Galaxy Morphology and Classification

Sidney van den Bergh

The classification of galaxies according to their shape is a fundamental tool in astronomy. It is through classification schemes that astronomers build a deeper understanding of how galaxies form and evolve. This long-awaited book by one of the pioneers of the field provides a concise and up-to-date summary of current ideas about galaxy morphology and classification.

This is the first book to be dedicated entirely to the shapes and classifications of galaxies. It introduces the most widely used schemes (including those by Hubble, de Vaucouleurs, Morgan, the author and Elmegreen), explains how they have developed and what they can tell us about galaxies. Professor van den Bergh also presents evidence for how galaxies might 'transmute' from one type to another. It is also shown how very distant galaxies (for instance, those seen in the Hubble Deep Field) often defy standard classification schemes. Finally, this book discusses recent work on the use of computers to classify digital images of galaxies automatically.

This topical volume provides graduate students and researchers with a unique and indispensable reference on the classification and shape of galaxies.

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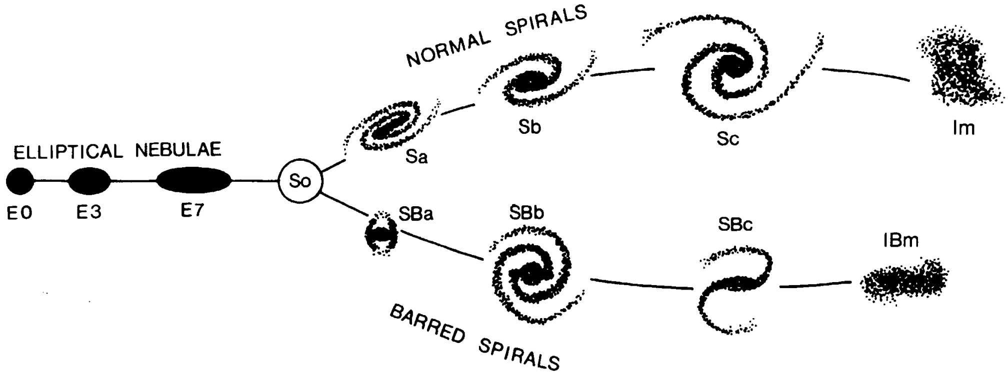

ELLIPTICAL NEBULAE
E0
E3
E7
So
NORMAL SPIRALS
Sa
Sb
Sc
Im
SBa
SBb
SBc
IBm
BARRED SPIRALS

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Preface

Yogi Berra once said that 'you can observe a lot by just watching'. The truth of this aphorism struck me when the first prints of the *Palomar Sky Survey* started to arrive at the Universitäts Sternwarte in Göttingen, where I was a graduate student in 1955. Just looking at this marvellous atlas immediately showed a number of interesting things that had not been so obvious on the smaller, and less homogeneous, databases that had previously been available: (1) The most luminous galaxies in clusters are 'pretty' because they have long well-defined spiral arms, whereas 'ugly' spirals of lower luminosity tend to exhibit short patchy arms. (2) Intrinsically faint galaxies generally have lower surface brightnesses than do luminous ones. (3) Galaxies in rich clusters sometimes exhibit peculiarities, like fuzzy spiral arms, that are rare among isolated field galaxies.

In the present volume, which is based on a series of lectures given at the University of Victoria in early 1997, I have tried to provide an up-to-date summary of current ideas on the morphology [*morphe* = shape] and classification of galaxies. I am indebted to Roberto Abraham for suggesting that I write this review. I also thank Ralf Bender, Scott Tremaine and Stephen Zepf for discussions on the interpretation of the classification of elliptical galaxies, and Guy Worthey and Masafumi Noguchi for discussion of the abundance ratio of elements to iron in normal and barred spirals. Thanks are also due to the Kitt Peak National Observatory and to the Cerro Tololo Inter-American Observatory, where I obtained the 4-m plates that are shown as half-tone illustrations in the present volume. I am particularly grateful to Janet Currie for typing numerous drafts of the manuscript, to David Duncan for drawing many of the figures and to Eric LeBlanc for help with bibliographical searches. Finally, I would like to express my deep gratitude to Roberto Abraham, Ralf Bender and John Kormendy for their numerous and valuable comments on the draft typescript of this book, and to copy editor Maureen Storey for many helpful suggestions.

