major.........	+3″.0	7″.0	8
(R) minor.........	+1″.3	12″.1	8

rings (cf. de Vaucouleurs 1959; RC2), i.e., spiral arms which only just fail to close into a ring after a half revolution. There is a continuum of structures from r through r′ to pure spirals, and therefore some ambiguity in the classification of transition objects. However, we will see in § VIII that pseudo rings behave exactly like true rings, so we can think of them as being added to the r sample. Also given in Table 3 is the total number of each type of galaxy used, and the number of objects which have been discarded as too edge-on or lacking visible bars.

Table 3 shows a striking correlation of r and l incidence with type. Of all SB0–SBa galaxies, 54% have lenses. In contrast, no survey galaxy of type SBab–SBc has a strong lens, but 76% have inner rings. Clearly *lenses are a very important component in early-type barred galaxies, and rings are similarly prominent in late-type systems.*

Although few late-type SB galaxies have even a weak lens, among nonbarred late-type galaxies, lenses are more common. A good example occurs in NGC 3504 [SAB(s)b; see the Hubble Atlas]. At all Hubble types, there are galaxies with both lenses and inner rings. However, a positive judgment as to which component is stronger was made whenever possible. Thus the apparent scarcity of transition objects is not real. Finally, a significant fraction of galaxies of all types have neither a lens nor a ring. Among the later types, these objects usually have pure spiral structure [denoted (s) by de Vaucouleurs 1959]. The latest-type galaxies rarely have rings. This may be due to their low mass, since the sophistication of galaxy structure generally correlates well with mass (e.g., luminosity classes of van den Bergh 1960).

IV. ORIGIN OF LENSES: TRIAXIAL COMPONENTS AND SECULAR EVOLUTION IN GALAXY STRUCTURE

a) The Evolution of Bars to Lenses

There are 20 galaxies in the survey which have both a bar and a dominant lens. One of the main results of this paper is the observation that, in 17 of these 20 objects, the bar exactly fills the lens in one dimension. That is, *nearly half of all early-type barred galaxies have bars and lenses of the same size.* Ten more such objects have also been found accidentally on plates taken for other purposes. Clearly there is a very intimate connection between bars and lenses.

The appearance of the closest SB(l) galaxies in the Hubble Atlas (e.g., NGC 5101) suggests a possible explanation. As noted by Sandage, the lens is broken at the ends of the bar. The rim of the lens is brighter on the side connected to the bar, and the bar becomes very broad at this point. One has the impression that the bar resonance is weak here, or even that stars are escaping into the lens.

These observations, and others discussed below, suggest, but do not prove, that *there exists a process which makes some bars evolve fairly rapidly to a nearly axisymmetric state. The result is a lens, and the suggestion is that all lenses originate in this way.* Since half of all early-type barred galaxies are transition cases, the process is clearly secular.

The direction of any evolution is more difficult to determine. Evolution from bar to lens is perhaps more likely, because bars are widely believed to form by dynamical instabilities during the violent phase of galaxy formation. On the other hand, gas and stars tend to respond to an oval distortion such as a lens by making a bar (Sanders 1977; Huntley, Sanders, and Roberts 1978), although this is perpendicular to the oval distortion if the mass distribution is very centrally concentrated (Sanders and Huntley 1976; see also Contopoulos and Mertzanides 1977). The morphology alone does not clearly predict the direction of evolution. We will assume that bars are making lenses, and note that none of the other conclusions of this paper depend on this assumption, or even require that evolution be taking place at all.

The nature of the evolution process is unknown. Probably it involves an interaction with some other component in the mass distribution, which gradually

TABLE 3

Frequency of Incidence of Inner Rings and Lenses

Type	0	0/*a* + *a*	*ab* + *b*	*bc* + *c*	*cd* + *d*
r′..............	0	0	14	7	0
r...............	4	21	48	43	8
r(l)............	9	7	19	7	0
rl..............	0	0	10	4	0
(r)l............	9	7	0	0	0
l...............	48	43	0	0	0
Neither.........	30	21	10	39	92
Total number	23	14	21	28	13
Discards......	7	7	2	3	3

allows stars to escape from the orbital resonance that creates the bar. Lenses seem to occur preferentially in the earliest type disk galaxies, which are the ones with strong spheroids. Therefore, it is worth investigating whether the postulated process is an interaction with the spheroid.

b) *Triaxial "Spheroids" in Barred Spiral Galaxies*

In this regard, it is interesting that secondary nuclear bars have been seen in several galaxies which appear to be making lenses, such as NGC 1291 and NGC 1329 (de Vaucouleurs 1974*a*, *c*). Usually these appear so deep in the potential well that it is difficult to see how they can be connected with the main bar. However, in the galaxy NGC 3945 (Fig. 2*c*), the "spheroid" is distorted into a secondary bar of major strength.

An isodensity tracing of NGC 3945 (Fig. 2*d*) shows that the outer bulge component is very elongated, while the inner core is round. Morphologically, this resembles a spheroid-bar combination. In fact, the bulge is so flattened that it probably cannot be an inclined spheroid. It has a maximum axial ratio of 0.67, while the lens has a larger axial ratio of 0.74 (Table 1). Even if the lens were triaxial, with an equatorial axial ratio of 0.85 (see § V*b*), an equivalent circular disk would have $b/a = 0.63$, hardly smaller than that of the bulge. Since this presumably has a considerable thickness, which increases its axial ratio, *the bulge component of NGC 3945 cannot be an inclined spheroid but must be at least prolate* (*and probably triaxial*). Binney (1976, 1978; see the latter paper for a review) has suggested that elliptical galaxies are generally triaxial. In the present barred galaxies, identified by Note 7 in Table 1, triaxial distortions are particularly prominent. These may be more closely connected with the presence of a bar than with Binney's general arguments. Possibly they represent a resonance phenomenon with the bar (cf. Contopoulos and Mertzanides 1977). However, a frictional interaction of a triaxial "spheroid" with the main bar is also possible, and clearly worth further investigation.

c) *Origin of Inner Rings*

All this is an early indication that a widely made assumption about galaxy structure is oversimplified. It has long been recognized that tidal effects can change galaxy structure. But we are used to thinking that isolated galaxies go through an early phase of violent collapse, establish an equilibrium structure, and never change thereafter (except in stellar content). Now we see that bars may be turning into lenses. Duus and Freeman (1975) have suggested another secular evolution process, which appears to account for internal rings. They have constructed a numerical galaxy, with a point-mass nucleus and a test-particle disk, on which a bar potential is imposed. They find that the bar rapidly rearranges the material in the disk, causing some of it to fall to the galaxy center, and the rest to form a ring around the ends of the bar (see also de Vaucouleurs and Freeman 1972; Sanders 1977). Such a process can occur simultaneously with any bar evolution, so that one expects, and in fact sees, many galaxies which have both a ring and a lens. Observed inner rings have all the morphological properties predicted by the Duus and Freeman model: they are round (§ V); they have the same diameter as the bar, and they have, as nearly as photographs can determine it, the same stellar content as the disk. For instance, in NGC 1398 and 2523 (Hubble Atlas) the bars are similar in content to the spheroids, while the rings are patchy, blue, and full of H II regions, like the disks.

Thus we already know of several secular evolution processes which appear to be important in SB galaxies. It is important to ask whether there are other purely internal processes which can, on a relatively short time scale, dramatically alter galaxy structure.

V. INTRINSIC SHAPES OF LENSES AND INNER RINGS

a) *Apparent Axial Ratio Distributions*

In this section we will investigate the intrinsic shapes of lenses and inner rings. Outer rings will be discussed in § VII.

Figure 4 shows the distribution of apparent axial ratios b/a for these components, and for a series of models of planar ellipses viewed at random orientations. The vertical dotted line is an observational cutoff imposed by the fact that lenses and rings cannot be recognized when seen nearly edge-on. It was determined from nine galaxies which either were too edge-on to classify, or which just showed a ring. Then the distribution for $b/a < 0.33 \pm 0.03(\sigma/\sqrt{9})$ should be ignored. Note that there are very few galaxies in each bin, so that the statistical weight of our conclusions is not high.

The distribution for rings is consistent with their being round and planar. If a significant fraction were as flattened as $b/a = 0.85$, a lack of apparently round objects would have been seen.

