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ON THE RELATIVE FREQUENCY OF FLOCCULENT AND GRAND DESIGN SPIRAL STRUCTURES IN BARRED GALAXIES

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ABSTRACT

The bars in late-type spiral galaxies (SBbc to SBm and SABbc to SABm) show little correlation with grand design spiral structure, unlike the bars in early-type galaxies. This is further evidence for two different types of bars in the SB morphological class, and two different types of ovals in the SAB class. The weak, short, and exponential-shaped bars that tend to occur in late-type galaxies may end far inside the corotation resonance and be unable to produce large-scale wave patterns in the outer stellar disks. The strong, long, and flat-shaped bars that tend to occur in early-type galaxies may extend closer to the corotation resonance and be able to produce strong and symmetric arms. This difference in bar-spiral correlation is consistent with the theoretical prediction that short-wavelength trailing spirals propagate outward beyond corotation and inward inside corotation.

Subject headings: galaxies: internal motions — galaxies: structure

I. INTRODUCTION

The bars in galaxies with early Hubble types have different photometric and kinematic properties than the bars in later-type galaxies (Elmegreen and Elmegreen 1985, hereafter EE85). Early-type galaxy bars tend to be stronger compared with the average intensity in the region of the bar, longer relative to both the galaxy radius and the length of the rising part of the rotation curve, and more uniform in radial light distribution than bars in late-type galaxies. The latter point is also illustrated by the variation with Hubble type of the ratio of the bar to disk scale length, r_b/r_d for 11 galaxies in Baumgart and Peterson (1986); this ratio is ~ 2 for Hubble types around SBab and ~ 0.3 for Hubble types around SBbc. Early-type bars also tend to correlate with symmetric two-armed spirals in the outer galaxy disks, as if either the bars generate the outlying spiral waves (e.g., Sanders and Huntley 1976; Schwarz 1984; Matsuda *et al.* 1987) or the bar/spiral pattern is a single dominant mode (e.g., Nishida *et al.* 1984; Thurstans 1987). Late-type galaxy bars tend to correlate with flocculent spiral patterns (EE85).

The two bar types may correspond to two different orbit resonances (EE85) in the sense that early-type bars may end near the corotation resonance (Feldman and Lin 1973; Lin and Lau 1975; Contopoulos 1980; Athanassoula 1980; Sanders and Tubbs 1980; Schwarz 1981; Contopoulos 1987; Sparke and Sellwood 1987; Sellwood and Sparke 1988) and late-type bars may end well inside corotation, possibly near the inner Lindblad resonance (Contopoulos 1975; Sanders and Huntley 1976; Sanders 1977; James and Sellwood 1978; Goldreich and Tremaine 1978; Lynden-Bell 1979; Schempp 1982) or 1:1 resonance (Petrou and Papayannopoulos 1986).

Here we use our survey (Elmegreen and Elmegreen 1987, hereafter EE87) of spiral arm classes for all of the 654 large ($R_{25} > 1'$) face-on ($i < 60°$) galaxies in the *Second Reference Catalogue of Bright Galaxies* of de Vaucouleurs, de Vaucouleurs and Corwin (1976, hereafter RC2) to study the relative frequency of long and symmetric spiral arms in galaxies with different bar and Hubble types. The purpose is to determine whether the previously found correlation between Hubble type and regularity of spiral structure for SB galaxies is still true in this larger sample, and to determine whether the non-axisymmetric potentials in SB and SAB galaxies have the same wave-generating properties.

II. THE RELATIVE FREQUENCY OF VARIOUS ARM CLASSES FOR SA, SAB AND SB GALAXIES

Table 1 gives the numbers of galaxies of various Hubble types with flocculent, multiple-arm, and grand design (two-arm) spiral arm classes in our catalog (EE87). The flocculent (F) galaxies are defined to have classes 1–4 (e.g., M63), the multiple-arm (M) galaxies have arm classes 5–9 (e.g., M74, M101), and the grand design (G) or two-arm galaxies have arm class 12 (e.g., M51, M81). The Hubble types are from the RC2. Also tabulated are the relative fractions in each arm class, given as percentages, and the relative fractions corrected for a likely selection effect, which arises because some galaxies tend to be larger than others and the survey in EE87 was size-limited. This size limitation implies that intrinsically larger galaxies are overrepresented in the survey because they are sampled from a larger volume of space than intrinsically small galaxies. The statistical errors in the tabulated frequencies f are equal to $[f(1-f)/N]^{1/2}$ for total number N in the corresponding bar and Hubble type.

