MORPHOLOGY OF GALAXIES: AN OVERVIEW

R. Buta
Department of Physics and Astronomy
University of Alabama, USA

1992 Astrophysics and Space Science Library, Vol. 178, p. 1

Abstract

Morphological classification has been and still is a very useful tool in modern extragalactic astronomy. In this overview, I discuss galaxy morphology with regard to the techniques and problems of classification, as well as recent advances in the field.

Contents

1 Introduction

Since Hubble's classification famous 1926 paper outlining his system, understanding galaxy morphology has been an important goal of extragalactic astronomy. For a long time, the subject was little more than descriptive because of a lack of basic data, but today morphology is very much more than a series of type codes and symbols. There is little doubt that morphology was a first logical step in approaching an understanding of galaxies. However, it is reasonable to ask where morphology has led us up to now. This is important to consider at a time when extragalactic astronomy is making great strides on both theoretical and observational fronts.

In this overview I will focus mainly on the fundamentals of morphological classification, both in theory and in practice. The subject is very broad and cannot cover all of the quantitative aspects which have been addressed in recent years. Nevertheless, an attempt is made to review advances in understanding specific types from research during the past 15 years.

2 Morphology: clues to formation and evolution

The principal goal of morphological studies has been to obtain insight into galaxy formation and evolution. Fundamental problems, such as the nature of S0 galaxies, the effects of environment, morphological segregation in clusters, the origin of bars, the driving mechanisms for spiral structure, the possibility of significant secular evolution of structure within a Hubble time, and the underlying factors which determined the various types at the time of galaxy formation, all require accurate knowledge of morphology in order to be addressed reliably. How effective morphology can be in addressing these problems depends on how well the relationships between the various types of galaxies are established, and the extent to which follow-up observations and theoretical analyses are carried out.

Morphology has been useful in spite of the fact that classification has been largely a subjective visual exercise. Its techniques, advantages, disadvantages, correlations, etc. have been discussed by many authors. The review by Sandage (1975) covers all of the older references (including those of Hubble, de Vaucouleurs, Holmberg, Morgan, and van den Bergh), while more recent papers include van den Bergh (1976, 1980a), van den Bergh, Pierce, and Tully (1990), Dressler and Sandage

(1978), Sandage and Brucato (1979), Dressler (1980a, 1984), Sandage and Binggeli (1984), Sandage (1986), Kormendy (1979, 1982), Kennicutt (1981), Bothun (1982a,b), and Vorontsov-Velyaminov (1987). The problems of classification are fairly well-understood, but this has not prevented astronomers from uncritically accepting the types in catalogues without regard to source, or from blaming the classifiers or the classification systems for the inadequacy of type information for some classes of galaxies. The following five points help to place the problems of galaxy morphology into a general perspective:

1. In galaxy morphology, many distinct structures or "components" are seen: bars, rings, lenses, bulges, disks, spiral patterns, etc. These features presented in various combinations and at various inclinations leave the impression that galaxy morphology consists of an almost "impenetrable thicket of forms" (to borrow a phrase from Stephen Jay Gould, 1985, from an essay on biological taxonomy).

2. Galaxies have a wide range of surface brightnesses, luminosities, and other measured properties. This means that *selection effects are always important.* Details that are needed for classification can be easily missed on inadequate image material.

3. Galaxy structure is by and large *continuous.* In a multi-dimensional classification space, *transition* cases almost always exist between any two distinct and sufficiently common morphologies.

4. The distribution of morphologies in rich clusters is often much narrower than for field galaxies. This implies that environment may be important in determining the galactic form.

5. Galaxies have a large cross section for collisions, mergers, or interactions. This can lead, on one hand, to the possible *evolution of rare or transient galactic forms* (e.g., ring galaxies), but, on another hand, it could also be responsible for some of the more common forms (e.g., E galaxies).

These points highlight the fact that galaxy morphology is a complex problem. The goal of classification is to reduce that complexity somewhat by searching for order within the "utter chaos" (again, to borrow a phrase from S. J. Gould) of a wide range of forms whose relationships to each other may not be obvious. If a classification system eventually sheds light on these relationships, then it could provide the needed physical insight for addressing the ultimate goals of understanding galaxy formation and evolution.

3 Morphological classification: theory

In theory, morphological classification is a fairly simple process. Basic types are defined within the scope of a system of nomenclature which assigns galaxies into "cells" of similar-appearing objects. Using a set of criteria, and a set of standards or prototypes which best illustrate the criteria, an observer attempts to determine the appropriate cell position for any object of interest not included among the standards or prototypes. As Long as only a few criteria define a system, and if image material of a similar quality to that which formed the basis of the system is used, then there will be a greater ease of applicability and reproducibility of that system by independent observers. If one later finds correlations between fundamental observables and classifications, then the system could lead to physical insight as has, for example, the Hubble sequence.