The statistics for lenses are too poor to justify detailed conclusions. However, the number of objects with $b/a \geq 0.7$ is significantly greater than the number with $b/a < 0.7$. This behavior cannot be matched well by any distribution of planar ellipses. Rather it resembles the distributions illustrated by Sandage, Freeman, and Stokes (1970) for elliptical galaxies. It suggests that lenses have a significant thickness, and therefore supports the conclusion of Paper I that lenses are intermediate between spheroids and disks. A larger sample to check this conclusion would be very valuable, but would require plates taken with large-scale reflectors.

b) *Special Cases of Known Inclination*

The examination of galaxy photographs left a strong impression that very few lenses appear exactly round. This shows up as a (statistically not significant) drop in the 0.85–1.0 b/a bin in Figure 4. Furthermore, many lenses clearly have a sharper outer edge on the major axis than on the minor. At least at brightnesses

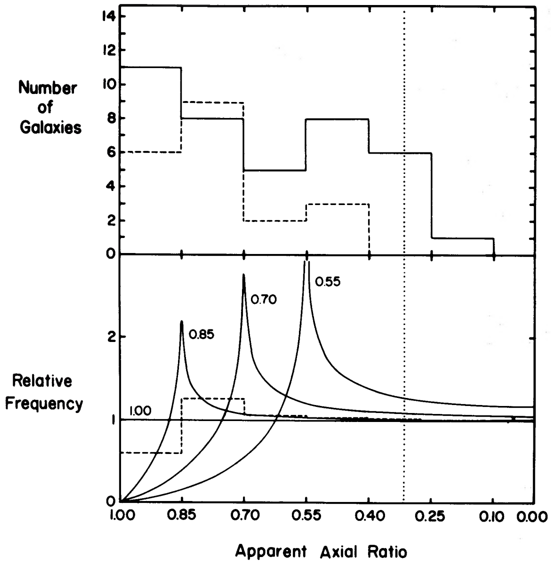

FIG. 4.—*Upper panel*, the distribution of apparent axial ratios b/a for inner rings (*solid*) and lenses (*dashed*). The dotted line at $b/a = 0.33$ is an observational cutoff, below which it is difficult to recognize either component. The lower panel shows the analogous distributions for populations of planar ellipses viewed at random orientations. Each curve is labeled with the intrinsic axial ratio of the ellipse.

near the cutoff, they must be slightly elliptical in their "equatorial planes." The apparent axial ratio distribution is consistent with this, but is too weak statistically to prove it. Fortunately there are several objects for which inclinations can be obtained. These show that the above conclusion is correct.

Figure 1 of Paper I shows isodensity tracings of the lens galaxies VII Zw 421 and II Zw 67. The lenses are quite elliptical, having axial ratios of 0.75 and 0.82, respectively. However, both the tracings and the brightness profiles (Figs. 1 and 3*g* of Paper I) show that the exponential disks are rounder than the lenses. The disks have axial ratios of 0.88 and 0.95, allowing us to rectify the galaxies. Thus, the lenses in VII Zw 421 and II Zw 67 have equatorial axial ratios of 0.85 and 0.86, respectively.

Mebold *et al.* (1977) have obtained H I velocity data in the outer ring of NGC 1291 (Figs. 2*b*, 9*c*), which allow its inclination to be determined. The velocity gradient across the ring in the bar direction is close to zero. At right angles, the total velocity range is ~ 40 km s^{-1} (see also Balick, Faber, and Gallagher 1976). If this material is being supported by rotation and is in steady state, then Mebold *et al.* show that the galaxy must be nearly face-on (inclination $\leq 10°$). But the lens has an observed axial ratio of 0.80.

Thus *lenses are slightly triaxial, moderately to highly flattened ellipsoids, with a preferred "equatorial" axial ratio of $\sim 0.9 \pm 0.05$*. A few are exactly round (e.g., NGC 1302 in the Hubble Atlas). Not very many can be as elliptical as 0.85 b/a; otherwise, practically no objects would have been observed in the 0.85–1.0 b/a bin in Figure 4.

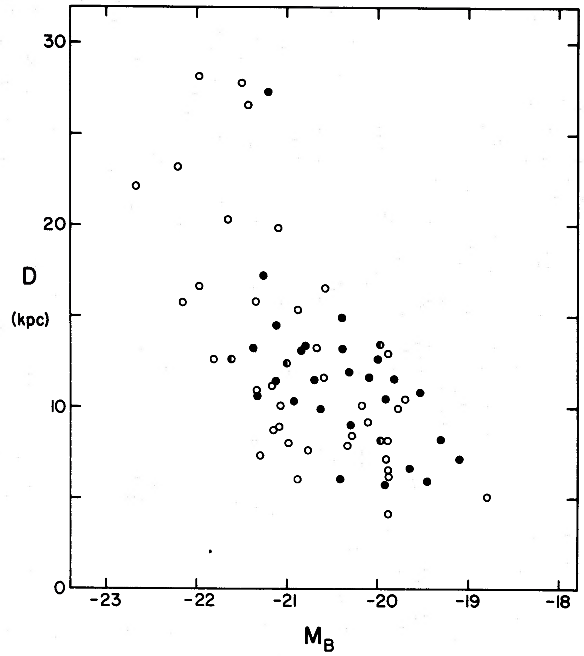

FIG. 5.—Diameters of lenses (*filled circles*) and inner rings (*open circles*) as a function of absolute magnitude. The cluster of points at $D \approx 28$ kpc and $M_B \approx -21.5$ is probably produced by errors in interpreting what to measure. For instance, the "lens" in NGC 936 is probably an outer lens L (§ VII). These points have been omitted in the subsequent analysis.

VI. DIAMETER DISTRIBUTIONS FOR BARS, LENSES, AND INNER RINGS

Surprisingly, almost nothing systematic is known about bar diameters. In this section we will study the diameter distributions of bars and related components, as a function of the component type, galaxy type, and absolute magnitude.

A little experimentation shows that the fundamental correlation is with absolute magnitude. We can use this to ask whether lenses and rings have the same sizes. Figure 5 shows the result. *Inner rings and lenses have the same diameters at the same M_B, so it is not the bar length which determines whether a galaxy makes a ring or a lens.*

Figure 6 shows the distribution for both components, divided up by morphological type. Apparently the D–M_B relation is different for different types, later-type galaxies being brighter at any D than earlier-type objects. The dispersion is larger at earlier types, and largest for the S0's.

The form of the D–M_B relation is derived in Figure 7. There is a good correlation for Sc+d galaxies; a least-squares fit gives $M_B = -4.69 \log D - 16.21$ mag, with a dispersion of only 0.12 in log D. The slope is not significantly different from -5. The relation would then imply either that the mean surface brightness is constant, or that we have introduced distance errors into an uncorrelated distribution (changing the distance moves points parallel to a line of slope -5). However, if the mean surface brightness is constant, the raw data should show the same correlation, since surface brightness is independent of distance. In fact, log D(arcsec) and B_T(observed) are correlated, with a dispersion as small as the above, and a slope of -4.95. Thus, *for each morphological type, the surface brightness is constant, independent of* M_B. The least-squares lines of slope -5 are shown in Figure 7. The indicated difference in mean surface brightness between Sbc–d and S0–b galaxies is 0.61 mag arcsec^{-2}, or a factor of 1.8. This difference is approximately consistent with the variation with type of M/L values derived from rotation curves.[1] That is, the mean *mass* density is approximately constant for *all* morphological types. The same conclusion was reached in a different way by Freeman (1970), for 28 of 36 disk galaxies, about half of which were barred. Note that both results refer to the total mean brightness outside the spheroid-dominated core, and not only to the disk light (see Kormendy 1977*b*).

The dispersion in surface brightness is smaller than Figure 7 suggests, since a variable spheroid contribution is still included. To estimate this contribution, we measured the diameter of the bright core perpendicular to the bar. In early-type galaxies this measures the spheroid. Most late-type galaxies also had a strong central light concentration, but it was disk-population material (patchy and full of stars and H II regions; cf. Freeman's mechanism for creating rings in § IV). We will call the ratio of this measurement to the (r, l) diameter the spheroid strength. Figure 8 shows that the deviation of galaxies from the log D–M_B relation is correlated with the spheroid strength. Thus much of the scatter in Figure 7 is produced by a variable spheroid contribution. This is especially true for early-type galaxies, and produces their relatively larger scatter. Part of the scatter also comes from combining S0 and Sb galaxies, which already have slightly different distributions.