The correction factor for the sampling effect is based on Table 2, which gives the average physical sizes and the statistical uncertainties of these averages for all of the 1081 spiral galaxies with tabulated velocities, sizes, bar types, and Hubble types in the RC2, as a function of bar and Hubble type. The size is taken to be the product of the inclination-corrected angular size in arcminutes, R_{25}, and the Hubble recession velocity, V_0. The relative proportion of the galaxy sizes in each bar and Hubble type was found to be nearly independent of the limiting velocity of the sample from the RC2, so the Table 2 results are for all of the galaxies. The Hubble types were binned in the three basic groups to improve the statistics. Table 2 indicates that SAB galaxies are slightly larger than SA or SB galaxies, and that Hubble types a through cd all have about the same size, but Hubble types d through m are smaller. Table

TABLE 1

RELATIVE FREQUENCIES OF ARM CLASSES FOR BARRED AND NONBARRED GALAXIES

	Arm Class Category								
	Number			Frequency (%)			Corrected (%)		
Hubble Type	F	M	G	F	M	G	F	M	G
SA:									
a, ab, b	29	17	5	57 ± 7	33 ± 7	10 ± 4	56 ± 7	37 ± 7	7 ± 3
bc, c, cd	29	49	13	32 ± 5	54 ± 5	14 ± 4	31 ± 5	60 ± 5	9 ± 2
d, dm, m	18	2	0	90 ± 7	10 ± 7	0 ± 0	95 ± 5	5 ± 4	0 ± 0
SAB:									
a, ab, b	13	29	11	24 ± 6	55 ± 7	21 ± 6	24 ± 6	62 ± 7	14 ± 4
bc, c, cd	60	75	19	39 ± 4	49 ± 4	12 ± 3	38 ± 4	54 ± 4	8 ± 2
d, dm, m	26	3	0	90 ± 6	10 ± 6	0 ± 0	95 ± 4	5 ± 3	0 ± 0
SB:									
a, ab, b	19	46	24	21 ± 4	52 ± 5	27 ± 5	22 ± 4	60 ± 6	18 ± 3
bc, c, cd	23	45	10	29 ± 5	58 ± 6	13 ± 4	29 ± 5	63 ± 6	8 ± 3
d, dm, m	45	3	1[a]	92 ± 4	6 ± 3	2 ± 2	96 ± 3	3 ± 2	1 ± 1

[a] This galaxy, A0244+37, has no velocity in the RC2, so the average size for this type of galaxy, RV = 1550 arcmin km s^{-1} from Table 2, was used for the distance correction.

2 also gives the average relative sizes in various bins, scaled to the average size of an SAB galaxy with a Hubble type between a and cd. For the sake of the following discussion, we let $r(H, B)$ denote the relative size of a galaxy of Hubble type H and bar-type B, as given in Table 2.

The additional variation of galaxy size with arm class was then determined for the galaxies that have arm classifications (in Table 1) by averaging together the sizes of these galaxies (again taken to be $R_{25} V_0$) divided by the relative proportions in Table 2. This average was made for two large bins containing all bar classes together for the Hubble types a–cd and d–m. That is, the size (in arcmin km s^{-1}) of each galaxy with arm class A, Hubble type H, and bar type B, denoted by $s(A, H, B)$, was first divided by $r(H, B)$ to "factor out" the Hubble–bar type variation. Then the average value of the resultant ratio, $a(A, H) = \langle s(A, H, B)/r(H, B)\rangle$ was determined for Hubble type bins H = a–cd and H = d–dm, without regard to bar type B. The result of this averaging is the residual variation in the relative sizes of galaxies with F, M, and G spirals, within the two major Hubble-type categories. This residual relative size variation is found to be 0.73, 0.70, and 0.83 for F, M, and G arm classes and Hubble types a–cd, and 0.80, 1, and 1 for A = F, M, G and H = d–dm. These six numbers give the residual variation of galaxy size with arm class, after the other variations with bar type and Hubble type have been removed using the larger sample in the RC2. This was thought to be a better way to determine the variation of size with arm class than to use only the small sample of classified galaxies in Table 1 for the variation with size of both the Hubble type and the arm class. When combined with the relative sizes in Table 2, these arm class versus size variations give the relative sizes R of galaxies in each category of bar type and Hubble type as a function of spiral arm class, i.e., $R(A, H, B) = a(A, H)r(H, B)$, as tabulated in Table 3.