Victoria, British Columbia, Canada S v.d. B

1 Introduction

Galaxies are like people. The better you get to know them the more peculiar they often seem to become. Each individual galaxy may be thought of as representing a deviation from some underlying ideal type. 'Classical morphology is useful because it succeeds to some extent in distinguishing galaxies which are physically different' (Kormendy 1982, p. 125). It is the task of a galaxy morphologist (1) to recognize the archetype to which a galaxy belongs, and (2) to organize these archetypes of galaxies into a simple scheme that might eventually be interpreted in terms of galactic evolution. This review is mainly devoted to the morphology and classification of normal galaxies, which may be regarded as objects that are in the 'ground state' (Ozernoy 1974). Galaxies in excited states, such as quasars and Seyfert galaxies, will not be discussed in detail. Furthermore no mention will be made of purely descriptive classification systems such as those of Wolf (1908) and of Vorontsov-Velyaminov & Krasnogorskaja (1962). For a more detailed discussion of such systems the reader is referred to Sandage (1975). *An Atlas of Peculiar Galaxies*, that appear to fall outside the range of morphological types that are usually encountered among galaxies, has been published by Arp (1966). The vast majority of objects pictured in Arp's atlas appear peculiar because they are interacting (or have recently interacted) with their companions. However, some objects in Arp's catalog are dwarfs that are not peculiar at all (e.g. Atlas Nos. 2, 3, 4 and 5). Such dwarfs were probably included only because late-type dwarf galaxies generally look patchier, and hence more chaotic, than more luminous galaxies. Furthermore such dwarfs are rare (and therefore unfamiliar to many of us) in galaxy samples that have been selected by apparent magnitude.

For an excellent introduction to the beauty and variety of galaxy morphology the reader is referred to *The Color Atlas of Galaxies* (Wray 1988) which shows how dust, old red stars, and young blue stars, are distributed in different types of galaxies.

1.1 The Hubble tuning fork diagram

The first galaxy classification system to have gained more-or-less universal acceptance was due to Hubble (1926) who arranged galaxies in his now famous 'tuning fork' diagram

```
          Sa–Sb–Sc
         /
E0–E7
         \
          SBa–SBb–Sbc
```

Along the normal and barred spiral tines of this diagram the position of a galaxy was determined by nuclear size and spiral arm tilt. The fact that the integrated colors and spectral types of galaxies exhibit a monotonic increase along the sequence E–Sa–Sb–Sc–Ir (Holmberg 1958, de Vaucouleurs 1959b, 1963) strongly suggests that the Hubble sequence is a manifestation of a deep linkage between the evolution and morphology of galaxies. In recognition of theoretical speculations that have long been forgotten, galaxies of types E and Sa are referred to as 'early' and those of types Sc–Ir as 'late'. Over the past 70 years the Hubble classification system has proved to be enormously useful. However, one of the few major failings of the Hubble paradigm is that it has not yet been possible to incorporate S0 galaxies in an entirely satisfactory fashion. Early proposals to place the S0 type at the intersection between E, Sa and SBa galaxies (Hubble 1936, Sandage 1961, 1975) have not proved to be entirely convincing because S0 galaxies are typically less luminous than either E or Sa galaxies. It is, however, quite possible that there exists a sub-class of S0 galaxies that are truly intermediate between ellipticals and spirals. Furthermore it appears that galaxies may approach the S0 morphology from differing initial states by moving along quite different evolutionary paths (van den Bergh 1990). On balance, it now seems more likely that the apparent chasm between elliptical and spiral galaxies might, at least in part, be bridged by disk-like structures that exist within some ellipticals (Kormendy & Bender 1996).

1.2 Galaxy types that do not fit into the Hubble scheme

In 1936 it was believed that the 'tuning fork' scheme described in Hubble's (1936) influential book *The Realm of the Nebulae* provided a complete framework for the morphological classification of normal galaxies. However, the discovery of the Sculptor and Fornax dwarf spheroidal galaxies by Shapley (1938, 1939) provided the first hint that the Hubble tuning fork diagram did not give an exhaustive description of the entire realm of galaxy morphology. The relation between the elliptical (E) and dwarf spheroidal (dSph) classes of galaxies has remained a subject of lively controversy (Jerjen & Binggeli 1997). Kormendy (1985) and Wirth & Gallagher (1984) regarded dwarf and giant ellipticals as physically distinct classes of objects, whereas Bingelli, Sandage & Tarenghi (1984) emphasized the continuity between the characteristics of giant and dwarf ellipticals. However, Kormendy (1987b) argues that the effects of seeing on ground-based observations of objects in the distant Virgo cluster may have blurred the distinction between elliptical and dwarf spheroidal galaxies. Gorgas *et al.* (1997) have found some evidence which suggests that the Mg/Fe ratio in the brightest (dwarf) spheroidal galaxies in the Virgo cluster is near solar. In this respect these spheroidal galaxies therefore resemble the disks of galaxies from S0 to Sc which have solar Mg/Fe ratios (Sil'chenko 1993), whereas ellipticals have high Mg/Fe values. This difference suggests that either (1) star formation started with a bang in E galaxies, but proceeded more slowly in the disks of S0–Sc galaxies, or (2) the mass spectrum with which stars were formed in ellipticals contained a larger fraction of massive objects that produced supernovae of Types Ibc and II on a short time-scale.

