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# GALAXY MORPHOLOGY AND CLASSIFICATION

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**Abstract.** A brief discussion of the de Vaucouleurs revised Hubble classification system is given, with special emphasis on ring and lens morphologies. The possible physical interpretations of each dimension of the system are summarized.

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## 1. INTRODUCTION

Of the many topics in astronomy Gérard de Vaucouleurs has worked in over the past 40 years, I think the one which brought him some of the greatest enjoyment and personal satisfaction was his research on galaxy morphology and classification. Not only is the beauty of galaxies enjoyable from an aesthetic viewpoint, but galaxy morphology is rich with the enigmas and puzzles that qualify it as one of the major research topics of today. Although for many years, there was so little firm theoretical understanding of galaxy morphology that the topic was little more than descriptive, this is certainly no longer true. Galaxy morphology today is, in fact, undergoing a major revolution. Not only has the Hubble Sequence been revitalized as a tool for understanding galaxy structure and evolution, but the many additional phenomena, such as bars and rings, that used to be regarded as secondary, have also been brought to the forefront. Never before, I believe, have the many types of structures visible in galaxy images been understood as well as today, although much remains to be learned.

It is not hard to summarize the main problems of galaxy morphology. Why is the Hubble sequence a continuous sequence, and what physical parameters underlie this continuity? What is the role of angular momentum, dissipation, and galaxy-galaxy interactions? How do the various patterns originate, and how do they change with time? What types of objects define the patterns? What role do the patterns have on the star formation processes in the disk? What is the role of dark matter? These questions have all been asked but definitive answers have been elusive. Ultimately, the answers to these questions will hinge on an understanding of galaxy formation, a topic which is currently a subject of considerable uncertainty and debate.

In honor of Gérard de Vaucouleurs, I should like to briefly describe his 1959 galaxy classification system, and then focus on a few aspects of galaxy morphology that have received much attention over the last few years. Comprehensive reviews on this subject have already been given by Sandage (1975) and Kormendy (1982). I will concentrate mainly on ring and lens morphologies in normal disk galaxies (S0 to Sbc), since these features were of great interest to Gérard and exemplify how much our understanding has progressed about galaxy morphology as a whole. Very comprehensive discussions of elliptical galaxies can be found in *I. A. U. Symposium No.* 127 (de Zeeuw 1987) and other articles in the present volume, while a thorough review of irregulars can be found in Gallagher and Hunter (1984, 1987).

## 2. THE REVISED HUBBLE CLASSIFICATION SYSTEM (RHS)

Gérard de Vaucouleurs's revised Hubble system is described in a lengthy *Handbuch der Physik* article published in 1959. It was not the only revision of the Hubble system available at the time: Hubble himself had been working on a revision since the 1930's, but died before completing it. In 1961, Allan Sandage published Hubble's revision in the form of an atlas. Both systems are still in active use today, and there are good reasons for this: the original Hubble system provided the first ordering of galaxies that represented more than just smooth changes in the properties of optical morphology. As data began to be accumulated for large numbers of galaxies, many physical parameters (e.g. colors, HI content, concentration indices, surface brightnesses) were found to correlate with these changes, implying that the Hubble sequence contains information on the basic physics of galaxies.

Although de Vaucouleurs's revision followed Hubble's framework in placing galaxies along a sequence of "stages" and in recognizing bar and ring morphologies, his view of the spread in morphologies at a given stage was clearly different from Hubble's: instead of a multi-pronged fork, de Vaucouleurs proposed to describe galaxy structure with a three-dimensional classification *volume* whose principal axis was the stage and whose secondary axes were the "family" and the "variety." These latter characteristics refer, respectively, to the presence or absence of a bar and of an *inner* ring. Continuity was implied along each axis. To highlight this, de Vaucouleurs introduced special notation to allow for transition cases. For family, SB would still denote barred spirals while SA would denote non-barred ("ordinary") spirals. Intermediate barred cases are denoted SAB, SAB, or SAB, depending on the degree of development of a bar. The same kind of notation was used for variety: pure ringed systems were denoted (r) while pure spiral (s-shaped) systems were denoted (s), with objects of intermediate characteristics highlighted by a compound notation such as (rs), (rs), and (rs).