The actual assignment of types is more an art than a physical measurement. De Vaucouleurs once told me that his approach to classification is to first identify what a galaxy is *not*. Then one narrows in on the part of the classification continuum where an object may appropriately belong. Classification is fairly straightforward for spirals, where a variety of features (bars, rings, bulge strength) and arm characteristics (resolution, openness) provide a basis for discrimination of types, as noted by Hubble. The classification of S0's depends on distinguishing a "fundamental plane" or envelope surrounding a bright bulge (Sandage, 1961), with the progressive differentiation of disk details, such as a lens, ring-like enhancements or dust lanes, or bars, providing further criteria for early and late S0's. True S0's by definition do not have spiral structure. S0'swith obvious lenses, rings, dust lanes, or bars are the least ambiguous and generally are not difficult to classify with good image material. However, non-barred S0's which are early in the S0 sequence, and which show only a trace of a disk or envelope or lens, are very difficult to distinguish from ellipticals and require high quality image material, generally better than the sky surveys.

Although cell morphology is useful, it does have limitations. For instance, it would be a mistake to consider any cell as having a sharp boundary because of point 3 above. Thus a galaxy may not be simply "barred" or "nonbarred", or "ringed or nonringed", but could be "weakly-barred", or have a "broken or partial ring". Some classification systems take this continuity into account better than others (e.g., de Vaucouleurs, 1959 three-dimensional classification volume as opposed to Hubble's revision in Sandage, 1961). Cell morphology is also not the only viable approach to galaxy structure. One could also view galaxies as being composed of a small number of "building blocks" known as distinct components which are assumed to interact. This approach was pioneered by Kormendy (1979; see also Djorgovski, this conference).

4 Morphological classification: in practice

Galaxy classification in practice is difficult for several reasons. First and foremost is that not every galaxy presents a favorable orientation to the line of sight. High inclination makes it difficult to (1) estimate a type consistent with low inclination galaxies, and (2) recognize bars (end-on ones especially), rings, or other disk details. In the case of spirals, the first problem arises because three criteria (bulge-to-disk ratio, the degree of resolution, and the degree of openness of the arms) can be used for typing face-on examples, while only one criterion (bulge-to disk ratio) generally can be used for edge-on examples. This can lead to problems since Hubble's three classification criteria for spirals have been known for a long time to be inconsistent in some galaxies (Sandage, 1961). The second difficulty means that the statistical frequency of important features such as bars and rings will be underestimated in highly inclined galaxies (see, e.g., de Vaucouleurs and Buta, 1980).

Another problem which makes classification difficult is that the image material often used for types (e.g., the small-scale sky surveys) is entirely inadequate for some types. As noted by Sandage and Brucato (1979), *"the classification of E, S0, and early Sa galaxies is often confused"* when the types are based on dense, overexposed plates or paper prints or on underexposed, small-scale plates taken with short focal length telescopes. On overexposed images such as are often found on the SERC IIIa-J southern sky survey films, high surface brightness bars, rings, or lenses are easily missed. Even on Palomar Sky Survey prints, overexposure of high surface brightness galaxies can lead to very misleading classifications; one interesting case, NGC 3928, looks like type E0 on the PSS but appears as a small, tight spiral on a CFHT prime focus plate (van den Bergh, 1980b; see also Taniguchi and Watanabe, 1987).

At the other extreme, underexposed images may cause important faint details to be completely missed. For example, low surface brightness rings, spiral patterns, disks, or other features (e.g., shells) can be difficult to detect on PSS prints or ESO-B films but clearly distinguishable on the SERC and Palomar II surveys or on processed or amplified images. Failure to detect these features could lead to serious misclassification or misinterpretations in some cases, or even to uncataloguing of an object in a diameter-limited survey (Bothun et al., 1987, 1990).

Another problem is that no classification system is perfect enough to encompass all galaxies. Many galaxies cannot be easily fit into one or another system. As emphasized by Sandage and Binggeli (1984), Hubble's classification system encompassed mainly giant, high luminosity galaxies whose forms did not readily extend to much lower luminosities. Galaxies near or outside the fringes of the old classification systems have often been peculiar (colliding or merging systems).

5 Systems of classification

The classification systems in use today are all in some way related to the system described in Hubble's (1926) paper. A detailed review of several of these, in particular Hubble's revised system, de Vaucouleurs' revised Hubble system, van den Bergh's modified Hubble (or DDO) system with luminosity classes, Morgan's spectral form classification (or Yerkes) system, and Vorontsov-Velyaminov's purely descriptive (or MCG) system, has already been provided by Sandage (1975).

The only system which has changed significantly since 1975 is van den Bergh's modified Hubble system. For various reasons, van den Bergh (1976) disagreed with Hubble's placement of S0's in the "transition region" between ellipticals and spirals, and instead proposed placing S0's in a sequence parallel to spirals (called the RDDO system). His sequence of modified Hubble types uses bulge-to-disk ratio as the main classification criterion, while Hubble's final division of spiral types was based principally on the appearance of the arms. Using B/D ratio as the sole stage criterion, van den Bergh identified transition cases between S0's and normal spirals which appeared to be spirals with little star formation in the arms. These were given the term "anemics" and were assumed to be poor in HI (see Bothun and Sullivan, 1980). Van den Bergh, Pierce, and Tully (1990) have recently discussed the application of a further modified RDDO system to CCD images of galaxies.