The class of cD galaxies identified by Morgan provides another example of a classification type that does not fit comfortably into the 1936 Hubble scheme. The fact that most cD galaxies only occur close to the centers of rich clusters of galaxies shows that galaxy morphology, and hence galaxy evolution, may be strongly affected by environment. Another class of objects that does not appear to fit naturally within the Hubble scheme is the amorphous (Am) galaxies (Sandage & Brucato 1979, Gallagher & Hunter 1987), some of which have also been called Ir II by Holmberg (1958). A complication is that galaxies such as NGC 3034 (= M82) and NGC 3077 probably started out as objects of quite different morphological types that subsequently evolved into Am galaxies by tidal capture of large amounts of gas. Furthermore the morphological peculiarity of some galaxies is, no doubt, due to the recent tidal capture of companions. Good examples are NGC 2685 (which Sandage (1961) refers to as 'perhaps the most peculiar galaxy in the *Shapley–Ames Catalog*') and NGC 5128 = Centaurus A. Surprisingly, Hubble did not extend his 'tuning fork' diagram to include irregular galaxies, even though such objects exhibit the same dichotomy that is observed among spirals. The Small Magellanic Cloud is, for example, a normal irregular whereas the Large Magellanic Cloud is a barred irregular. Also Hubble never gave an objective criterion for distinguishing very late-type spirals from irregulars. Another weakness of the Hubble system is that its classification of elliptical galaxies along the sequence E0–E7 is a function of both the intrinsic shape of these objects *and* the direction from which they are being viewed. Van den Bergh (1976b) has noted the existence of 'anemic' spiral galaxies, which appear to be spirals that have been modified by the cluster environment. Furthermore it is found that galaxies in the cores of rich clusters, such as A957 (Abraham *et al.* 1994), do not fit comfortably into the Hubble scheme, which grew mainly out of experience with classification of galaxies in the field and in small groups. Finally, observations with the *Hubble Space Telescope* show that the fraction of galaxies that fit comfortably into the Hubble system drops precipitously with increasing look-back time (Abraham *et al.* 1996a, van den Bergh *et al.* 1996).

1.3 Modifications of the Hubble scheme

Most modifications of the Hubble classification system (e.g. de Vaucouleurs 1959a, van den Bergh 1960a,b,c, Elmegreen & Elmegreen 1982) have added features to the original Hubble scheme. However, Morgan (1958, 1959a) devised a classification system that was even simpler than Hubble's original scheme. He classified galaxies mainly on the basis of their central concentration of light. This contrasts with the Hubble system which is based on *both* the central concentration of light *and* on the morphology of their spiral structure. Abraham *et al.* (1994) have shown that a one-dimensional classification system, such as that introduced by Morgan, is particularly well suited to classification of digital images by computers. Furthermore, Morgan's 'Yerkes' system avoids the conflicts that occasionally arise between the classifications based on arm morphology and those relying on central concentration of light. An example of an object where such a conflict arises is the galaxy NGC 4866 which is assigned to type Sa, even though it has a rather small core. Abraham *et al.* (1994) also find that Morgan's one-parameter classification system can be used to provide an adequate description of the morphologies of galaxies in very rich clusters. In such clusters the Hubble system provides little resolution because almost all galaxies are of types E and S0.

1.4 Some historical notes

An excellent review of the early history of the classification of spiral galaxies is given in Sandage (1975). In its most primitive form the presently used classification system goes back to Hubble (1926), who placed all spirals within the sequence Sa–Sb–Sc. Subsequently Hubble (1936) sub-divided the 'early' end of his classification sequence by splitting class Sa into S0 and Sa. Later Shapley & Paraskevopoulos (1940) recognized the need to sub-divide the Sc galaxies at the 'late' end of the classification sequence into types Sc and Sd. As a result the complete sequence became S0–Sa–Sb–Sc–Sd–Ir. A somewhat different way to classify spirals was introduced by Holmberg (1958) who sub-divided the spiral sequence into stages $Sa–Sb^{-}–Sb^{+}–Sc^{-}–Sc^{+}$. Holmberg was able to show that the classification types of galaxies correlate closely with their mean color indices $C = m_{pg} - m_{pv}$. The mean colors of galaxies (corrected for internal absorption, Galactic foreground absorption and redshift) as a function of Holmberg type are given in Table 1. Note that the mean intrinsic colors of the stellar populations change smoothly from red to blue along this classification sequence. This suggests that the mean age of the stellar populations also changes monotonically along the Hubble classification sequence. Red early-type galaxies are dominated by an old stellar population, whereas the light of blue late-type galaxies is dominated by young stars.

A somewhat different way of sub-dividing the classification of disk galaxies was proposed by de Vaucouleurs (1959a) who used the sequence Sa–Sb–Sc–Sd–Sm–Im to provide even higher resolution at the 'late' end of the Hubble classification sequence. In this notation the 'm' denotes magellanic, i.e. like the Magellanic Clouds.

Inspection of the data in Table 2 shows a smooth progression between the $B-V$ and $U-B$ colors of galaxies (corrected for Galactic absorption, to pole-on orientation, and to a redshift of 1000 km s^{-1}) and classification types according to de Vaucouleurs (1961).