For stage, de Vaucouleurs adopted two refinements. First, transition stages, Sab and Sbc, between the original Hubble spiral categories Sa, Sb, and Sc were recognized to eliminate the need for notation such as $Sa^+$, $Sb^-$, etc. Second, more stages were added along the Hubble sequence beyond Sc to allow for intermediate spiral stages between Sc and Irr I. De Vaucouleurs adopted Shapley and Paraskevopoulos's (1940) suggestion of the need for an Sd classification (very late, small-bulge systems like NGC 7793), and identified the Magellanic Clouds as an even later stage along the spiral sequence, Sm. Transition stages were denoted as Scd and Sdm. The true Irr I galaxies were denoted Im. S0 galaxies were divided into three categories, $S0^-$, S0°, and $S0^+$, but these do not correlate exactly with the three S0 categories in Hubble's revision (Sandage 1961). As in Hubble's revision, S0 galaxies are placed between E and Sa galaxies on the stage sequence, the transition stage to spirals being denoted S0/a. The various combinations and permutations of symbols possible gave de Vaucouleurs's classification system a complexity unprecedented in galaxy morphology studies, but as he noted, symbols can be dropped according to the amount of detail visible in an image or the desired level of complexity.

The availability of two revised Hubble systems means that care must be exercised in interpretation of published Hubble types, particularly the stage parameter where the stage "Sc" in the Hubble revision encompasses galaxies classified over the wide range of stages, Sbc-Sm, in de Vaucouleurs's revision. The arrangement of the late spiral stages and the validity of de Vaucouleurs's extensions have been repeatedly demonstrated from the correlations found between type and a wide variety of measured parameters (de Vaucouleurs 1977; see also Figure 1). The extensions are therefore fully justified and well-founded, and form one of the major advantages of de Vaucouleurs's revision over Hubble's revision.

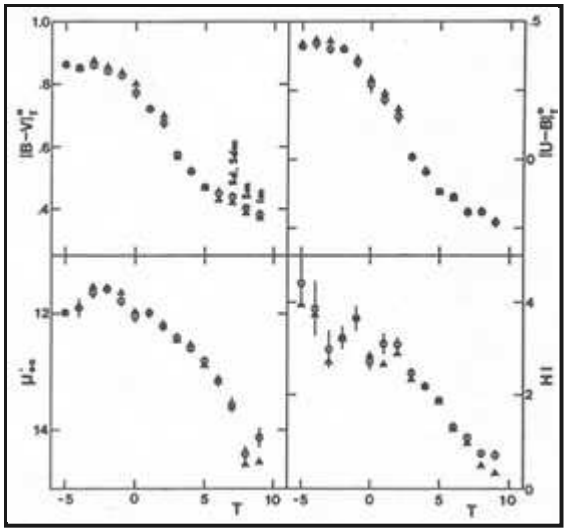


**Figure 1.** Dependence of several photometric parameters on the stage in de Vaucouleurs's system. Here HI refers to the hydrogen index and $\mu'_{eo}$ is the mean surface brightness within the effective isophote. Based on new data from the *Third Reference Catalogue of Bright Galaxies.* Triangles are median values, while circles are means. Stages Sd and Sdm are combined here.

Care must also be exercised in the interpretation of the part of the classifications involving bars and rings. Recently, much research has focussed on these secondary structures; on their classifications, independent observers are not very consistent. For example, some galaxies classified as (r)-variety by de Vaucouleurs (1963) are classified as (s)-variety by Sandage and Tammann (1981; ST) because the inner ring appears to be made of very tightly wrapped spiral arms. Hubble's revised classification system, as applied by ST, has very broad categories along the spiral sequence that encompass a wide range of forms, yet the ring category they envision is extremely conservative (as is also the bar category). I believe that overconservatism leads to unrealistically sharp edges to the morphological "cells" that may be misleading; the cell boundaries are in reality rather fuzzy. The advantage of de Vaucouleurs's revision is that it views galaxy structure in the broadest possible way, that is, as a continuum of forms in all possible dimensions.

Surprisingly, many astronomers today still persist in adhering to the original Hubble revision, perhaps because it is simpler to understand and apply in practice, and because it serves their needs. However, modern extragalactic astronomy demands a system with greater versatility and applicability, which can serve as a basis for the type of research that can now be done with the sophisticated telescopes and instruments currently in use.

## 3. EXTENSIONS AND ADDITIONS

Over the past 10-15 years, the imaging capabilities for galaxies have been greatly improved, especially with the advent of CCD's. Not only this, but the great Sky Surveys produced with Schmidt telescopes since the 1950's have greatly increased the number of galaxies for which detailed morphology can be clearly studied. This exposive growth in the number of available images has in recent years led to great curiosity about the apparently secondary and more subtle aspects of galaxy structure, and to a few possible revisions to the classification systems. Some of these are described here.

### a. Rings and Pseudo-Rings

It is well-known that in addition to the inner rings used for the variety dimension in the RHS, two other types of ring are occasionally found: *nuclear* rings, sometimes seen in the nuclei of barred galaxies, and *outer* rings, occasionally seen enveloping the main bodies of early-type spirals and lenticulars. Although these features may not be as widely present or as easily discernible as family, variety, and stage, their characteristics and their physical interest make it worthwhile to recognize them with their own type symbols. In the revised Hubble classification notation, outer rings and pseudo-rings do have type symbols, (R) and (R'), respectively, to be used preceding the main part of the classification. However, for nuclear rings and pseudo-rings, there is currently no notation, and the first possible extension or addition to the RHS that I propose is the use of (nr) and (nr') for such structures. Note that this classification is not entirely straightforward: some nuclear rings appear to be pseudo-rings only

because of dust (e.g. NGC 1512, Lindblad and Jorsater 1981; NGC 4314, Benedict 1980). Table 1 illustrates the possible use of this notation and some examples.