We therefore conclude that the mean mass density outside the central core is remarkably constant for

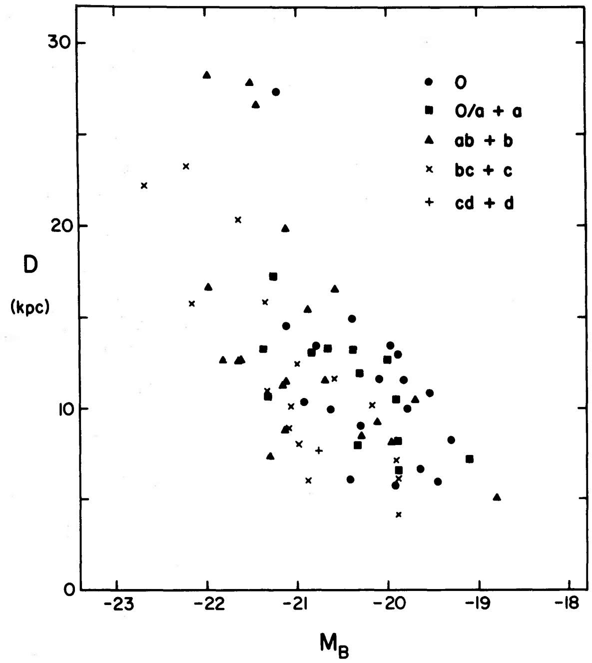

FIG. 6.—Size distribution of lenses and inner rings as a function of morphological type. The D–M_B correlation is different for different types, later-type galaxies being brighter at any D than earlier-type galaxies.

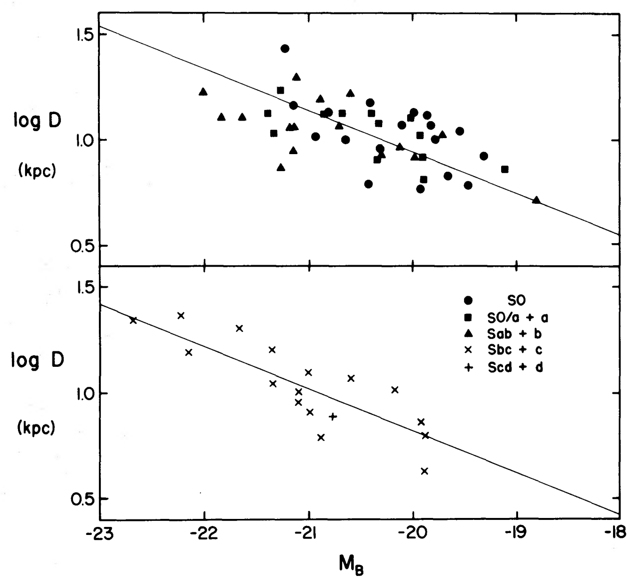

FIG. 7.—Logarithm of the major axis diameter of lenses and inner rings versus total absolute magnitude. Lines $M_B = -5 \log D +$ constant are shown; these imply that the mean surface brightness is independent of luminosity.

[1] The evidence for this conclusion is not unambiguous. Apparently contrary arguments have been put forth by de Vaucouleurs (1974*b*), Dickel and Rood (1978, hereafter DR), and others. However, we need values referring only to the optically luminous parts of galaxies, say those within a Holmberg (1958) radius R_H, and not total masses (as discussed by DR). Dickel and Rood show that the constancy of total M/L with type results from two compensating effects: at later types, less of the mass is interior to R_H, but that interior mass has a smaller M/L. In fact, the ratio of fractional masses within R_H for S0–b and Sbc–d galaxies, number weighted as in our sample, is 1.4 (from DR, p. 406). If the total M/L is independent of type, this is also the ratio of M/L values (within R_H) for S0–b and Sbc–d galaxies. This may be an underestimate, since our S0–b sample is heavily dominated by S0's.

More explicitly, we can use M/L values from detailed rotation curve work, summarized by Burbidge and Burbidge (1975, hereafter B^2). Then 45 determinations for 35 Sb–c galaxies give $\langle M/L \rangle = 4.9$ ($\sigma = 3.9$, $\sigma/\sqrt{45} = 0.6$; $H_0 = 75$ km s^{-1} Mpc^{-1}). However, only two S0's are listed. Recent work increases this number to six: NGC 128 (Bertola and Capaccioli 1977), NGC 3115 (see B^2; Morton and Chevalier 1973; Williams 1975), NGC 4111 (B^2), NGC 4473 (Young *et al.* 1978), NGC 4762 (Bertola and Capaccioli 1978), and NGC 7332 (Morton and Chevalier 1973). We have included the E5 galaxy NGC 4473 because both rotation and velocity dispersion were analyzed; otherwise, results based only on velocity dispersions are omitted. These six galaxies have a mean $M/L = 9.9$ ($\sigma = 5.3$, $\sigma/\sqrt{6} = 2.2$). This value seems to be significantly higher than 4.9. The ratio is 2.0. Thus, although the story is far from complete, there are several indications of a variation with type of M/L (within R_H) which is similar to the factor of 1.8 found here for the surface brightness variation.

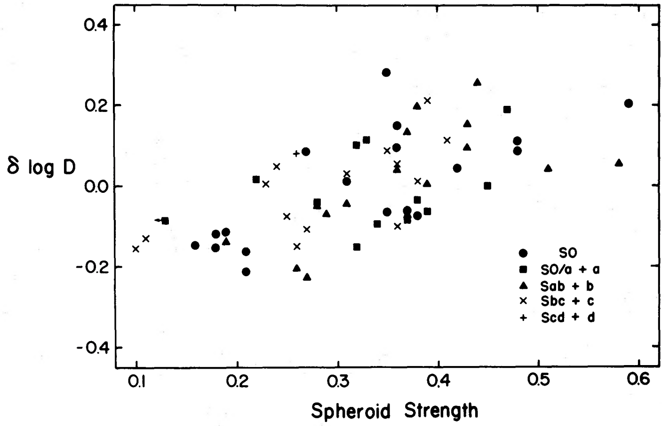

FIG. 8.—Deviation in log D of points from the "slope -5" lines shown in Fig. 7, as a function of spheroid strength. The correlation implies that much of the dispersion in Fig. 7 is produced by a variable spheroid contribution to the total magnitude.

all morphological types, independent of M_B. *The total mass uniquely determines the size of the bar, and therefore of all components associated with the bar.* This appears to be a fundamental fact that any theory of galaxy formation should explain.

VII. OUTER RINGS

Of the 121 galaxies in the survey, 13 were classified in the RC2 as having outer rings (R), or else were found to have such features when the plates were examined. These galaxies are listed in Table 4, together with three non-survey objects of particular interest. The observed major and minor axis diameters are given, together with the position angle with respect to the (r) or (l) major axis. The angles are not very accurate, but allow an approximate rectification. This process, discussed below, produces the true diameters given in columns (6) and (7).

The rings do not all have the same appearance. Column (2) is an attempt to divide the morphology into three groups, denoted R, R′, and L. Figure 9 (Plate 15) shows four typical (R) rings. The prototypes of this group are NGC 3945, 1291, and 2859 (Hubble Atlas). The ring is broad, and has a well-defined dark interior. It is connected to the ends of the bar, being tangent to the (l) or (r) at that point. The NGC 3945 type of barred S0, consisting of a spheroid, bar, lens, and outer ring, is well defined and fairly common, and is easily recognized among more distant galaxies.

Pseudo outer rings (R′, following de Vaucouleurs 1959) are really spiral arms which just fail to close into a ring after one-half revolution. Examples are seen in NGC 3504 and especially NGC 1398 (Hubble Atlas). These are the outer-ring analogs of pseudo inner rings, and are distinguished from them by their width, their well-defined larger size with respect to the bar, and their peculiar axial ratio (below).

Some features which are called outer rings in the RC2 are really almost uniform disks, sometimes with a slightly brighter rim, and always with a rather sharp

TABLE 4

OUTER RINGS

NGC	RING TYPE	OBSERVED D (arcsec) Major	Minor	POSITION ANGLE TO DISK (degrees)	RECTIFIED D (arcsec) Major	Minor
1302	L	208	208	0	208	208
2217	L(R)	189	169	80	222	170
2685	R?	243	101	...	...	...
2859	R	206	152	54	217	156
3892	LR?	142	122	80	182	123
3945	R	243	128	1	243	172
4274	R′L	358	81	4	363	212
4314	R′	209	189	85	270	189
4593	R′	203	149	33	231	194
4596	L	216	176	...	...	...
5101	L	297	284	0	297	319
5377	R?	216	122	...	...	...
5701	R	216	189	19	218	201
1291	R	473	439	88	594	439
3504	R′	108	99	84	192	100
3081	R	136	121	54	183	145

outer edge. Four such objects are illustrated in Figure 10 (Plate 16). We have called these "outer lenses" L, partly because of speculations on their origin, discussed in § VIII, but mostly because they are reasonably well described by our definition of a lens (cf. also § VIII of Paper I). In fact, the three lenses identified in § III as being larger than the bar are similar features (they have less sharp outer edges than an ordinary lens, but look just normal enough to be included by the definition). We will see in § VIII that these three "lenses" may more properly belong to the present category.