Table 3 and Figure 1 show the distribution of M_B versus Hubble type (Sandage & Tammann 1981) for the galaxies in *A Revised Shapley–Ames Catalog of Bright Galaxies.* Figure 1 clearly shows that the galaxies of latest classification types in Sandage's modification of the Hubble classification system have systematically lower luminosities than do those of earlier types. In other words this classification system does not clearly distinguish between effects on galaxy morphology that are due to Hubble type, and those that result from luminosity effects. The latest type in the sequence of *giant* spirals occurs for objects such as M101 (= NGC 5457). Supergiant Ir galaxies have not been found in the nearby regions of the Universe.

The frequency distribution of galaxy types in the Shapley–Ames Catalog (Sandage & Tammann 1981, p. 91) is a function of both the intrinsic frequency of each type and the distance to which objects of that particular type are bright enough to be included in this catalog. Very late-type objects are intrinsically fainter than galaxies assigned to earlier Hubble stages. Such late-type galaxies will therefore be heavily under-represented in the

Table 1. *Mean corrected galaxy colors according to Holmberg (1958)*

	Holmberg type						
	E	Sa	Sb^-	Sb^+	Sc^-	Sc^+	Ir
$<C>_0$	0.77	0.53	0.48	0.38	0.24	0.17	0.12

Table 2. *Corrected mean galaxy colors according to de Vaucouleurs (1961)*

	de Vaucouleurs type						
	E	S0	Sa	Sb	Sbc	Sc	Sm/Im
$<B-V>_0$	0.92	0.92	0.82	0.81	0.63	0.52:	0.50
$<U-B>_0$	0.50	0.48	0.28	0.27	−0.02	−0.12	−0.20

Table 3. *Normalized frequency distribution of spiral galaxies in the Revised Shapley–Ames Catalog (Sandage & Tammann 1981)*[a]

M_B	Sa	Sab	Sb	Sbc	Sc	Scd	Sdm	Sm + Im
−23.75			0.01					
−23.25	0.01	0.03	0.02	0.04	0.01			
−22.75	0.03	0.10	0.19	0.01	0.03			
−22.25	0.13	0.10	0.12	0.12	0.05			
−21.75	0.13	0.15	0.24	0.22	0.17			
−21.25	0.29	0.21	0.13	0.29	0.16			
−20.75	0.17	0.21	0.14	0.14	0.20	0.08		
−20.25	0.16	0.21	0.07	0.10	0.15	0.15		0.10
−19.75	0.08		0.04	0.04	0.12	0.23	0.08	0.10
−19.25	0.03		0.02	0.04	0.06	0.15	0.17	
−18.75			0.01	0.01	0.03	0.23	0.17	0.10
−18.25					0.01	0.08	0.17	0.10
−17.75						0.08	0.17	
−17.25							0.08	0.20
−16.75								0.10
−16.25							0.08	0.10
−15.75								
−15.25								0.20
−14.75							0.08	