**Table 1.** Summary of Additional Notation to Revised Hubble System

| Structure | Notation | Examples | Type |
|---|---|---|---|
| Nuclear ring | (nr),(nr') | NGC 1512 | SB(r,nr)ab |
| | | NGC 4314 | (R')SB(l,nr')a |
| | | NGC 3081 | (R)SAB(r,nr)0/a |
| Nuclear lens | (nl) | NGC 1433 | $(R'_1)$SB(r,nl)ab |
| Inner lens | (l) | NGC 1553 | SA(rl)0° |
| Outer Lens | (L) | NGC 1440 | (L)SB(s)$0^+$ |
| | | NGG 4596 | (L)SB(r)$0^+$ |
| Type I Schwarz Outer Ring/ | $(R_1)$,$(R'_1)$ | NGC 3504 | $(R'_1)$SAB(s)ab |
| Pseudo-Ring | | ESO 508-78 | $(R'_1)$SB(r)a |
| | | NGC 1808 | $(R'_1)$SAB(s)a |
| Type II Schwarz Outer Ring/ | $(R_2)$,$(R'_2)$ | NGC 688 | $(R'_2)$SAB(s)b |
| Pseudo-Ring | | NGC 841 | $(R'_2)$SAB(s)b |
| | | IC 1439 | $(R'_2)$SAB(s)a |
| | | ESO 294-16 | $(R'_2)$SB(s)a |
| Mixed-mode Outer Ring/ | $(R_1R'_2)$ | ESO 509-98 | $(R_1R'_2)$SB(s)a |
| Pseudo-Ring | | NGC 1291 | $(R_1R'_2)$SB(l,nl)0/a |
| | | IC 1438 | $(R_1R'_2)$SAB(r)0/a |

The second possible extension or addition to the RHS is perhaps more subtle. In a recent paper (Buta 1986a), I have suggested a possible refinement to the classification of outer rings which is motivated by the recent theoretical work of Schwarz (1979, 1981). From the appearance of over 300 outer rings and pseudo-rings in SB and SAB galaxies on the SRC IIIa-J Southern Sky Survey films, it appears that at least two distinct subtypes exist: the first type ($R'_1$) shows the characteristics that the arms which emerge from each end of the bar seem to wind 180° and return to the opposite side, dipping in to form a broad figure eight pattern (Figure 2a, NGC 3504); in the second type ($R'_2$), the arms go an extra 90° before intersecting each other, and no figure eight characteristic is made (Figure 2c, ESO 294-16). Between these extremes, intermediate cases are found which appear to show aspects of both types (Figure 2b, ESO 509-98).

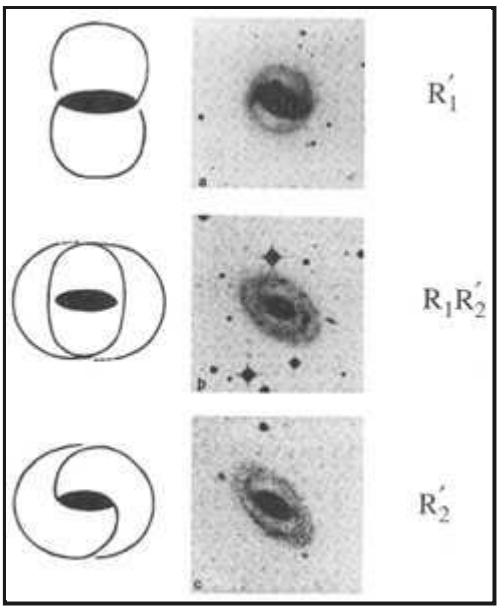


**Figure 2.** New Outer Pseudo-Ring Morphologies and Notation.

These distinctive morphologies were discovered by Schwarz (1979) in simulations of barred galaxy gas dynamics, and it is a small triumph for the theory that they were found in real galaxies *after* they had been predicted to exist. The predictions came at an especially opportune time because the availability of the deep IIIa-J SRC Southern Sky Survey films made it possible to detect outer rings and pseudo-rings in galaxies that otherwise would have been very difficult to study on the ESO Quick-Blue Survey or the Palomar Sky Survey plates. For reasons described in section 4, the mixed morphology ($R_1R'_2$) was not predicted to exist, but its apparent existence in real galaxies underscores once again the "fuzziness" characteristic of galaxy morphological cells.