In objects which have both an inner and an outer ring, such as NGC 4274 and 7428, the two features have very different axial ratios. Clearly they cannot both be round. Since we showed in § V that inner rings are round, these outer rings are strongly prolate, in the sense that the smallest dimension is the one approximately filled by the bar. Is this true in general?

The answer is provided by a log D–M_B relation (Fig. 11) similar to the one for inner rings. In the upper panel, the rings are assumed to be round, and the major axis diameter is shown. The scatter is large. On the other hand, if the better assumption is that inner rings and lenses are round, then we can rectify outer rings using the relation

$$D = D_{\text{obs}} \frac{(1 - \cos^2 i \sin^2 \phi)^{1/2}}{\sin i} .$$

Here D_{obs} and D are the observed and true major diameters, i is the inclination $\sin^{-1} [(b/a)_{(l,r)}]$, and $\phi = 90°$ minus the angle between the (R) and (l, r) major axes. The rectified log D–M_B relation is shown in the lower panel of Figure 11. There is now a much smaller dispersion, analogous to that for inner rings. This argues that the assumptions are correct, and that outer rings are prolate.

Thus the mean intrinsic axial ratio of outer rings is $\langle b/a \rangle = 0.76 \pm 0.04(\sigma/\sqrt{13})$. Several objects are round; the smallest axial ratio observed is 0.5. One effect of this is that inclinations derived from disk and ring axial ratios in barred spirals under the assumptions that they are round can be greatly in error.

The log D–M_B relation for outer rings again implies a constant surface brightness. However, the rings contain relatively little light, so they should not necessarily provide the size scale that determines M_B. This suggests that the sizes of outer rings are fixed by the size of the bar. The ratio of mean ring diameter to bar diameter has an average value of $2.21 \pm 0.12(\sigma/\sqrt{13})$. The small dispersion again implies a causal connection between ring and bar sizes. The possible nature of this connection is explored below.

The origin of outer rings is unknown. However, it is very suggestive that for likely pattern rotation speeds, the gravitational potential of a rotating bar has a round, ring-shaped minimum with a diameter approximately twice that of the bar (de Vaucouleurs and Freeman 1972). Furthermore, outer rings are unusually rich in H I (e.g., Bieging and Biermann 1977; Bieging 1978; see also Balick, Faber, and

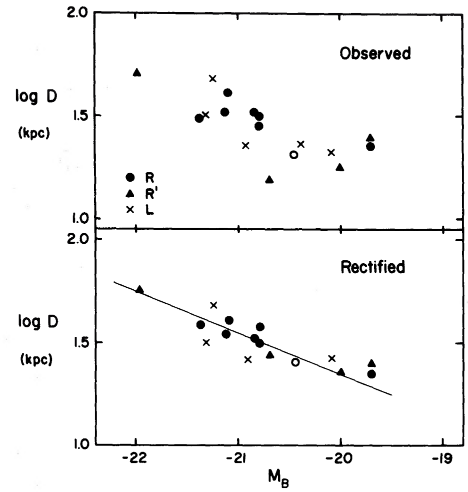

FIG. 11.—Log diameter–M_B correlation for outer rings. The upper panel shows the observed major axis diameters; the scatter is moderately large. In the lower panel, the rings have been rectified as described in the text. The correlation is much stronger, despite the fact that only about one-third of the points were significantly affected. The open circle represents NGC 4736, discussed in § VIII. A line $M_B = -5 \log D +$ constant is also shown.

Gallagher 1976), and in cases where sufficient resolution is available, the gas is clearly associated with the ring (Bosma, Ekers, and Lequeux 1977; Bosma, van de Hulst, and Sullivan 1977). Does one obtain an (R) ring in a barred galaxy whenever there happens to be gas available (whether accreted or intrinsic to the galaxy), because it falls into the bar's potential minimum, almost necessarily does so supersonically, and therefore forms stars? An examination of Sky Survey prints shows that outer rings are in fact very blue, and large-scale plates show that they often have azimuthal filaments of bright knots (Figs. 2*c*, 9, and 13*a*). Even the prolate shape can be understood in terms of the gas response to an oval disk (Sanders and Huntley 1976; see Fig. 2 and especially § IV).

Finally, we note a possible problem with the foregoing analysis. Two of the galaxies, NGC 2685 and 5377 (Fig. 12 [Pl. 17]) have outer rings which appear not to be in the same plane as the disk. Despite the evident success of our rectification procedure, it is possible that other galaxies have similar behavior.

VIII. SPECIAL CASES OF GALAXIES WITH OUTER RINGS

a) *NGC 4736*

The nearby bright spiral NGC 4736 (Fig. 13*a* [Pl. 18]) has a prominent outer ring which is strikingly similar to the (R) rings discussed above. If the inner disk is approximately round, this ring has an axial ratio of 0.71. It is tangent to the disk at its smallest, and the disk's largest apparent diameter. Furthermore, it fits exactly on the log D–M_B relation for barred spirals (Fig. 11, *open circle*). The ratio of mean ring diameter to inner disk diameter is 2.6, consistent with values for barred galaxies.

NGC 4736 does not have a bar. However, its inner disk, though late in morphological type, seems to satisfy the definition of a lens (see also de Vaucouleurs 1959). The ring properties provide a connection to barred galaxies, and suggest that the galaxy may once have had a bar. This seems to have evolved completely away, leaving behind a lens and outer ring. Thus the object is again suggestive of an evolution of bars to lenses. Partial confirmation would be provided by a clearer demonstration that the inner disk is a lens, using detailed surface photometry, or by showing that it is intrinsically elliptical and has its largest dimension in the direction in which it is connected to the ring.

b) *NGC 4596*

NGC 4596 is one of those extremely useful objects which by themselves suggest the solution to a puzzle. In this case the puzzle is the nature of (L) rings. The object is illustrated in Figure 13*b*. There is a bar, terminating at the edge of a lens. Even more than in NGC 5101, the lens is broken on one side of the bar. A low-contrast two-armed spiral begins at the rim of the lens, winds out through the disk, and becomes tangent to its outer edge. We have suggested that the lens consists of stars which have escaped from the bar, especially near its end. Can it be that in some objects the lens is not closed dynamically, but allows stars to spill off of the broken edge and populate a larger, secondary lens outside the first (cf. Danby 1965)? This would provide a natural explanation for at least some of the lenslike features which are prominently larger than the bar. A similar process might account for the extraordinarily uniform and sharp-edged disk in VII Zw 793 (Paper I). We have provisionally denoted these features "outer lenses" (L). In sum, a few lenslike features which are larger than bars need no longer be exceptions to our bar-lens evolution process, which must be explained in a different way. Further investigation of the above speculation would be desirable, but difficult, because any evolution is again secular.

IX. SPIRAL STRUCTURE IN BARRED GALAXIES

The suggestion has often been made that bars effect the form of the spiral structure, and in particular, that they provide one possible driving mechanism for density waves (Toomre 1969; Feldman and Lin 1973; Sanders and Huntley 1976; Huntley, Sanders, and Roberts 1978, and references therein). In this section, we will explore the morphological connection between bars and spiral structure, and show that the evidence supports the above suggestion.

a) *Pseudorings and Spiral Structure*

Pseudorings illustrate well an important feature of spiral structure in barred galaxies. NGC 1398 in the Hubble Atlas provides a good example. The outer "ring" clearly consists of spiral arms, but the pitch angle is not constant. If the inner ring is round, then the arms after one-quarter revolution actually have negative pitch angle, so that they approach the galaxy nucleus between one-quarter and one-half revolution. The rectified "axial ratio" of the arms is 0.86, and the "mean diameter" is 2.7 times that of the inner ring, consistent with values for true rings. (Since the arms are spiraling outward, it is not surprising that the R′ diameter is slightly larger than normal compared to the inner ring.) The spiral arms have the usual properties of density waves, except that they are very different from logarithmic spirals. That is, *the galaxy clearly makes its spiral structure in the cheapest possible way, by making it resemble an outer ring as much as it can.* This behavior is present even in pure SB(s) spirals like NGC 1300 (Fig. 13*c* and Hubble Atlas). The pitch angle of the arms changes abruptly after one-half revolution, to make them resemble inner and outer rings. Observed pseudo rings closely resemble the prolate-ringlike spiral features obtained in the calculations of Sanders and Huntley (1976, see Fig. 2). All this shows that the spiral arms feel and react to the potential of the bar.

b) *The Absence of Non–Density-Wave Galaxies among Barred Spirals*

If bars drive a density wave, then essentially all barred galaxies should have global spiral patterns. The disk structure of each galaxy was examined to investigate this question. The results are given in Table 5. Of the 61 survey galaxies with spiral structure, 55 have global patterns. None has pure NGC 2841–type structure; i.e., many short spiral filaments but no global pattern (see the Hubble Atlas; Sandage 1975; and Paper I). There are six transition cases, but they tend toward being massive-armed, and generally occur in galaxies with weak bars. In contrast, even the incomplete sample of generally brighter galaxies illustrated in the Hubble Atlas contains many nonbarred galaxies with pure NGC 2841–type structure. These facts, and the evidence above that spiral patterns react to the bar potential, support the hypothesis that bars provide a driving mechanism for density waves.