Revisions to other systems are less drastic. Slight revisions to the Yerkes system are described by Morgan, Kayser, and White (1975), while Sandage and Brucato (1979) discuss refinements to the classification system in Sandage (1961). The *Revised Shapley-Ames catalogue* (RSA, Sandage and Tammann, 1987), which is one of the main applications of Hubble's revised system, now recognizes Sd and Sm types as in the de Vaucouleurs revised Hubble system. In addition, what de Vaucouleurs has called I0 and which was assigned a coded numerical stage T = 0 in the *Second Reference Catalogue of Bright Galaxies* (RC2, de Vaucouleurs et al., 1976), is now regarded as a special class of objects outside the scope of the Hubble sequence (Sandage and Brucato, 1979; see section 7.3).

6 Morphological classification: recent applications

The most important sources of morphological information have been the large catalogues of galaxies produced since the 1960's. Morphological classifications on the de Vaucouleurs revised Hubble system available prior to 1976 for some 4400 galaxies are summarized in RC2. A standard reference for morphology for many years, RC2 will soon be replaced by RC3 (de Vaucouleurs et al., 1991; see below).

Sandage and Tammann in the RSA have applied Hubble's own revision (with modifications) to the 1,246 galaxies in the old Shapley-Ames all-sky survey of bright galaxies, the southern part of which is based in part on a Las Campanas imaging survey described by Dressler and Sandage (1978) and Sandage and Brucato (1979). This is a valuable source for morphology for a relatively well-defined sample. High quality photographs of many of these objects are provided in Sandage and Bedke (1988). Dressler (1980b) also applied the Hubble-Sandage system to thousands of galaxies in 55 rich clusters. A recent application of the Yerkes system was made by Wirth and Gallagher (1980) in the Hydra I and Fornax Clusters based in part on CTIO 4-m prime focus plates. Because of the great recent interest in the so-called "Great Attractor", van den Bergh (1989) gives RDDO classifications for several hundred spirals in that direction.

The Palomar Sky Survey led to some of the largest catalogues of morphological information ever produced. These include the UGC (Nilson, 1973) and the MCG (see Vorontsov-Velyaminov, 1987 and references therein). The more recently produced ESO-B and SERC sky surveys have also proven to be gold-mines for morphology in the zones south of declination $-17°$. Hubble types based on the ESO-B survey are provided for 16,000 galaxies by Lauberts (1982), while Corwin, de Vaucouleurs, and de Vaucouleurs (1985) took advantage of the much finer grained and deeper SERC films and plates to produce the *Southern Galaxy Catalogue* (or SGC), which includes, among other things, detailed de Vaucouleurs revised Hubble types and DDO luminosity classes for 5,364 galaxies. This was followed by the Extension to the Southern Galaxy Catalogue (ESGC, Corwin and Skiff, 1990, in preparation), which provides more accurate type information (based on Palomar I copy plates) in the little studied zone from $-17° < \delta < -2°$.

More specialized catalogues have also been based the SERC charts or their northern equivalent, the Palomar II Sky Survey. For example, the SERC survey has been used for the *Atlas of Southern Peculiar Galaxies and Associations* (Arp and Madore, 1987) and the *Catalogue of Southern Ringed Galaxies* (or CSRG, see Buta, 1986a, 1991a), while the PSS II is being used to compile new lists of northern low surface brightness galaxies (Schombert and Bothun, 1988).

Finally, RC3 continues the tradition of its predecessors RC1 and RC2 in bringing together basic information on many galaxies from a variety of sources, including morphological types. The types are based on 10 sources, but mainly the large databases in RC2, SGC, ESGC, UGC, and CSRG. The overlap among these different sources was used to make triangular comparisons between estimates of the coded numerical de Vaucouleurs stage index, T, which allowed estimates of the mean errors of each type and checks on the reproducibility of the system. In a detailed analysis by S. Mitra first, and later by myself, it was found that scale errors and zero point differences between sources are small and that, on average, the error of an estimate of T (not marked * or ?) for a galaxy having $D_{25} = 2'$ and axis ratio $R_{25}^{-1} = 0.6$ is $\sigma(T) \sim 0.7$. Since the vast majority of types from these sources are based on the small-scale sky surveys, this error is representative of those types and not types based on large scale plates taken with 2.5-5m class telescopes, which should be considerably better. The comparisons confirmed that the revised Hubble system is reproducible at a reasonable level of certainty. Combining all sources, RC3 gives types for 17,775 galaxies and is the largest source of Hubble morphological type information ever produced.

7 Recent advances in morphology and new classes of galaxies

Modern technology has given us high-quality images of more galaxies than ever before. The greater depth of exposures possible, and the all sky coverage due to the PSS, ESO, and SERC surveys, has led to the recognition of new types of galaxies and to more enlightened views of some older classes. In this section I focus on a few of these recent advances.