The relative frequencies of the different ring patterns have not been firmly established. De Vaucouleurs and Buta (1980) selected carefully defined samples from the *Second Reference Catalogue of Bright Galaxies* (de Vaucouleurs et al. 1976, hereafter RC2) to judge the frequencies of inner rings. These occur in about 25% of spirals, but if inner pseudo-rings are considered, the total frequency would exceed 50%. In a study exclusively dealing with barred spirals, Kormendy (1979) found that 76% of early-to-intermediate barred spirals possess inner rings. Outer rings appear to be most frequent near stage S0/a (de Vaucouleurs 1975). The tentative results of Buta (1986a) suggested that the $R'_1$ subtype is perhaps three times as frequent as the $R'_2$ subtype, although only 55% of recognizable outer pseudo-rings could be categorized in either way. No definitive statistics exist yet for nuclear rings, whose detection is strongly influenced by selection effects.

**b. Lenses**

A lens is a relatively uniform or shallow zone in the luminosity distribution of disk galaxies which, on direct photographs, appears to have a fairly sharp edge. Several are illustrated in the Hubble Atlas. They were first recognized by Hubble in S0 galaxies, but were never formally given a type symbol. Instead, they were regarded as characteristic of S0 galaxies in general. They also do not have a type symbol in de Vaucouleurs's revision, although de Vaucouleurs has proposed using the code "L" for S0 galaxies, to imply "lenticular," and has presented information on lens sizes in the notes to the *Reference Catalogue of Bright Galaxies* (de Vaucouleurs and de Vaucouleurs 1964). Kormendy (1979, 1982) has done detailed studies of the frequency and other properties of lenses, and believes them to be an important "distinct component" of galaxies whose true frequency cannot be judged from RC2 types. He has criticized RC2 types because he believes these misclassify lenses as inner rings. He has also pointed out that even though all S0 galaxies might be denoted "L," many do not have lenses.

These disagreements reflect some of the subjectivity of galaxy classification and I wish to make two points about them. First, since the RC2 does not give quantitative information on the strength of luminosity enhancements associated with rings, one cannot determine whether a ring is strong or weak from RC2 types. However, if a ring is very weak, then in less than optimum seeing the enhancement may be washed out and one will see a "plateau" (or lens) in the light distribution. The distinction between calling a galaxy "inner-ringed" or "inner-lensed" then reduces to semantics in such circumstances, unless rings and lenses are genuinely distinct phenomena. A second point is that rings tend to be blue in color and fairly narrow, while lenses are red and broad. When both are present in the same galaxy, they overlap and have the same shape, implying a close causal

connection.

This suggests at least two interpretations: either rings and lenses are variations on the same phenomenon, differing only in the mean age of the stellar population and the amplitude of the enhancement which is superposed on the usual decreasing background of the bulge plus disk; or they are distinct phenomena which happen to coincide in position and shape. The first interpretation would view lenses as being a direct result of ring formation, in the sense that the lens would represent the aging component of a ring whose star formation rate has been fairly uniform over a Hubble time, such that a more diffuse, broader component has been built up. This view finds some support in the integrated colors of rings (Buta 1986b, 1987a, 1988b), the existence of non-axisymmetric color gradients ( Buta 1986b ), the existence of lens analogues of each type of ring ( de Vaucouleurs 1974 ; Kormendy 1979 ; Sandage and Brucato 1979 ; Buta 1986b ), and the existence of rings lacking an old component (e.g. NGC 1398, Buta 1988b) or a young component (Gallagher and Wirth 1980). How diffuse an old ring will be will most likely depend on its age and velocity dispersion. Only for several lenses have velocity dispersions so far been measured, so that a definitive comparison cannot yet be made. As shown by Kormendy (1984), lenses tend to be fairly hot.

However, the nature of lenses is probably more complicated than might be inferred from the above arguments, because lenses usually contain a lot of light and at the same time have oval intrinsic shapes which make them characteristically bar-like. It is quite interesting how some galaxies show inner, outer, and nuclear rings just like those in SB galaxies, yet no obvious bar crosses the inner ring. In such a circumstance, we might conclude that the lens cannot be simply an "old" ring, but is the near-axisymmetric analogue of a bar; it is therefore distinct from rings, but capable of appearing to be associated with them in the same manner as an SB-type bar. Several interpretations have been proposed in this vein. Kormendy ( 1979, 1981, 1982 ) believes that lenses originate secularly from bar dissolution in SB galaxies. Although bars are believed to be fairly robust (Miller and Smith 1979b), Contopoulos (1983) has stated that strong bars can generate enough stochasticity inside corotation that stars on stochastic orbits will populate a less elongated, oval zone. On the other hand, Athanassoula (1983) believes that lenses represent disk instabilities just like conventional SB-type bars, the main difference concerning the degree of random motions.