The corrected numbers of galaxies of each type were found by dividing the observed numbers in Table 1 by the cube of the average relative sizes in Table 3. This accounts for the limited volume sampled by each type in our size-limited survey.

Table 1 indicates that the grand design fraction among *early* Hubble types depends on whether the galaxy is of type SA, SAB, or SB; i.e., the fraction of galaxies with long and symmetric arms, taken to be the sum of the M and G fractions, increases along this sequence of bar type as 0.44, 0.76, and 0.78. This implies that, whereas most early-type SA galaxies tend to be flocculent (see Table 1), most early-type SAB and SB galaxies have multiple arms or two prominent arms in a grand design pattern. If the sequence SA to SAB to SB is a sequence of increasing nonaxisymmetric perturbation from an inner oval potential, then the increasing grand design fraction for early-type galaxies along this sequence suggests that the outer disks of early-type galaxies are strongly influenced by a bar.

This situation contrasts with the results in Table 1 for intermediate- and late-type galaxies, for which the spiral arm class varies little through the sequence SA to SAB to SB: the fractions of galaxies with strong, long arms along this sequence

TABLE 2

SIZES[a] OF GALAXIES WITH VARIOUS BAR AND HUBBLE TYPES

	Size (in 10^3 arcmin km s^{-1})			Relative Size	
Hubble Type	a, ab, b	bc, c, cd	d, dm, m	a–cd	d–dm
SA	3.53 ± 0.19	3.42 ± 0.16	1.48 ± 0.22	0.92	0.39
SAB	3.75 ± 0.20	3.78 ± 0.14	1.78 ± 0.17	1.0	0.47
SB	3.49 ± 0.15	3.51 ± 0.16	1.55 ± 0.09	0.93	0.41

[a] The size is taken equal to the product of the corrected angular size (in arcmin) and the recession velocity (in km s^{-1}).

TABLE 3

RELATIVE SIZES OF DIFFERENT ARM CLASSES

	Arm Class		
Hubble Type	F	M	G
SA:			
a–cd	0.81	0.77	0.92
d–m	0.37	0.47	0.47
SAB:			
a–cd	0.88	0.84	1.0
d–m	0.45	0.57	0.57
SB:			
a–cd	0.82	0.78	0.93
d–m	0.39	0.49	0.49

are 0.69, 0.62, and 0.71 for intermediate Hubble types, and 0.05, 0.05, and 0.04 for late Hubble types. Intermediate Hubble type galaxies tend to be multiple-arm or flocculent, with a small grand design fraction (Table 1), and late Hubble type galaxies tend to be flocculent, regardless of the oval or bar in the center. This indicates that the optical ovals and bars in intermediate- and late-type galaxies generally do not correlate with prominent density waves in the outer disks.

A possible explanation for this variation of the bar-spiral correlation with Hubble type is that the bars in early-type galaxies extend out to the vicinity of the corotation resonance, whereas the bars in late-type galaxies end far inside that resonance, possibly in the vicinity of an inner Lindblad or 1:1 resonance (see references in § I). This difference in resonance location is important because the short-wavelength, trailing spiral waves to which our arm classification system is most sensitive presumably move *outward* in galactic disk *beyond* the corotation resonance and *inward between* the inner Lindblad resonance and the corotation resonance (Toomre 1969; Lin and Lau 1975). If a bar is to drive a global spiral pattern from the inner regions of a disk to the outer regions, then it would seem to be able to do this best when the bar perturbation extends to the corotation resonance. Thus, short-wavelength modes driven by a bar in an early-type galaxy can fill the entire disk outside the bar, but short-wavelength modes excited by a bar in a later-type galaxy may not be able to propagate outward in the region immediately beyond the bar.

The relative galaxy sizes in Table 3 are also interesting. Among early and intermediate Hubble types, and independent of bar type (cf. Table 2), the grand design galaxies in our sample tend to be slightly larger than the flocculent galaxies, which tend to be slightly larger than the multiple-arm galaxies. This is apparently a manifestation of the well-known correlation between galaxy luminosity and luminosity class (van den Bergh 1960). The present results suggest that the implied correlation between luminosity class and size (Iye and Kodaira 1976) is indeed present but is not very strong (see also Kennicutt 1982; Sandage, Binggeli, and Tammann 1985).

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