X. SUMMARY

Since a morphological study tends to consist of a large number of loosely connected facts, it is useful to conclude with a detailed summary.

TABLE 5

FREQUENCY OF SPIRAL DISK STRUCTURE TYPES

Disk Structure	Number of Galaxies
Two-armed	45 } 55
Multiarmed global patterns	10 }
Two-arm-(filamentary) transition*	4
(Two-arm)-filamentary transition*	2
NGC 2841 filamentary–armed	0
Non-spiral disks	42
Discards (/, no bar, etc.)	18

* The weaker feature is in parentheses.

TABLE 6

LIST OF COMPONENTS*

Code	Component	Possible Formation Mechanism
E	Spheroid	Dynamical collapse (high gas density in protogalaxy)
S	Disk†	Dynamical collapse? (low gas density in protogalaxy)
B	Bar	Dynamical collapse (instability)
(l)	Inner lens	Made from bar by destruction of resonance?
(r)	Inner ring	Disk material rearranged by bar (Freeman)
(R)	Outer ring	H I falling into a ring-shaped minimum in the bar potential?
(L)	Outer lens?	Made from (l) by material spilling out to large radii?
⋮	⋮	⋮

* This list applies to isolated galaxies. For galaxies in clusters, we would add cD halos. These are also various types of tidal damage, but these would generally not warrant classification as a distinct component (de Vaucouleurs 1974*b*).

† Disks may exist in different forms which qualify for listing as separate components. For instance, some are exponential and others are not (Paper I). Since no systematic study has been made, no attempt at a refined classification is possible yet.

A tentative list of distinct components identified to date is given in Table 6. Spheroids, disks, and bars are believed to form by dynamical collapse during the violent phase of galaxy formation (e.g. Eggen, Lynden-Bell, and Sandage 1962; Gott and Thuan 1976). These are the most fundamental components. However, a number of secondary components have been identified, which seem to have a distinct structure and origin. In particular, lenses and inner rings are important components in barred galaxies, occurring, respectively, in 54% of SB0–Sba and 76% of SBab–SBc objects (later types rarely have either a ring or a lens).

Duus and Freeman (1975) have suggested that inner rings are manufactured out of disk material rearranged by the bar. One of the main suggestions of this paper is that secular evolution processes may generally be important in galaxies. In particular, we suggest that lenses (l) are manufactured from bars by a process which makes the latter evolve away into a nearly axially symmetric state. Evidence in favor of this includes the following.

1. In at least 17 of 20 galaxies with both a lens and a bar, the bar exactly fills the lens in one dimension. If the disks in the remaining three objects are outer lenses (L), there are no exceptions.

2. The appearance of the nearest SB(l) galaxies suggests that material is streaming off of the ends of the bar.

3. The stellar content of lenses resembles that of bars (red color, smooth light distribution).

4. The intrinsic shapes of lenses resemble moderately flattened triaxial ellipsoids, with a preferred axial ratio in the "equatorial plane" of $\sim 0.9 \pm 0.05$. In cases where the inclination is known, the longest dimension is that of the bar, suggesting a causal connection between bars and the triaxial shape of the lens. However, the galaxies VII Zw 421 and II Zw 67 have triaxial lenses but no bars.

5. The galaxy NGC 4736 has an outer ring which is remarkably similar to outer rings in barred galaxies. The inner disk appears to be a lens. However, there is no bar. Again the suggestion is that the galaxy may have had a bar in the past.

6. NGC 3081, illustrated in the Hubble Atlas, presently has a bar which is so low in contrast that it probably cannot affect the structure. However, it has an exceptionally strong inner ring, and a very faint outer ring, shown in Figure 9. Both have the usual properties of SB rings. Detailed photometry is required to determine whether there is a lens. The suggestion is that the bar was once stronger.

7. In general, lenses contain bars of a wide variety of strengths, from relatively strong (NGC 5101), to almost invisible (NGC 1343 and 3081), to no bar at all (NGC 1553 and 3245).

The postulated evolution process may involve an interaction with the spheroid, whose presence is one of the main features distinguishing early-type barred galaxies (which have lenses) from late-type ones (which only rarely have lenses).

In at least one object, NGC 3945, the spheroid is prominently distorted into an inner bar-shaped (triaxial) structure. Less prominent examples include NGC 1291 and other objects discussed by de Vaucouleurs (1974*c*), and objects identified by Note 7 of Table 1. A large-scale photographic survey of SB0–ab galaxies is presently under way, in collaboration with D. Koo, to search for more such objects. Triaxial distortions of the bulge component make an interaction with the main bar quite plausible.

Inner rings are nearly round. Outer rings are often highly prolate, the shortest dimension being the one defined by the bar. The mean axial ratio for all observed (R) rings is $0.76 \pm 0.04(\sigma/\sqrt{13})$. The noncircularity of lenses and outer rings, and the distortion of spiral structure discussed below, make the derivation of inclination angles difficult.

Bars, lenses, inner rings, and outer rings all have diameters well correlated with the total absolute magnitude of the galaxy. The correlation implies that the surface brightness is constant at each morphological type. Later-type galaxies are brighter because they contain more young stars; the mean *mass* density seems to be constant in *all* types (see also Freeman 1970). Thus the total mass does not determine whether the galaxy makes a bar; but if it does make one, the total mass determines the bar size uniquely. This seems to be a fundamental fact to be explained by theories of galaxy formation.

The form of the correlation $M_B + 5 \log D =$ constant is such that bar, lens, and ring diameters cannot be used as distance indicators. At a given apparent magnitude, intrinsically faint galaxies nearby will have the same characteristic diameters as intrinsically bright galaxies which are far away.

Based on their appearance, we have divided outer rings into three classes: well defined rings (R) with dark insides, spiral arms (R′) which nearly close to form a pseudo ring, and nearly uniform disks (L) with sharp outer edges. It is not clear whether the distinction is fundamental, or merely one of degree: all of them have similar axial ratios and size distributions. Their origins are unknown, but are presumably connected with the bar, since outer rings are on average 2.21 ± 0.12 times the size of the bar, which is the same size as the ring-shaped minimum in the gravitational potential of a bar (de Vaucouleurs and Freeman 1972). The blue color and abundant H I content of (R) rings suggests an investigation of whether they result from gas falling into the potential minimum of the bar, thereby being induced to form stars. For at least some "outer lenses" (L), we speculate that material may be escaping from the inner lens to populate an outer disk, based on the appearance of NGC 4596.

Spiral structure is strongly influenced by the presence of a bar. Virtually all SB galaxies have global spiral structure usually interpreted as a density wave. In contrast, many nonbarred galaxies have filamentary arms lacking a global pattern. Also, the density wave in SB galaxies seems to be made in the "cheapest" possible way, resembling the most nearly similar ring structure as much as possible. That is, the arms clearly feel the bar potential. All this is evidence in favor of the suggestion that bars help to drive a density wave.

It should again be emphasized that this morphological study provides results of two different kinds: conclusions about the occurrence and shapes of components, which are well established, and suggestions on dynamical processes, for which there are strong hints but rarely concrete proofs. We have chosen to give as complete a picture as possible of the implications of SB morphology in the hopes of stimulating further work, while recognizing that some of our suggestions may be wrong. We have attempted to indicate which are more secure, and which are the less well supported speculations. A morphological approach has been used because it is so efficient in suggesting the presence of new phenomena. The structure of normal galaxies, and especially of those with bars, has an amazingly rich variety, which we are only beginning to appreciate and explore.