Note: [a] Due to rounding errors not all columns add up to 1.00

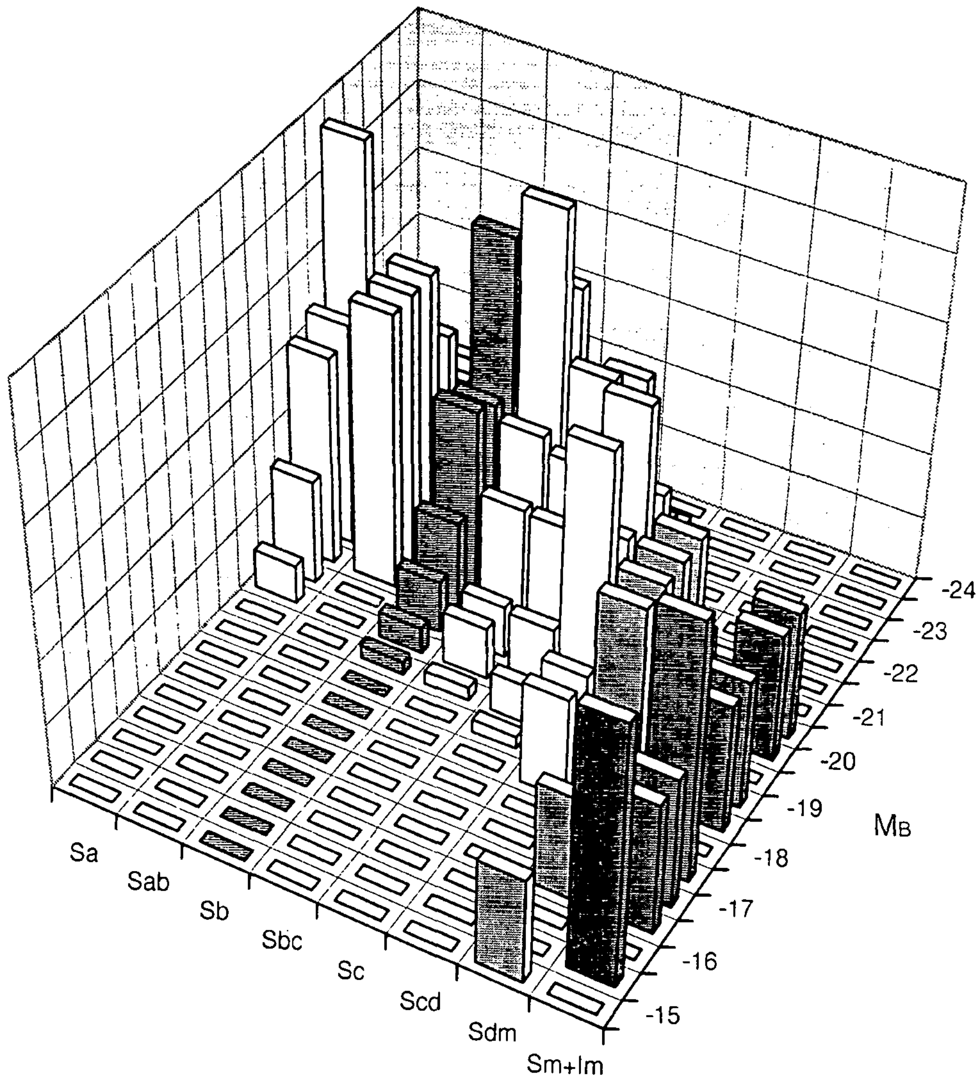

Fig. 1 Luminosity distributions for Shapley–Ames galaxies (Sandage & Tammann 1981) as a function of Hubble type. Objects of types Sd–Sm–Im are seen to be much less luminous than those with types Sa–Sb–Sc.

Shapley–Ames Catalog. On the other hand galaxies of Hubble stages Sa, Sb and Sc are seen to have very similar luminosity distributions. The relative numbers of these objects in the *Shapley–Ames Catalog* should therefore closely match their intrinsic values. Combining normal and barred varieties one finds that the ratio Sa + Sab : Sb + Sbc : Sc is 1.0 : 1.7 : 2.2. The relative numbers of spirals of different Hubble stages depends critically on luminosity, with relatively early types predominating at high luminosities. Combining normal and barred spirals one finds the following distribution among galaxies in the

Shapley-Ames catalog: For 163 bright galaxies[1] with $-23.0 < M_B \leq -22.0$ the frequency of Hubble stages is Sa–Sab (17%), Sb–Sbc (44%), Sc (17%), Scd–Im (0%), compared to Sa–Sab (0%), Sb–Sbc (4%), Sc (25%), Scd–Sm (29%) for 55 galaxies with $-19.0 < M_B < -18.0$.

1.5 Summary

The Hubble classification system provides an excellent framework for the classification of galaxies in the field and in nearby small clusters. However, it is less useful for the classification of galaxies in rich clusters and for the classification of galaxies that are viewed at large look-back times. Particular problems are:

- The evolutionary relationships between E, dE and dSph galaxies are not yet understood.
- The Hubble system does not provide criteria for objectively distinguishing between late-type spiral and irregular galaxies, nor does it provide for an unambiguous and clear-cut way of distinguishing E and S0 galaxies.
- Elliptical galaxies are classified on the basis of their *apparent* axial ratios.
- The Hubble/de Vaucouleurs/Sandage classification systems do not distinguish clearly between the effects of luminosity and of mean population age within the sequence Sc–Sd–Sm.
- The original Hubble system ignores the dichotomy between normal and barred irregulars.

[1] The symbol M_B is used here, and in the remainder of this book, to designate $M^{o,i}_{B_T}$ of Sandage & Tammann (1981).

2 The Hubble classification system

2.1 The Hubble tuning fork diagram

The Hubble classification system recognizes three form families: ellipticals (E), spirals (S) and irregulars (Ir). The ellipticals are assigned an ellipticity ϵ defined as $\epsilon = 10(a - b)/a$, in which a and b are the major and minor image diameters, respectively. Classification types for ellipticals range from E0, for objects that appear circular in projection, to E7 for the most highly flattened ellipticals. Spiral galaxies occur in two flavors – normal spirals (S), and barred spirals (SB). Within each of these there are three stages: Early-type galaxies of stage Sa/SBa have large nuclei and tightly coiled (and usually rather smooth) arms, objects in stage Sb/SBb have a more open spiral structure, and smaller central bulges. Late-type galaxies in stage Sc/SBc have small nuclear bulges and exhibit wide-open and rather patchy spiral arms. Finally, irregular galaxies have a patchy structure and exhibit no spiral arms. The original Hubble (1926) classification scheme was modified by Hubble (1936) who introduced a class of lenticular (S0) galaxies to span the chasm between spiral and elliptical galaxies (see Figure 2). The Hubble classification system is described and richly illustrated in *The Hubble Atlas of Galaxies* (Sandage 1961). Classifications for 1246 bright galaxies are given in *A Revised Shapley–Ames Catalog of Bright Galaxies* by Sandage & Tammann (1981). The Hubble/Sandage classification system reaches its ultimate form in *The Carnegie Atlas of Galaxies* (Sandage & Bedke 1994). An atlas of highly resolved late-type galaxy images, useful for measurement of the cosmological distance scale, has also been published by Sandage & Bedke (1988). It is important to note that the Hubble classification scheme for spiral galaxies is based on *both* their central concentration of light *and* on the morphology of their spiral arms.