Regardless of the physical interpretation of lenses, I agree with Kormendy (1979) that perhaps they should be given their own type symbols in the classification. He has proposed the use of (l) for inner lenses and (L) for outer lenses, with (nl) an obvious extension for nuclear lenses.

The relative frequencies of lenses are as poorly known as those of rings. Statistics for inner lenses (l) are most secure. Kormendy (1979) found using a carefully defined sample that inner lenses are present in 54% of early-type SB galaxies. The frequencies of nuclear and outer lenses remain to be determined.

## 4. PHYSICAL INTERPRETATIONS OF REVISED HUBBLE CLASSIFICATIONS

The establishment of an ordering of galaxies into taxonomic categories is clearly only one step towards understanding the physical nature of galaxy structure. It is important first to re-state what Hubble himself emphasized: that the classification system is entirely empirical and has no basis in theory. Nevertheless, we wish to understand the physical parameters which may underlie each dimension of the RHS, and here I wish to summarize a few of the current ideas.

Table 2 lists some of the parameters which may provide the physical basis of each dimension of the RHS. The stage and family have been thoroughly discussed in reviews by Sandage (1986) and Kormendy ( 1981, 1982 ), and I refer the reader to those papers for more details. Variety was the least-known dimension of the system until recently, and here I would like to focus mainly on this dimension as it provides an opportunity for a beautiful confrontation between theory and observation.

**Table 2.** Possible Physical Bases of Stage, Family, and Variety

| Dimension | Basis | Selected References |
|---|---|---|
| Stage | (a) Initial M(h) distribution? | Sandage et al. 1970 |
| | (b) Initial density? | Gott and Thuan 1976 |
| | (c) Halo mass fraction? | Tinsley 1981 |
| | (d) Total mass? | Tully et al. 1982 |
| | (e) Initial $\sigma_v$ of dark matter? | Lake and Carlberg 1988 |
| Family | (a) $T_{mean}/\|W\|$? | Ostriker and Peebles 1973 |
| | (b) Rotation curve, mass dist.? | Lynden-Bell 1979 |
| | (c) Angular momentum transfer? | Lynden-Bell and Kalnajs 1972 |
| Variety | (a) Bar pattern speed? | de Vaucouleurs and Freeman 1972; Schwarz 1979, 1984b |
| | (b) Rotation curve, mass dist.? | Schwarz 1979 |
| | (c) Gas fraction, total mass? | Huntley 1980; de Vaucouleurs and Buta 1980 |
| | (d) Bar strength? | Schwarz 1984c |
| | (e) Evolutionary state of pattern? | Schwarz 1979 |

It is probably fairly safe to say that the main characteristic galaxies were "born" with is their bulge-to-disk ratio. Whether these two components formed together, or if one preceded the other, is still a point of controversy. Nevertheless, once the bulge and disk formed non-axisymmetric disturbances could have developed in the stellar distribution, and bars or bar-like distortions could have grown rapidly. Once these structures formed, they could stir up any remaining gas in the disk; e.g. bars could drive trailing spiral structures in the outer disk. Any patterns would evolve slowly in form, owing to gravity torques and shocks.

The ring-like patterns defining the (r)-variety as well as nuclear and outer rings are believed to be related to orbit resonances with a bar, oval distortion, or density wave (de Vaucouleurs and Freeman 1972; Duus and Freeman 1975; Schwarz 1979; Schempp 1982; Kormendy 1982 and further references therein; Athanassoula 1983). The link with resonances was most firmly established by Schwarz (1979), who used a particle dynamical scheme to simulate the flow of gas in response to a static bar potential. Using a fairly simple method to simulate dissipation via cloud-cloud collisions, he found that gas in a barred galaxy can naturally collect near the main orbit resonances: inner Lindblad resonance (ILR), outer Lindblad resonance (OLR), and the inner 4:1 ultraharmonic resonance (UHR).

The rings form because large secular effects can occur at these resonances (Lynden-Bell and Kalnajs 1972), where periodic orbits achieve their maximum local eccentricity (Contopoulos 1979). If the bar forcing is strong enough, orbits slightly within a resonance can become sufficiently elongated that they will cross orbits slightly outside a resonance which are either shaped differently (as at UHR; Schwarz 1984c) or elongated in the orthogonal sense (as at ILR and OLR; Sanders and Huntley 1976). If gas clouds are present, they will not be able to settle into such orbits without experiencing dissipation. Spiral shock fronts develop in the gas, but these slowly change their form owing to gravity torques exerted by the bar. The net effect is that gas in the spirals tends to slowly drift and settle into ring-like concentrations near one or several of the major resonances.