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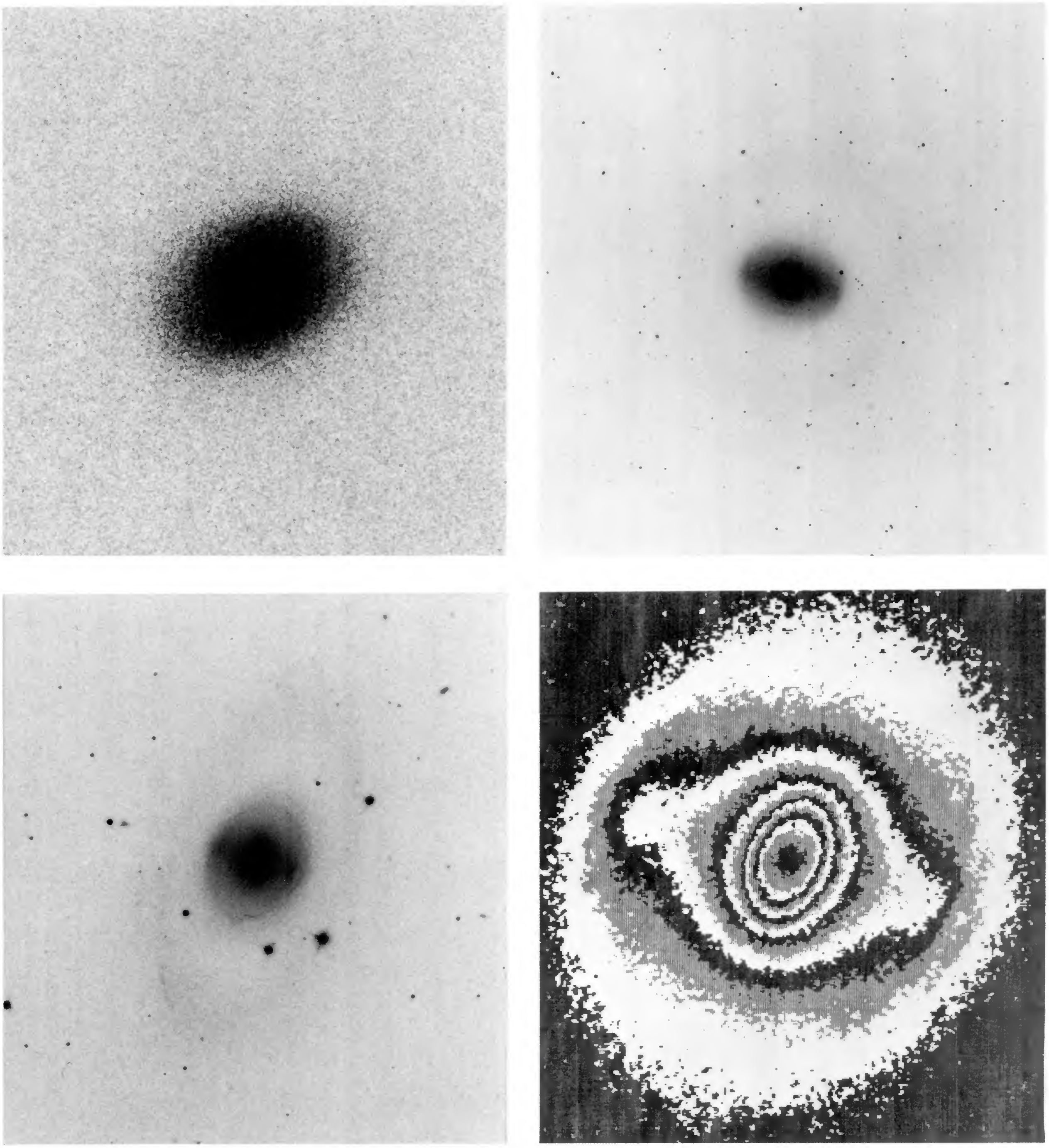
PLATE 13



KORMENDY (*see* page 715)

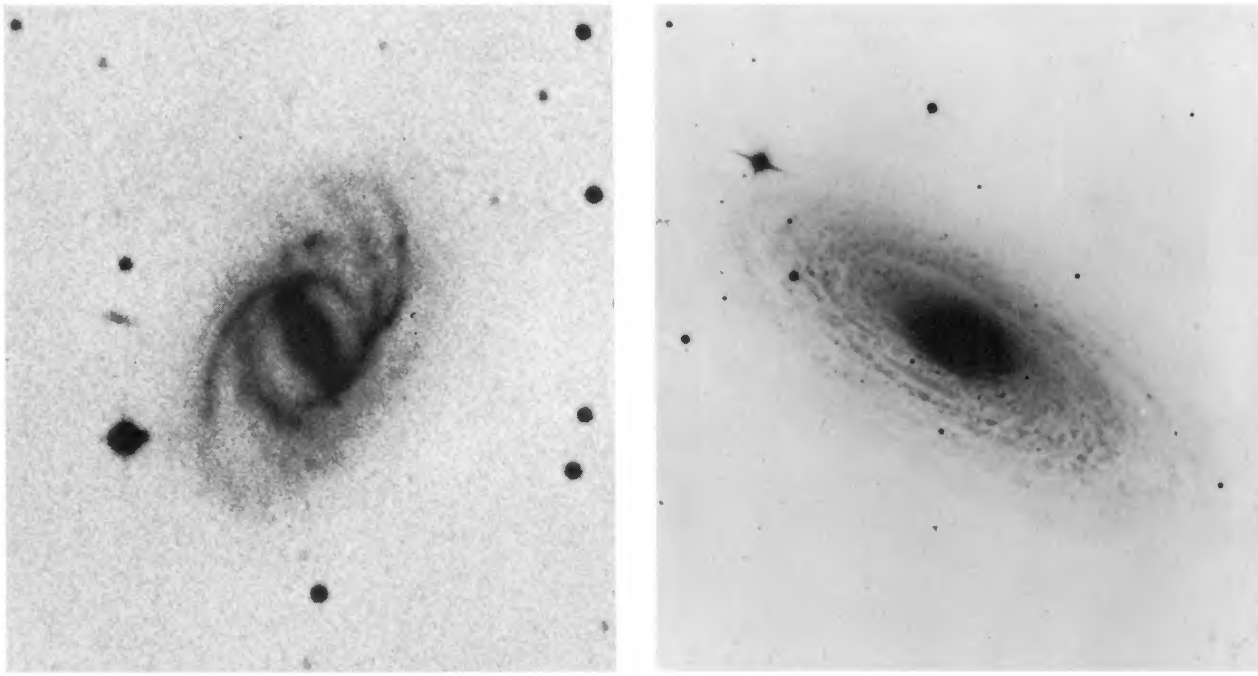


FIG. 2.—(*a*) (*opposite, upper left*) Short-exposure photograph of VII Zw 421, showing the spheroid and lens. A deep print of the lens and outer disk was shown in Paper I. The present photograph is a 15 minute 124-01 + Wr4 plate taken with the Mount Wilson 2.5 m telescope. (*b*) (*opposite, upper right*) Short exposure of NGC 1291, showing the spheroid, bar, and lens. The outer ring is shown in Fig. 9*c*. Both are from a 15 minute 127-04 + GG 495 plate taken with the Cerro Tololo 4 m telescope by R. Kron. (*c*) (*opposite, lower left*) Short exposure of NGC 3945; cf. Fig. 2*b*, above. This is a 55 minute 124-01 + Wr2c plate taken under exceptionally good conditions with the Mount Wilson 2.5 m telescope. The outer ring is shown at the same scale in Fig. 9*a*. (*d*) (*opposite, lower right*) Isodensity tracing of NGC 3945, enlarged 4× from Fig. 3*c*, and with a density step size of 0.2 *D*. Note how the outer bulge component has an axial ratio of 0.67, while the central core is round. (*e*) (*above left*) NGC 2523, a galaxy with a well-developed inner ring. This is a 1^h IIIa-J + Wr2c plate taken with the Palomar Schmidt telescope; the object is also shown in the Hubble Atlas. (*f*) (*above right*) NGC 2841, the prototype galaxy with a filamentary-armed disk, but no global spiral pattern (1^h 124-01 + Wr2c plate taken with the Mount Wilson 2.5 m telescope; see also the Hubble Atlas).