2.2 Spiral arm morphology

Shortly after Hubble (1926) published his classification system Reynolds (1927) commented that '[Hubble's] classification of spirals seems to me to be altogether too simple for the great range of types found . . .. No classification would be complete unless development of the spiral form itself were taken into consideration'. Attempts to carry out such a more detailed classification of spiral arms were subsequently made by van den Bergh (1960a,b,c) and by Elmegreen & Elmegreen (1982, 1987).

As one progresses to later Hubble types along the sequence Sa–Sb–Sc–Sd the spiral arms become progressively patchier and more dominated by OB associations and H II

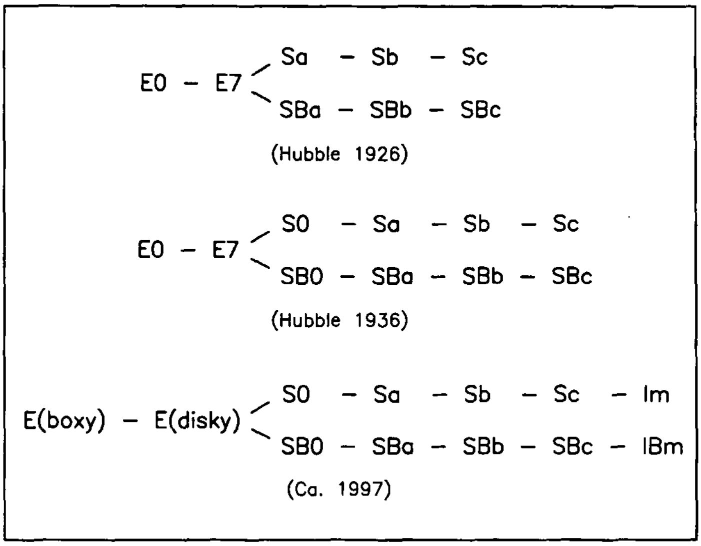

Fig. 2 Evolution of the Hubble 'tuning fork' diagram.

regions. From UBVR photometry Bresolin & Kennicutt (1997) conclude that this change in the characteristics of H II regions and associations is due to differences in the clustering properties of massive stars, rather than to a progressive change in the mass spectrum with which stars are formed.

2.3 Pitch angle of spiral arms

The pitch angle ψ of a spiral arm is defined as the angle between the tangent to the arm and the circle with r = constant. The close correlation between the pitch of spiral arms (Kennicutt 1981) and the Hubble types of their parent galaxies (Sandage & Tammann 1981) is shown in Table 4 and plotted in Figure 3. Such a correlation is, of course, expected because arm pitch angle was one of the criteria that Hubble used to determine the stage of a spiral galaxy. The entries in this table are for galaxies to which Sandage & Tammann assign $M_B < -21.0$. Less luminous galaxies tend to have a more open spiral structure. As will be pointed out in Chapter 7 no systematic differences are found between the pitch angles of normal and barred spiral galaxies of a given morphological stage. Table 4 shows that the mean pitch angle of spiral arms increases smoothly from $< \psi > = 0°$ for galaxies of type S0/a to $< \psi > = 17°$ for spirals of type Sc.

2.4 A luminosity dependent tuning fork?

Figure 2 incorporates the idea (Kormendy & Bender 1997) that elliptical galaxies might be assigned to the sequence E(boxy)–E(disky)–S0. Such an ordering of galaxies is sup-

Table 4. *Mean pitch of spiral arms*[a]

Type	ψ(°)	n
S0/Sa	0.0	1
Sa	6.7 ± 0.7	10
Sab	7.0 ± 1.1	4
Sb	12.5 ± 1.1	16
Sbc	14.4 ± 0.6	16
Sc	17.4 ± 0.9	28

Note: [a] Spirals fainter than $M_B = -21.0$ have been excluded.