Schwarz identified ILR, UHR, and OLR with the nuclear, inner, and outer rings, respectively, of barred galaxies. A considerable body of observational evidence has provided support for these interpretations. This has come from studies of the distributions of apparent shapes, relative sizes, and apparent orientations of rings with respect to bars (Kormendy 1979; Athanassoula et al. 1982; Schwarz 1984a; Buta 1984, 1986a) and from surface photometry and spectroscopy of individual examples (Buta 1984 and references therein; 1986b, 1987a, b, c, 1988a, b). One of the great successes of Schwarz's work is the prediction of the distinct outer ring morphologies discussed in section 2. The morphologies arise because at OLR, spiral structure and evolution are influenced by two major families of periodic orbits, a perpendicular-aligned family slightly inside the resonance and a parallel-aligned family slightly outside the resonance. Owing to dissipation, a pseudo-ring can develop near OLR whose shape and orientation are similar to one of these families; which one dominates depends on the gas distribution, the strength of the bar, and the ability of the dissipation to deplete the other family. A natural interpretation of the mixed morphology in Figure 2b is that both of these orbits are populated, although such a circumstance ought to be disallowed as the orbits would cross. Indeed, Schwarz did not predict the existence of a mixed outer ring morphology. However, there is clearly more work to be done, and further insight into the nature of these structures may be found in models with growing bars (Elmegreen and Elmegreen 1985 and references therein).

These findings allow us to make some evaluations of the differences that might underlie the family and variety dimensions in the RHS more clearly than could be done before. First, an SB(s) spiral could be a case where the pattern speed $\omega_p$ is high enough to preclude the existence of the main ring-forming resonances within corotation (that is, ILR and UHR). OLR could still exist, so that the spiral pattern could extend to this resonance and still evolve into an outer ring or pseudo-ring. On the other hand, if $\omega_p$ is low such that the ILR and the UHR exist, then the galaxy could become an SB(r,nr). If all three resonances exist, then the galaxy could become an (R)SB(r,nr). A good example where all three probably do exist is NGC 3081.

In SA galaxies, the interpretation of inner rings seems to be different. De Vaucouleurs and Buta (1980) showed that inner ring sizes depend strongly on both family and variety, in the sense that linear and relative ring diameters decrease from SB to SA and from S0/a to Sd. The first correlation was discovered by de Vaucouleurs, and is depicted in his famous cross-sectional drawing of the RHS (de Vaucouleurs and de Vaucouleurs 1964). It can be interpreted in terms of a correlation between ring size and apparent bar strength, or in terms of different resonance associations (that is, "(r)" in SA galaxies is associated with a different resonance from "(r)" in SB galaxies). I believe the observations favor the latter interpretation. Most of the inner rings of SA galaxies are probably linked to ILR, not the UHR, although features analogous to SB inner rings and lenses are identifiable quite frequently in SA systems (Kormendy 1979; Buta 1984, 1986a). Some SA inner rings lie almost exactly at the "turnover radius" of the rotation curve (Buta 1987a), again implying a possible link with ILR rather than UHR.

This brings me to the final question I wish to discuss in this conference, the possibility that galaxies could change "cell" positions over time scales equal to or less than a Hubble time. Sandage (1986) has asked how long, at present day star formation rates, it would take for a galaxy of a given stage to use up enough of its remaining gas to change by one step in the classification. He finds, using integrated birth rate functions, that this time is a function of increasing gas fraction and decreasing luminosity, and that, depending on the mode of star formation, it could be equal to or longer than a Hubble time. In fact, Sandage believes that the evidence supports the possibility that galaxies may have acquired their final position on the Hubble Sequence not long after the initial collapse, and most have not changed by one step since that time. Of course, this would apply only in the case of isolated evolution. Mergers and collisions can modify galaxy morphology on very short time scales, as much recent research continues to establish (e.g. Hernquist and Quinn 1987; Schweizer and Seitzer 1988; Whitmore and Bell 1988; Higdon 1988 and references therein).

In the case of family and variety, and independent of any external influence, the time scales for significant change could be much less than a Hubble time. For example, in n-body numerical models of galaxy collapse, bars can develop in a few disk rotations (Hohl 1975; Miller and Smith 1979a, b), and in the n-body simulations of gas flow in bar potentials (Schwarz 1979; Combes and Gerin 1985), rings can develop after only 7-10 bar rotations. Thus, it would seem that if secular evolution is occurring in galaxy structure, the most significant changes may be among family and especially variety, since rings evolve from more open spiral patterns. If bars can grow or weaken via angular momentum transfer processes (Lynden-Bell and Kalnajs 1972), or via interactions with the spheroid (Kormendy 1979), then family could change from SB to SAB, or from SA to SAB to SB. That such evolution may be taking place is provided by non-barred, ringed S0 galaxies like NGC 7702 (Figure 3). That a galaxy with little or no obvious bar could have such a bright inner ring made purely of stars is a clear contradiction to theoretical models which rely on bar and gas dynamics for ring formation. Either NGC 7702 once had a strong bar that caused a ring to form before it vanished, or ring formation does not require the presence of a strong bar or a significant amount of gas. Clearly, such galaxies need to be studied in greater detail before we can consider our understanding of family and variety complete.