KORMENDY (*see* page 715)

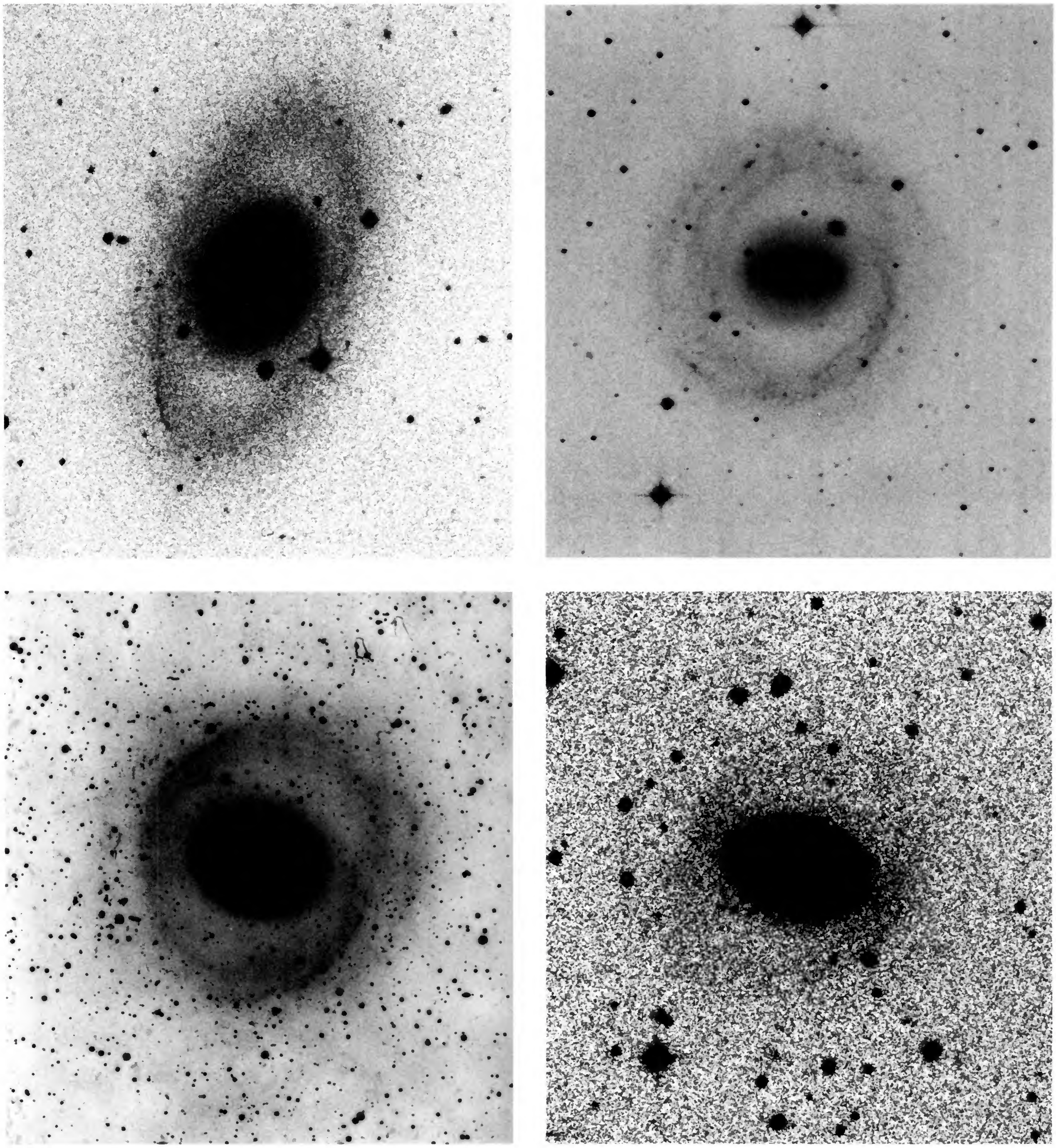


FIG. 9.—Deep photographs of four typical (R) ring galaxies: *upper left*, NGC 3945; *upper right*, NGC 5701; *lower left*, NGC 1291; and *lower right*, NGC 3081 (see also Hubble Atlas). The outer ring is connected to the lens or inner ring (central overexposed ellipse) at the extremities of the bar. Note that the interior of (R) rings is relatively dark; contrast Fig. 10. The NGC 1291 plate is the same one used in Fig. 2, but is printed at very high contrast. The NGC 3945, 5701, and 3081 plates are 2 hr, 1½ hr, and 1½ hr, IIIa-J + Wr2c exposures from the Palomar Schmidt telescope.

KORMENDY (*see* page 723)

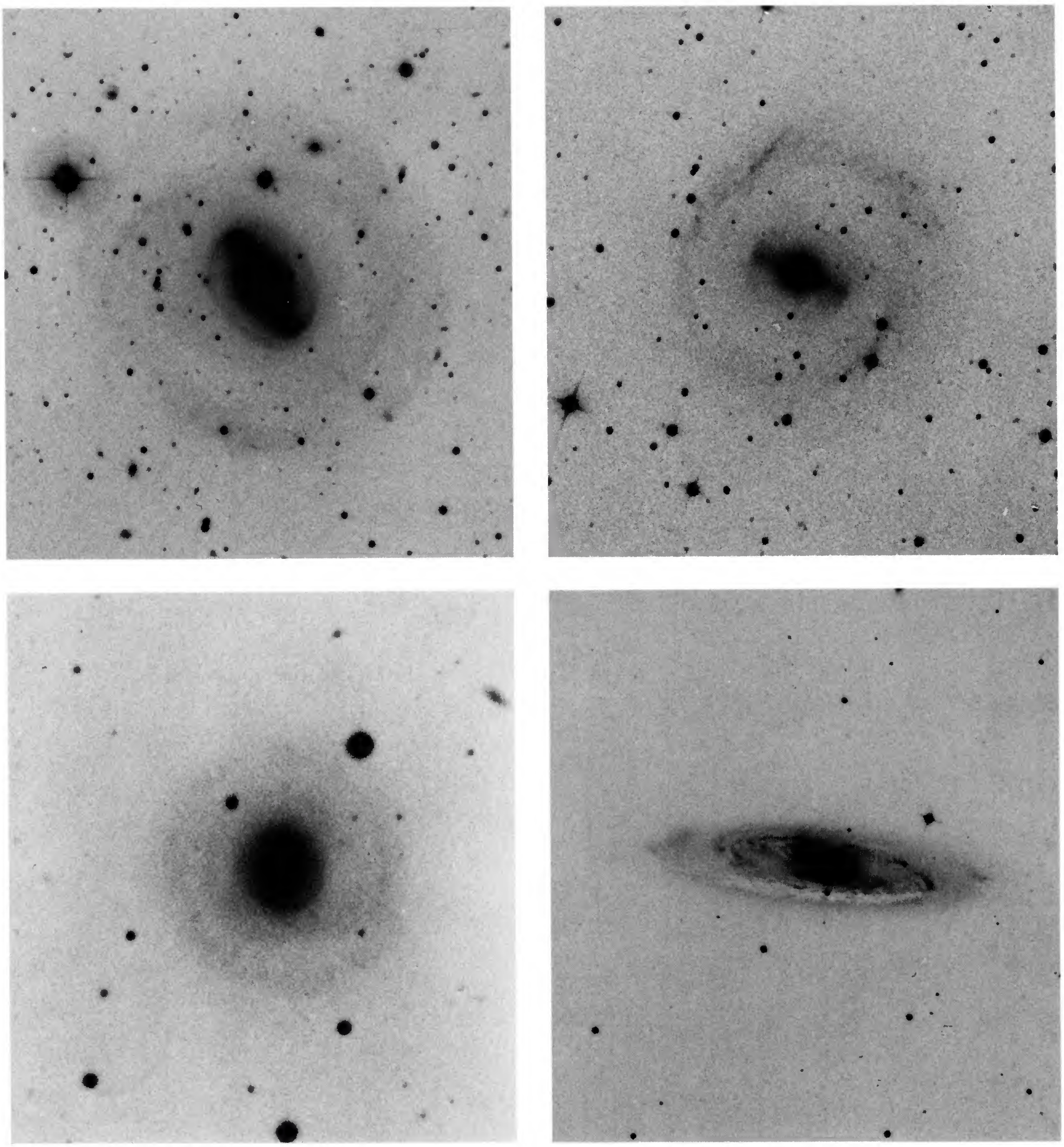


FIG. 10.—Four typical galaxies with "outer lenses" (L). *Upper left,* NGC 5101; *upper right,* NGC 2217; *lower right,* NGC 3623 all taken from the Hubble Atlas. NGC 1302, also shown in the Hubble Atlas, is from a 1 hr IIIa-J exposure taken with a Wr2c filter and the Palomar Schmidt telescope.