7.1 Early-type galaxies

There can be little doubt that accurate classification of early-type galaxies requires imaging material of the highest quality. Careful and extensive studies of large numbers of E and S0 galaxies have, over the past 10 years, revealed some of the complexities and inhomogeneities in these two classes of objects.

Several excellent recent reviews of E galaxies already exist (e.g., Nieto, 1988; Kormendy and Djorgovski, 1989, Franx, 1990), as well as a whole I. A. U. Symposium (de Zeeuw, 1987), so I will not list any specific references here. The general consensus of these works, which summarize a great deal of highly focussed research, is that the apparent simplicity of E galaxies is highly deceptive. It is now generally accepted that E's may be characterized more by triaxial intrinsic shapes than oblate shapes, that a significant fraction of E's have dust, that some have formed through merger processes as suggested by boxy isophotes and interleaved shells, that many have weak disks that are hard to detect if face-on, and that many have accreted material since they first formed which manifests itself in unusual HI properties, counter-rotating cores, disks of dust, or polar-type rings. The most interesting aspect of all of this research is just how much can be learned from a concerted and widespread effort on a single type of galaxy.

S0 galaxies have also been studied in great detail, but their relationship to spirals is still controversial. Most interesting has been the detection of neutral gas (e.g., Wardle and Knapp, 1986; van Driel, 1987) and ionized gas (Pogge and Eskridge, 1987) in some S0's. Photometric decompositions (e.g., Simien and de Vaucouleurs, 1986) and bulge studies (Dressier and Sandage, 1983) have favored Hubble's placement of S0's between E's and spirals, rather than in a parallel sequence to spirals, while recent spectroscopic studies (Gregg, 1989) and color analyses (e.g., Bothun and Gregg, 1999) have favored the "burnt-out" spiral theory where S0's are simply spirals that have exhausted their gas supply through astration. However, from a statistical study of S0 luminosities, van den Bergh (1990) has concluded that the S0 class is a *"repository of physically quite distinct sorts of objects that exhibit only superficial similarities"*, indicating that the *"various kinds of S0 galaxies might have arrived at their present morphological state along quite different evolutionary tracks."* This suggests to me that there is still quite a bit more to be learned about the S0 phenomenon in general.

Finally, the properties of the Morgan D and cD classes, the latter usually found in the centers of rich Abell clusters, have been studied in great detail recently by Schombert (1986, 1987, 1988), who also discusses the classification of these objects in terms of morphology and surface brightness profile properties. The understanding now is that cD galaxies form a unique class of objects that may be related to mergers. "BCM's" are reviewed by Schombert (this conference).

7.2 Spiral arm character, multiplicity, and disk resonances

One of the most important recent advances in morphology concerns spiral arm character. Kormendy and Norman (1979) demonstrated that spiral arm morphology depends directly on whether the disk suffers from a global instability, such as a bar, oval, or companion. In the absence of an internal or external non-axisymmetric perturbation, and in the presence of differential rotation, a galaxy will tend to have "flocculent" (or piece-meal) spiral structure, while the presence of perturbations will generally lead to well-defined global or "grand design" spiral patterns in spite of differential rotation. Elmegreen and Elmegreen (1982) proposed a system of "arm classes" to recognize this distinction and everything in between for the purpose of studying density waves in galactic disks. A summary of the physical insights derived from this scheme is given by Elmegreen and Elmegreen (1987).

An important recent use of morphology has been to identify resonance locations in galactic disks, leading to estimates of pattern speeds. In the case of pure spirals, Elmegreen, Elmegreen, and Seiden (1989) and Elmegreen and Elmegreen (1990) have used regularities (gaps, enhancements) in the arms of M 51, M 81, M 100 and NGC 1566 to trace wave resonances and evaluate the modal and stellar dynamical theories of spiral structure. In other galaxies, rings may be the most prominent tracers of specific bar resonances (Schwarz, 1979, 1981; Buta, 1986a,b). The inner and outer Lindblad, inner 4/1, and corotation resonances figure prominently in these studies because the morphological expectations of each of these resonances are fairly well-understood (see B. G. Elmegreen, 1990 and references therein). Arm multiplicity is also important for density wave studies (B. G. Elmegreen, 1990; D. M. Elmegreen, 1990), and may also shed light on resonance associations and pattern speeds.

The relationship between bars and the form of spiral structure has been an additional important topic. Kormendy (1979) demonstrated that most barred spirals have global spiral structure. Elmegreen and Elmegreen (1982) confirmed this observation and found that 79% of field barred or oval galaxies have grand design patterns. This fraction increased to more than 90% when restricted to binary galaxies.

7.3 Amorphous galaxies

This class was introduced by Sandage and Brucato (1979) to encompass galaxies *"which are not E, S0, or any type of spiral but which have an amorphous appearance to the unresolved light, sometimes with imbedded resolved stars... All members of the class have well-developed early-type absorption spectra spread throughout the disk."* These galaxies are related to Holmberg's Irr II class and de Vaucouleurs I0 class. A detailed study of a prototype amorphous galaxy, NGC 1800, was made by Gallagher, Hunter, and Knapp (1981). They suggested that the properties of this object favor a system that for some reason has a flatter IMF than normal and has been extremely efficient in forming stars. The color properties and star formation histories of a larger sample of amorphous galaxies are discussed by Gallagher and Hunter (1987).