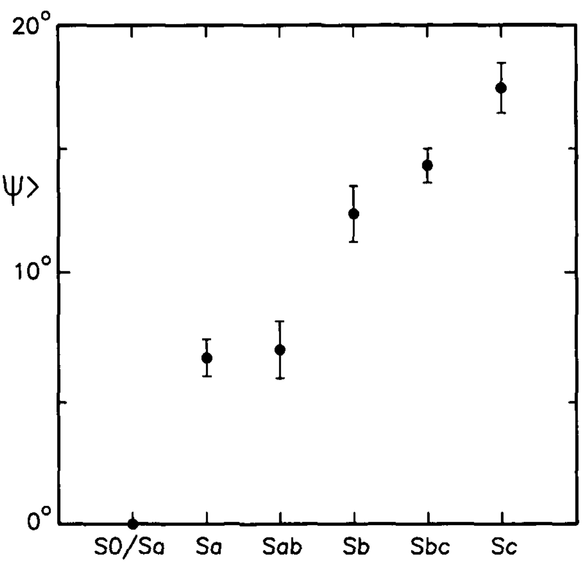

Fig. 3 Plot of mean pitch angle of spiral arms versus Hubble classification type. The figure shows that the pitch angle increases smoothly towards later Hubble types.

ported by the work of Scorza (1993) who finds continuity between the characteristics of the disks in early-type galaxies and the disks that are embedded in disky ellipticals. However, a problem with the simple scheme shown at the bottom of Figure 2 is that boxy ellipticals tend to be more luminous that disky ones (Bender *et al.* 1989).

In Chapter 5 it will be shown that the morphology of disk galaxies is strongly dependent on galaxy luminosity. Furthermore the original Hubble system was defined in terms of luminous giant and supergiant prototypes. This suggests that the Hubble tuning fork diagram might itself be a function of galaxy luminosity. A very tentative proposal for a three-dimensional tuning fork diagram, in which galaxy luminosity constitutes the third dimension is shown in Figure 4. In this figure the notation E/S0/dSph is used to indicate that the interrelation between these three types of objects is not yet clearly understood.

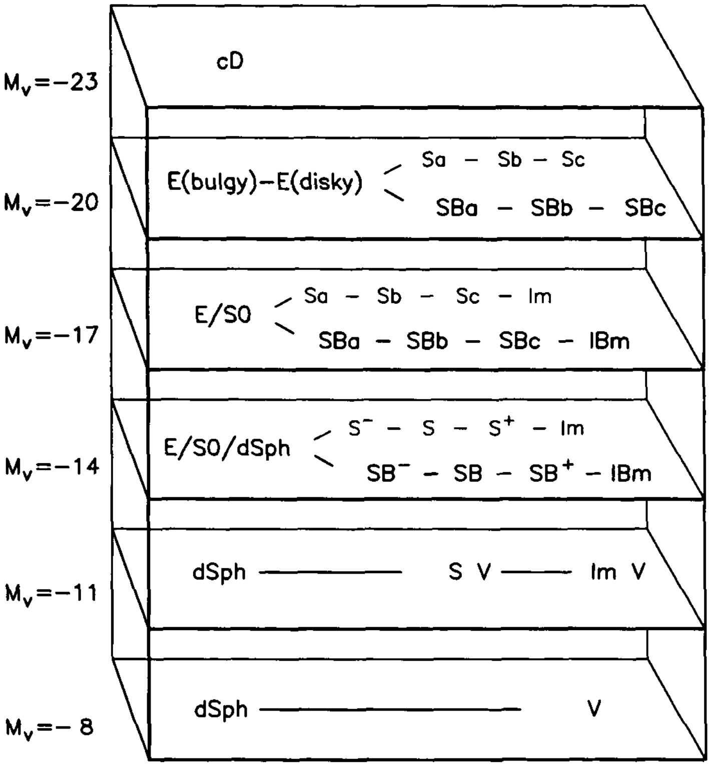

Fig. 4 Tentative proposal for a three-dimensional tuning fork diagram.

2.5 Summary

Three lines of evidence suggest that the version of the Hubble tuning fork diagram illustrated in Figure 2 may be somewhat misleading:

- In Chapters 9 and 10 it will be shown that S0 galaxies are, in the mean, fainter than either E or Sa galaxies. This makes it unlikely that all lenticular galaxies are physically intermediate between ellipticals and spirals.
- Late-type barred spirals are less luminous than ordinary spirals of the same Hubble stage (see Chapter 7).
- Boxy ellipticals tend to be more luminous than disky ones.

3 De Vaucouleurs' system

3.1 Description of the system

In an attempt to accommodate the entire range of morphological characteristics of galaxies de Vaucouleurs (1959a) introduced a three-dimensional classification scheme which is illustrated in Figure 5. The main axis of this classification system is the sequence E–S0–Sa–Sb–Sc–Sd–Sm–Im, where the index m refers to magellanic, i.e. resembling the Magellanic clouds. Finer sub-divisions may be provided by distinguishing between E, E^+, $S0^-$, S0, and $S0^+$, in which the minus superscript denotes early (= smooth) and the plus superscript indicates late (= patchy). In Figure 5 the second dimension is, as in the Hubble tuning fork diagram, provided by differentiating between galaxies with no bars (SA), those with weak bars (SAB) and those with strong bars (SB). Finally a third dimension is provided by distinguishing between objects that exhibit rings *r*, intermediate features *rs* and pure spiral arms *s*. De Vaucouleurs (1959a) notes that the distinction between his A and B families and between his *r* and *s* varieties is most clearly marked at the transition stage S0/a and vanishes between E and S0, and between Sm and Im. The position of a galaxy along the main axis from E to Im in Figure 5 correlates strongly with integrated color, and hence with the mean age of the stellar population. The A and B families do not differ systematically in color and hence, presumably, contain populations of comparable ages. However, as will be noted in Chapter 7, there is a systematic difference between the luminosity distributions of late-type barred and ordinary spirals. At a given Hubble stage there appear to be no systematic luminosity differences between galaxies of the *r* and *s* varieties. The *r* and *s* varieties occur with comparable frequencies among early-type spirals. However, objects of the *s* variety vastly outnumber those of the *r* variety in late-type spirals.