**Figre 3.** CCD image of NGC 7702 (I-band, AAT), a "non-barred" ringed S0 (note possible small nuclear bar; field stars are removed).

Note that resonances may not be able to explain all rings observed in disk galaxies. Some possibly form by accretion of gas-rich satellites. A particularly striking case may be Hoag's Object (Schweizer et al. 1987) and many "polar-ringed" galaxies (Schweizer, Whitmore, and Rubin 1983).

## 5. CONCLUSIONS

In this brief review, I have by no means attempted to cover all of the papers concerning galaxy morphology published since the excellent Kormendy (1982) Saas Fee Lectures. However, in agreement with Kormendy, I hope I have shown that galaxy morphology continues to be an exciting topic of research that today is making rapid advances owing to the improvements in both theoretical and observational capabilities. Although most of the cells of the revised Hubble classification system have not yet been thoroughly studied, major breakthroughs have been made (e.g., in understanding rings), and it is likely that further progress will be made as galaxies are studied in ever greater detail. There is still, however, much to be learned and more observations to be made, specifically within the family and variety dimensions of the RHS, as I believe further research on those characteristics should be very fruitful. I have highlighted the usefulness and versatility of Gérard de Vaucouleurs's revised Hubble classification system, which is one of the finest achievements of the man whose work we are honoring with this symposium.

## REFERENCES


1. Athanassoula, E., 1983, in *I. A. U. Symp. 100, Internal Kinematics and Dynamics of Galaxies*, ed. E. Athanassoula (Dordrecht: Reidel), p. 243.
2. Athanassoula, E., Bosma, A., Creze, M., and Schwarz, M. P. 1982, *Astron. Astrophys.* **107**, 101.
3. Benedict, G. F. 1980, *Astron. J.* **85**, 513.
4. Buta, R. 1984, "The Structure and Dynamics of Ringed Galaxies," *Univ. Texas Publ. in Astron.* No. **23**.
5. Buta, R. 1986a, *Astrophys. J. Suppl.* **61**, 609.
6. Buta, R. 1986b, *Astrophys. J. Suppl.* **61**, 631.
7. Buta, R. 1987a, *Astrophys. J. Suppl.* **64**, 1.
8. Buta, R. 1987b, *Astrophys. J. Suppl.* **64**, 383.
9. Buta, R. 1987c, *Bul. Am. Astron. Soc.* **19**, 1063.
10. Buta, R. 1988a, *Astrophys. J. Suppl.* **66**, 233.
11. Buta, R. 1988b, in preparation.
12. Combes, F. and Gerin M. 1985, *Astron. Astrophys.* **150**, 327.
13. Contopoulos, G. 1979, in *Photometry, Kinematics, and Dynamics of Galaxies*, ed. D. S. Evans (Austin: Astron. Dept. Univ. Texas), p. 425.
14. Contopoulos, G. 1983, *Astrophys. J.* **275**, 511.
15. Duus, A. and Freeman, K. C. 1975, in *La Dynamique des Galaxies Spirales*, ed. L. Weliachew (Paris: CNRS), p. 419.
16. Elmegreen, B. G. and Elmegreen, D. M. 1985, *Astrophys. J.* **288**, 438.
17. Gallagher, J. and Hunter, D. A. 1984, *Ann. Rev. Astron. Astrophys.* **22**, 37.
18. Gallagher, J. and Hunter, D. A. 1987, *Astron. J.* **94**, 43.
19. Gallagher, J. S. and Wirth, A. 1980, *Astrophys. J.* **241**, 567.
20. Gott, J. R. and Thuan, T. X. 1976, *Astrophys. J.* **204**, 649.
21. Hernquist, L. and Quinn, P. 1987 in *I. A. U. Symp. 127, The Structure and Dynamics of Elliptical Galaxies*, ed. T. de Zeeuw (Dordrecht: Reidel), p. 467.
22. Higdon, J. L. 1988, *Astrophys. J.* **326**, 146.
23. Hohl, F. 1975, in *I. A. U. Symp. 69, Dynamics of Stellar Systems*, ed. A. Hayli (Dordrecht: Reidel), p. 349.
24. Huntley, J. M. 1980, *Astrophys. J.* **238**, 524.
25. Kormendy, J. 1979, *Astrophys. J.* **227**, 714.
26. Kormendy, J. 1981, in *The Structure and Evolution of Normal Galaxies*, ed. S. M. Fall and D. Lynden-Bell (Cambridge: Cambridge University Press), p. 85.
27. Kormendy, J. 1982, in *Morphology and Dynamics of Galaxies* (Geneva: Geneva Observatory), p. 115.
28. Kormendy, J. 1984, *Astrophys. J.* **286**, 116.
29. Lake, G. and Carlberg, R. G. 1988, *Astron. J.* **96**, 1581.
30. Lindblad, P. O. and Jorsater, S. 1981, *Astron. Astrophys.* **97**, 56.
31. Lynden-Bell, D. 1979, *Mon. Not. Roy. Astron. Soc.* **187**, 101.
32. Lynden-Bell, D. and Kalnajs, A. J. 1972, *Mon. Not. Roy. Astron. Soc.* **157**, 1.
33. Miller, R. H. and Smith, B. F. 1979a, *Astrophys. J.* **227**, 407.
34. Miller, R. H. and Smith, B. F. 1979b, *Astrophys. J.* **227**, 785.
35. Ostriker, J. P. and Peebles, P. J. E. 1973, *Astrophys. J.* **186**, 467.
36. Sandage, A. 1961, *The Hubble Atlas of Galaxies*, Publ. No. **618** (Washington, D.C.: Carnegie Institution of Washington).
37. Sandage, A. 1975, in *Galaxies and the Universe*, ed. A. Sandage, M. Sandage, and J. Kristian (Chicago: Univ. of Chicago Press), p. 1.
38. Sandage, A. 1986, *Astron. Astrophys.* **161**, 89.
39. Sandage, A. and Brucato, R. 1979, *Astron. J.* **84**, 472.