7.4 Dwarf and low surface brightness galaxies

A detailed photographic study of low-luminosity members of the Virgo Cluster, which *contains galaxies of every known morphological type*, has been presented by Sandage and Binggeli (1984). With this large body of morphological data they propose a refined classification of dwarf galaxies that covers late and early-type galaxies. Particularly interesting is their recognition of a dwarf S0 class (dS0), that is, a class of low surface brightness dwarfs which morphologically are distinguishable from dwarf E's in showing direct evidence for a disk or an inflection in the brightness distribution. The recognition of dwarf S0's, however, does not imply the existence of dwarf spirals of comparable luminosity to the dS0's. Sandage and Binggeli comment that *"there are ... no convincing candidates in the Virgo Cluster for dSa"*, and that *"there is no equivalent in the spirals of the Hubble sequence at faint absolute magnitudes."*

Other interesting findings from this paper are a new class of galaxies which are dwarfs in luminosity but not in size ("huge" Im and dE types), and of variations in the properties of the dwarf ellipticals (e.g., with or without nuclei, see also Kunth et al., 1988). Sandage and Binggeli find that 80% of the Virgo Cluster galaxies fainter than 14th magnitude are dE's while 20% are Sm or Im types. A more detailed study of a subset of dE's in Virgo is given by Impey, Bothun, and Malin (1988).

Perhaps one of the most interesting realizations the past few years is that there exist disk galaxies which are low in surface brightness but which are nevertheless neither dwarfs in luminosity nor in size. Bothun et al. (1987, 1990) discuss two examples discovered so far, Malin 1 and F 568-6, and the implications of their properties with regard to the evolutionary time-scales of disks. These galaxies are examples of massive, low surface brightness disk galaxies.

7.5 Ringed and lensed galaxies

Revisions to the classification of ringed and lensed galaxies in the de Vaucouleurs system are discussed by Kormendy (1979) and Buta (1986a, 1989), the former based on a survey of 121 barred galaxies and the latter on the CSRG discussed above. These cover mostly the recognition of lenses as distinct from rings and account for variations in the morphology of pseudo-outer rings in barred galaxies.

A small number of especially well-defined ringed nonbarred or weakly-barred S0 and S0/a galaxies, NGC 3081, 7187, 7020, and 7702, from the CSRG has been studied by Buta (1990a,b,c, 1991). These galaxies highlight how high contrast rings are often associated with galaxies which are not classified as SB or even SAB. The rings are discussed in terms of resonances and the secular evolution of bars idea proposed by Kormendy (1979).

7.6 Morphology of bars

Barred galaxies have received much attention the past 15 years, but only recently have the properties of the bar form been analyzed in detail. Elmegreen and Elmegreen (1985) have identified two subcategories of bars which are distinguished by their *photometric properties*: "flat" bars, where the intensity along the bar length is roughly uniform; and "exponential" bars, where the intensity along the bar declines exponentially. There is a rough correlation between these bar types and Hubble type: flat bars are prevalent among early-type SB galaxies while exponential bars are prevalent among later type SB galaxies. The Elmegreens discuss these differences in terms of orbit resonances in the disk plane.

Another line of morphological work concerns the shape of bars. The bars of a significant fraction of early-type galaxies appear to be somewhat rectangular in shape (e.g., Athanassoula et al., 1990; Ohta, Hamabe, and Wakamatsu, 1990), while the bars of some late-type SBm spirals can be somewhat triangular (Odewahn, 1989). A particular striking example of a rectangular bar with oval "ears" has been found in the southern outer-ringed galaxy NGC 7098 (Crocker and Buta, 1991, in preparation).

7.7 "Boxy" or "peanut" bulges and "x" galaxies

Boxy or peanut bulge galaxies have been an active subject of study the past 10 years. Major lists of the best cases have been compiled by Jarvis (1986) and Shaw (1987). The phenomenon has been variously explained in terms of cylindrical rotation (see Rowley, 1988, and references therein), edge-on or other preferred views of bars (Combes and Sanders, 1981, Combes et al., 1990), or merger effects (Whitmore and Bell, 1988). The boxy or peanut character is usually very subtle in photographs, although it can be extremely obvious in some cases, as in, for example, NGC 128 (Sandage, 1961; Jarvis, 1989) and IC 4767 (Whitmore and Bell, 1988). With suitable image processing, the latter object also shows an X-shaped structure crossing its inner regions, which has been interpreted by Whitmore and Bell as evidence for a recent merger. The highly inclined, but non-edge-on, S0 galaxy NGC 7020 shows a similar but possibly unrelated feature (Buta, 1990c).

7.8 Ring, polar ring, and "hoag-type" ring galaxies

These rare phenomena have been the subject of a fair amount of recent research. Ring and polar ring galaxies are believed to be produced by collisions or mergers. Recent studies of morphology and statistics of ring galaxies have been made by Few and Madore (1986), Appleton and Struck-Marcell (1987 and references therein), and Arp and Madore (1987). A catalogue of polar rings has been compiled by Whitmore et al. (1990), who also give many of the previous relevant references.