KORMENDY (*see* page 724)

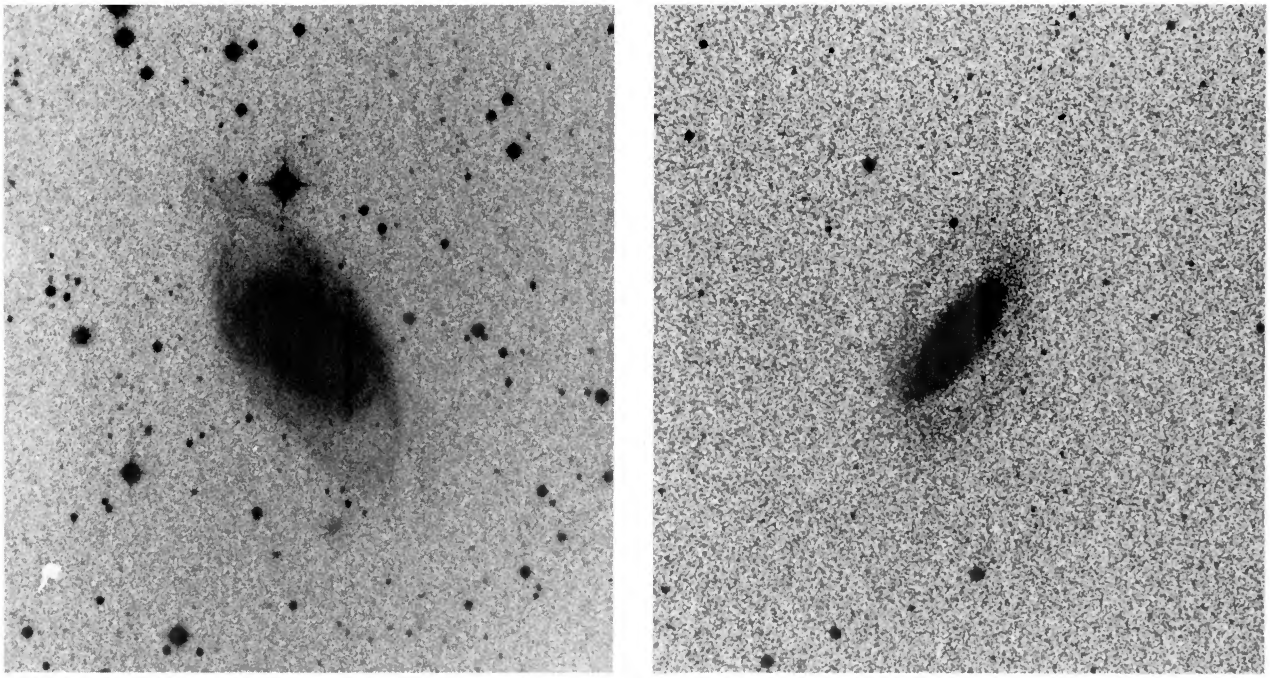


FIG. 12.—High-contrast photographs of two nearly edge-on galaxies whose outer rings do not seem to be in the same plane as the disk. NGC 2685 is shown at left, from a 2^h50^m exposure on a IIIa-J + Wr4 plate taken with the Palomar Schmidt telescope (see also the Hubble Atlas). At right is NGC 5377, enlarged from the Sky Survey red plate.

KORMENDY (*see* page 724)

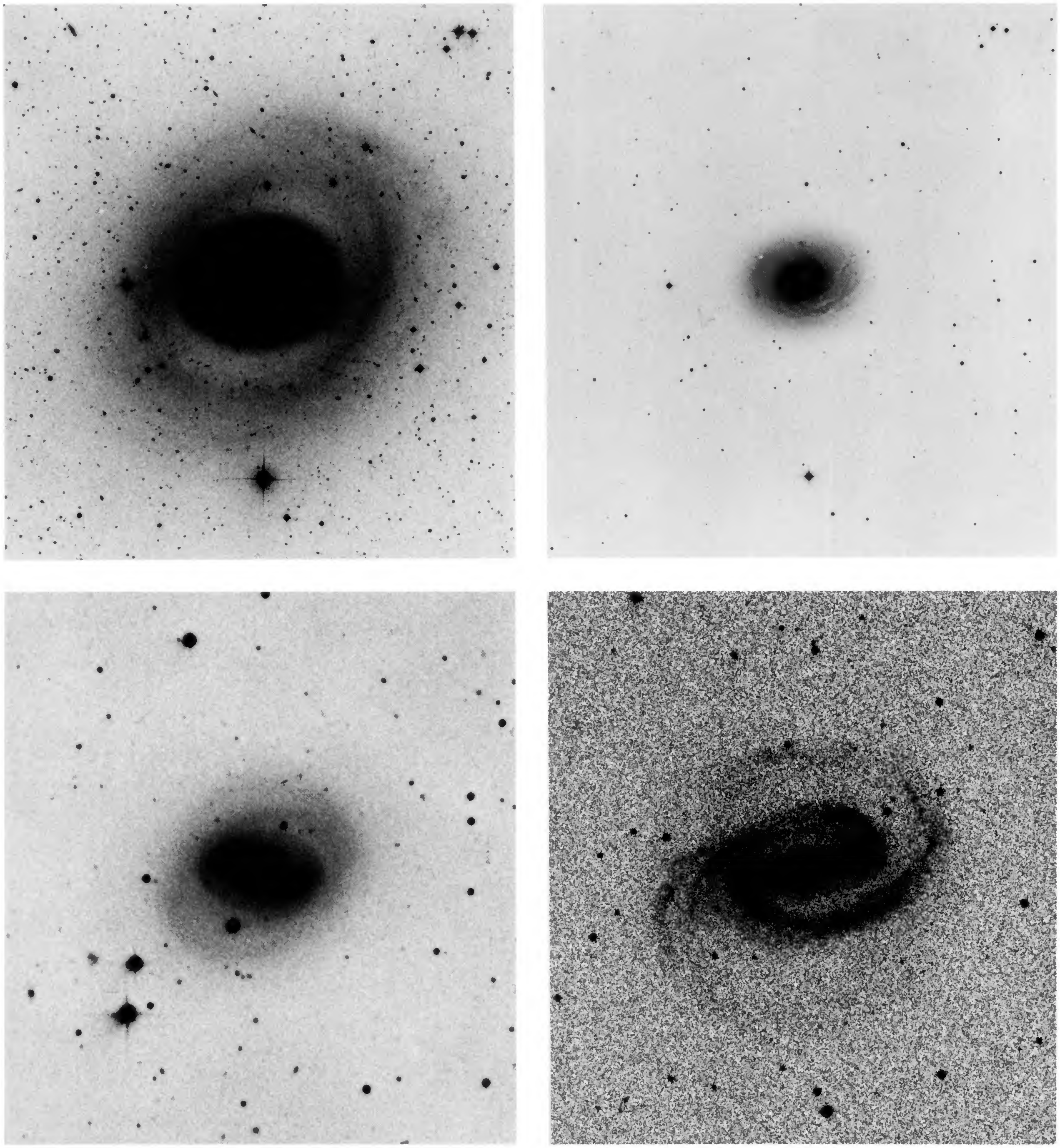


FIG. 13.—Three galaxies with outer-ring-like features of particular interest. (*a*) NGC 4736 has an (R) ring (*top left*) exactly like those in barred galaxies. However, there is no bar, only a high-surface-brightness lens (*top right*). These are, respectively, $2\frac{1}{2}$ hr and 45 minute IIIa-J + Wr4 plates taken with the Palomar Schmidt telescope. (*b*) NGC 4596, at lower left, is the prototype outer lens galaxy (2^h IIIa-J + Wr2c plate, taken with the Palomar Schmidt telescope and kindly made available by J. Gunn and J. Hoessel.) (*c*) NGC 1300, at lower right, is a typical SB(s) galaxy. However, there is an abrupt change in the pitch angle of the arms after one-half revolution, so that the inner portion resembles an inner ring, while the outer parts are like an (R) ring in shape. This is a 15^m 103a-J + Wr2c Schmidt plate; see also the Hubble Atlas.

KORMENDY (*see* page 724)