40. Sandage, A. and Tammann, G. 1981, *A Revised Shapley-Ames Catalogue*, Publ. No. **635** (Washington, D.C.: Carnegie Institution of Washington).
41. Sandage, A., Freeman, K. C., and Stokes, N. R. 1970, *Astrophys. J.* **160**, 831.
42. Sanders, R. H. and Huntley, J. M. 1976, *Astrophys. J.* **209**, 53.
43. Schempp, W. V. 1982, *Astrophys. J.* **258**, 96.
44. Schwarz, M. P. 1979, Ph.D. Thesis, Australian National University.
45. Schwarz, M. P. 1981, *Astrophys. J.* **247**, 77.
46. Schwarz, M. P. 1984a, *Astron. Astrophys.* **133**, 222.
47. Schwarz, M. P. 1984b, *Mon. Not. Roy. Astron. Soc.* **209**, 93.
48. Schwarz, M. P. 1984c, *Proc. Astron. Soc. Aus.* **5**, 458.
49. Schweizer, F. and Seitzer, P. 1988, *Astrophys. J.* **328**, 88.
50. Schweizer, F., Whitmore, B., and Rubin, V. 1983, *Astron. J.* **88**, 909.
51. Schweizer, F., Ford, W. K., Jedrzejewski, R., and Giovanelli, R. 1987, *Astrophys. J.* **320**, 454.
52. Shapley, H. and Paraskevopoulos, J. 1940, *Proc. Nat. Acad. Sci.* **26**, 31.
53. Tinsley, B. M. 1981, *Mon. Not. Roy. Astron. Soc.* **194**, 63.
54. Tully, R. B., Mould, J. R., and Aaronson, M. 1982, *Astrophys. J.* **257**, 527.
55. de Vaucouleurs, G. 1959, *Handbuch der Physik* **53**, 275.
56. de Vaucouleurs, G. 1963, *Astrophys. J. Suppl.* **8**, 31.
57. de Vaucouleurs, G. 1974, in *I. A. U. Symp. 58, The Formation and Dynamics of Galaxies*, ed. J. It. Shakeshaft (Dordrecht: Reidel), p. 335.
58. de Vaucouleurs, G. 1975, *Astrophys. J. Suppl.* **29**, 193.
59. de Vaucouleurs, G. 1977, in *The Evolution of Galaxies and Stellar Populations*, ed. B. Tinsley and R. Larson (New Haven: Yale University Observatory), p. 43.
60. de Vaucouleurs, G. and de Vaucouleurs, A. 1964, *Reference Catalogue of Bright Galaxies*, (Austin: Univ. of Texas Press).
61. de Vaucouleurs, G., de Vaucouleurs, A., and Corwin, H. G. 1976, *Second Reference Catalogue of Bright Galaxies*, (Austin: Univ. of Texas Press).
62. de Vaucouleurs, G. and Freeman, K. C. 1972, *Vistas in Astron.* **14**, 163.
63. de Vaucouleurs, G. and Buta, R. 1980, *Astrophys. J. Suppl.* **44**, 451.
64. de Zeeuw, T. 1987, ed. *I. A. U. Symp. 127, The Structure and Dynamics of Elliptical Galaxies*, (Dordrecht: Reidel).
65. Whitmore, B. and Bell, M. 1988, *Astrophys. J.* **324**, 741.