The prototype of "Hoag-type" ring galaxies is Hoag's Object (A1515 + 2146), which has been studied in great detail recently. This object is remarkable for having a clear ring surrounding a distinct spheroidal galaxy, with no trace whatsoever of a bar. It has been interpreted as a ringed galaxy whose bar dissolved after the ring formed (Brosch, 1985), and as a case where an E galaxy accreted a small companion into something like a polar ring (Schweizer et al., 1987). Wakamatsu (1990) studied another example, NGC 6028, but demonstrated the presence of a small bar in the central region and suggested that at least in this case, bar-driven gas dynamics could explain the presence of the ring. A possible related object is NGC 7187 (Buta, 1990b).

8 Conclusions

This review has only covered a limited portion of a very broad topic, and I apologize for any other important aspects I have left out. However, I hope I have conveyed an adequate impression of what morphology is all about and how it has helped in our understanding of galaxies. In my opinion, the best approach to morphology is to view it as an imprecise science which serves as a means to an end but which is not an end in itself. Morphology cannot generally stand alone and, as pointed out by Dressler (1980a), is not a suitable substitute for physics. However, as pointed out by Kormendy (1979) and Dressler (1980a), morphology can suggest powerful avenues for further research. A purely physical classification is not likely to replace morphological classification for many years.

To answer the question as to where morphology has led us in understanding galaxies, I think it has given us insights by causing us to focus our attention on specific types of objects. Spiral galaxies were the subject of much research in the 1960's and 1970's, while the 1980's could be called the decade of the elliptical galaxies. For the various classes of galaxies, we have sought to measure more basic physical parameters, such as optical and infrared luminosities, colors, surface brightness distributions, HI contents and distributions, CO distributions, rotation curves and mass distributions, diameters and intrinsic flattenings, velocity dispersions, radio continuum fluxes and distributions and kinematics and dynamics of internal structures, and we have used these physical measurements to piece together what determines morphology and what role the invisible parts of galaxies may play in the overall dynamics. The beauty of morphology is that there are not purely random correlations between many of these parameters and galaxy structure, as is highlighted by the smooth variations of some quantities with position along the Hubble Sequence (see Whitmore, 1984 and Watanabe et al., 1985 for recent applications of principal component analysis). Thus, morphological classification in conjunction with physical measurement has been an important tool in extragalactic astronomy.

The advent of CCD technology, the high quality sky surveys, and the Hubble Space Telescope suggest to me that there is an exciting future for morphological studies. Considering the extensive interest in early-type galaxies among the attendees at this conference, a homogeneous imaging survey of all real or suspected E, S0 galaxies in a well-defined sample (e.g., Sadler, 1984) may be more practical than ever before and may help to alleviate some of the uncertainty in interpreting HI and other properties of these objects. Even more exciting are the prospects from HST, which at some point should allow the study of morphology in very distant galaxies where we may be able to see evidence for secular evolution. This will be important not only for star formation histories, but also for bars, rings, spiral structure, and the distribution of types. For nearer galaxies, CCD's are already providing excellent image material for morphology studies. The efficiency and linearity of these detectors makes it possible to image more galaxies on a large scale and to a deeper limiting surface brightness than ever before. With such high quality images becoming available, more and more attention will be paid to finer details of morphology as theories and observations get more sophisticated. Finally, future large surveys will probably involve computer classification from digital images to a great extent (see Thonnat, 1989; and Delfini, Accomazzi, Kurtz, and Mussio, this conference).

References

[1] ppleton, P.N. and Struck-Marcell, C.: 1987, *Astrophys. J.* 312, 566.

[2] rp, H.C. and Madore, B. F.: 1987, *A Catalogue of Southern Peculiar Galaxies and Associations,* Cambridge Univ. Press, Cambridge.

[3] thanassoula, E., Morin, S., Wozniak, H., Puy, D., Pierce, M.J., Lombard, J., and Bosma, A.: 1990, *Mon. Not. R. Astr. Soc.* 245, 130.

[4] othun, G.: 1982a, *Astrophys. J. Suppl. Ser.* 50, 39.

[5] othun, G.: 1982b, *Publ. Astron. Soc. Pac.* 94, 774.

[6] othun, G. and Gregg, M.: 1990, *Astrophys. J.* 350, 73.

[7] othun, G. and Sullivan, W.T.: 1980, *Astrophys. J.* 242, 903.

[8] othun, G., Impey, C.D., Malin, D.F., and Mould, J.R.: 1987, *Astron. J.* 94, 23.

[9] othun, G.D., Schombert, J.M., Impey, C.D., and Schneider, S.E.: 1990, *Astrophys. J.* 360, 427.

[10] rosch, N.: 1985, *Astron. Astrophys.* 153, 199.

[11] uta, R.: 1986a, b, *Astrophys. J.* 306, 768.

[12] uta, R.: 1989, *The World of Galaxies* (H.G. Corwin and L. Bottinelli, Eds.), 29, Springer, N.Y..

[13] uta, R.: 1990a, *Astrophys. J.* 351, 62.

[14] uta, R.: 1990b, *Astrophys. J.* 354, 428.

[15] uta, R.: 1990c, *Astrophys. J.* 356, 87.

[16] uta, R.: 1991a, *Dynamics of Galaxies and Molecular Clouds Distribution*, I.A.U. Symposium no. 146 (F. Combes and F. Casoli, Eds.), in press, Kluwer, Dordrecht.

[17] uta, R.: 1991b, *Astrophys. J.* in press.

[18] orwin, H.G., de Vaucouleurs, A., and de Vaucouleurs, G.: 1985, *Southern Galaxy Catalogue*, Univ. Tex. Mon. Astr. no. 4, Austin. - (=SGC).

[19] ombes, F. and Sanders, R. H.: 1981, *Astron. Astrophys.* 96, 164.

[20] ombes, F., Debbasch, F., Friedli, D., and Pfenniger, D.: 1990, *Astron. Astrophys.* 233, 82.

[21] e Vaucouleurs, G.: 1959, *Handbuch der Physik*, 53, 275.

[22] e Vaucouleurs, G. and Buta, R.: 1980, *Astrophys. J. Suppl. Ser.* 44, 451.

[23] e Vaucouleurs, G., de Vaucouleurs, A., and Corwin, H.G.: 1976, *Second reference Catalogue of Bright Galaxies*, Univ. Tex. Mon. Astr. no. 2, Austin. - (=RC2).

[24] e Vaucouleurs, G., de Vaucouleurs, A., Corwin, H.G., Buta, R., Paturel, G., and Fouque, P.: 1991, *Third Reference Catalogue of Bright Galaxies*, Springer, N.Y. - (=RC3).

[25] e Zeeuw, T., Ed.: 1987, *The Structure and Dynamics of Elliptical Galaxies*, I.A.U. Symposium no. 127, Reidel, Dordrecht.

[26] ressler, A.: 1980a, *Astrophys. J.* 236, 351.

[27] ressler, A.: 1980b, *Astrophys. J. Suppl. Ser.* 42, 565.

[28] ressler, A.: 1984, *Ann. Rev. Astron. Astrophys.* 22, 185.

[29] ressler, A. and Sandage, A.: 1978, *Publ. Astron. Soc. Pac.* 90, 5.

[30] ressler, A. and Sandage, A.: 1983, *Astrophys. J.* 265, 664.

[31] lmegreen, B.G.: 1990, In *Galactic Models* (J.R. Buchler, S.T. Gottesman, and J.H. Hunter, Jr., Eds.), 40, New York Acad. Sci., N.Y..

[32] lmegreen, D.M.: 1990, In *Galactic Models* (J.R. Buchler, S.T. Gottesman, and J.H. Hunter, Jr., Eds.), 53, New York Acad. Sci., N.Y..

[33] lmegreen, D.M. and Elmegreen, B.G.: 1982, *Mon. Not. R. Astr. Soc.* 201, 1021.

[34] lmegreen, B.G. and Elmegreen, D.M.: 1985, *Astrophys. J.* 288, 438.

[35] lmegreen, D.M. and Elmegreen, B.G.: 1987, *Astrophys. J.* 314, 3.

[36] lmegreen, B.G. and Elmegreen, D.M.: 1990, *Astrophys. J.* 355, 52.

[37] lmegreen, D.M., Elmegreen, B.G., and Seiden, P.E.: 1989, *Astrophys. J.* 343, 602.

[38] ew, J.M.A. and Madore, B.F.: 1986, *Mon. Not. R. Astr. Soc.* 222, 673.

[39] ranx, M.: 1990, In *Galactic Models* (J.R. Buchler, S.T. Gottesman, and J.H. Hunter, Jr., Eds.), 67, New York Acad. Sci., N.Y..

[40] allagher, J.S., Hunter, D.A., and Knapp, G.R.: 1981, *Astron. J.* 86, 344.

[41] allagher, J.S. and Hunter, D.A.: 1987, *Astron. J.* 94, 43.

[42] ould, S.J.: 1985, *The Flamingo's Smile.*

[43] regg, M.: 1989, *Astrophys. J.* 337, 45.

[44] ubble, E.: 1926, *Astrophys. J.* 64, 321.

[45] mpey, C.D., Bothun, G.D., and Malin, D.F.: 1988, *Astrophys. J.* 330, 634.

[46] arvis, B.J.: 1986, *Astron. J.* 91, 65.

[47] arvis, B.J.: 1989, *Dynamics and Interactions of Galaxies* (R. Wielen, Ed.), 416, Springer, Berlin.

[48] ennicutt, R.C.: 1981, *Astron. J.* 86, 1847.

[49] ormendy, J.: 1979, *Astrophys. J.* 227, 714.

[50] ormendy, J.: 1982, *Morphology and Dynamics of Galaxies,* p. 115, Geneva Obs., Geneva.

[51] ormendy, J. and Norman, C.: 1979, *Astrophys. J.* 233, 539.

[52] ormendy, J. and Djorgovski, S.: 1989, *Ann. Rev. Astron. Astrophys.* 27, 235.

[53] unth, D., Maurogordato, S. and Vigroux, L.: 1988, *Astron. Astrophys.* 204, 10.

[54] auberts, A.: 1982, *The ESO-Uppsala Survey of the ESO (B) Atlas,* European Southern Observatory, Munich.

[55] organ, W.W., Kayser, S., and White, R.A.: 1975, *Astrophys. J.* 199, 545.

[56] ieto, J.-L.: 1988, *Boletin de la Academia de Ciencias Cordoba,* 58, 329.

[57] ilson, P.: 1973, *Uppsala General Catalogue of Galaxies,* Upp. Obs. Ann., Vol. 6. - (=UGC).

[58] dewahn, S.: 1989, PhD Thesis, University of Texas.

[59] hta, K., Hamabe, M., and Wakamatsu. K.I.: 1990, *Astrophys. J.* 357, 71.

[60] ogge, R.W. and Eskridge, P.B.: 1987, *Astron. J.* 93, 291.

[61] owley, G.: 1988, *Astrophys. J.* 331, 124.

[62] adler, E.M.: 1984, PhD Thesis, Australian National University.

[63] andage, A.: 1961, *The Hubble Atlas of Galaxies,* Carnegie Institution of Washington Publication no. 618, Washington, D.C.

[64] andage, A.: 1975, *Galaxies and the Universe, Stars and Stellar Systems Vol. IX* (A. Sandage, M. Sandage, and J. Kristian, Eds.), 1, Chicago.

[65] andage, A: 1986, *Astron. Astrophys.* 161, 89.

[66] andage, A. and Bedke, J.: 1988, *Atlas of Galaxies Useful for the Cosmological Distance Scale,* NASA, Washington, D.C.

[67] andage, A. and Binggeli, B.: 1984, *Astron. J.* 89, 919.

[68] andage, A. and Brucato, R.: 1979, *Astron. J.* 84, 472.

[69] andage, A. and Tammann, G.A.: 1987, *A Revised Shapley-Ames Catalog of Bright Galaxies,* Carnegie Institution of Washington Publ. no. 635, Washington, D.C. - (=RSA).

[70] chombert, J.M.: 1986, *Astrophys. J. Suppl. Ser.* 60, 603.

[71] chombert, J.M.: 1987, *Astrophys. J. Suppl. Ser.* 64, 643.

[72] chombert, J.M.: 1988, *Astrophys. J.* 328, 475.

[73] chombert, J.M. and Bothun, G.D.: 1988, *Astron. J.* 95, 1389.

[74] chwarz, M.P.: 1979, PhD Thesis, Australian National University.

[75] chwarz, M.P.: 1981, *Astrophys. J.* 247, 77.

[76] chweizer, F., Ford, W.K., Jedrzejewski, R., and Giovanelli, R.: 1987, *Astrophys. J.* 320, 454.

[77] haw, M.: 1987, *Mon. Not. R. Astr. Soc.* 229, 691.

[78] imien, F. and de Vaucouleurs, G.: 1986, *Astrophys. J.* 302, 564.

[79] aniguchi, Y. and Watanabe, M.: 1987, *Astrophys. J.* 313, 89.

[80] honnat, M.: 1989, The *World of Galaxies* (H.G. Corwin and L. Bottinelli, Eds.), 53, Springer, N.Y..

[81] an den Bergh; S.: 1976, *Astrophys. J.* 206, 883.

[82] an den Bergh, S.: 1980a, *Phil. Trans. R. Soc. London, Ser. A,* 296, 319.

[83] an den Bergh, S.: 1980b, *Publ. Astron. Soc. Pac.* 92, 409.

[84] an den Bergh, S.: 1989, *Astron. J.* 97, 1556.

[85] an den Bergh, S.: 1990, *Astrophys. J.* 348, 57.

[86] an den Bergh, S., Pierce, M., and Tully, R.B.: 1990, *Astrophys. J.* 359, 4.

[87] an Driel, W.: 1987, PhD thesis, University of Groningen.

[88] orontsov-Velyaminov, B.A.: 1987, *Extragalactic Astronomy*, Harwood Publ., New York, N.Y..

[89] akamatsu, K.: 1990, *Astrophys. J.* 348, 448.

[90] ardle, M. and Knapp, G.R.: 1986, *Astron. J.* 91, 23.

[91] atanabe, M., Kodaira, K., and Okamura, S.: 1985, *Astrophys. J.* 292, 72.

[92] hitmore, B.C.: 1984, *Astrophys. J.* 278, 61.

[93] hitmore, B.C. and Bell, M.: 1988, *Astrophys. J.* 324, 741.

[94] hitmore, B.C., Lucas, R., McElroy, D.B., Steiman-Cameron, T.-Y., Sackett, P.D., and Oiling, R.P.: 1990, *Astron. J.* 100, 1489.

[95] irth, A. and Gallagher, J.S.: 1980, *Astrophys. J.* 242, 469.