A problem with the classification scheme proposed by de Vaucouleurs is (see Table 3 and Figure 1) that galaxies simultaneously become fainter and bluer along the sequence Sc–Sd–Sm, i.e. luminosity effects are intertwined with evolutionary effects.

3.2 De Vaucouleurs' T system

The main axis of de Vaucouleur's classification system, which extends from E to Im, may be represented by his *T* parameter. This parameter (de Vaucouleurs, de Vaucouleurs & Corwin 1976) is defined in Table 5. The *T* values of galaxies correlate strongly with their

Table 5. *Relation between Hubble, de Vaucouleurs, and T types*

Hubble	E	E/S0	S0	S0/a	Sa	Sa-b	Sb	Sb-c	Sc	Sc-Ir	Ir
de Vaucouleurs	E	L^-	L	S0/a	Sa	Sab	Sb	Sbc	Scd	Sdm	Im
T	−5	−3	−2	0	1	2	3	4	6	8	10

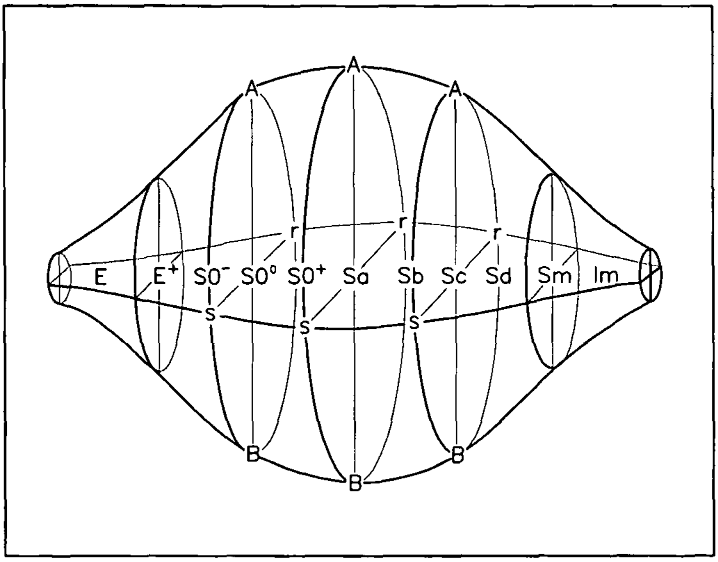

Fig. 5 Schematic representation of the de Vaucouleurs classification system. In this scheme the primary classification parameter is the Hubble stage E–Im. The second parameter relates to the presence (SB) or absence (SA) of a bar. The third distinguishes between ring (*r*) and spiral (*s*) varieties. The second and third parameter effects are largest near Hubble stage Sa.

integrated colors. As noted above a problem is that the effects of type and luminosity are intertwined for galaxies with $T > 6$.

3.3 Summary

De Vaucouleurs' system provides three parameters to describe the morphology of galaxies: (1) position along the main axis E–Im, (2) position along the sequence SA–SAB–SB, and (3) assignment to the ring (*r*), spiral (*s*) and mixed (*rs*) flavors.

- The fact that the integrated colors of SA and SB galaxies of a given Hubble stage do not differ significantly suggests that the dichotomy between normal and barred spirals may not be based on profound physical differences that directly affect their stellar populations.

- It appears that the *r* and *s* dichotomy represents only an ephemeral change in morphology, which is possibly due to differences in density wave pattern speed.
- A problem with de Vaucouleurs' scheme is that galaxies simultaneously become fainter and bluer along the sequence Sc–Sd–Sm, i.e. luminosity effects and evolutionary effects are projected onto a single classification parameter.

4 Elmegreen's classification of spiral arms

4.1 Observations of spiral arm types

From inspection of photographs of spiral galaxies Reynolds (1925) noted that some galaxies had 'massive' arms, whereas others exhibited 'filamentous' spiral structure. Another early attempt to classify galaxies on the basis of arm morphology was made by Danver (1942). More recently Elmegreen & Elmegreen (1982, 1987) have devised a twelve-stage classification system for spiral arms. These classifications range from Type 1 'flocculent' arms, which are ragged, patchy, or chaotic to Type 12 'grand design' arms, which are long, symmetrical, sharply defined, and dominate the appearance of the spiral galaxy in which they occur. After excluding barred spirals Elmegreen & Elmegreen (1982) find that 32 $\pm$ 10% of isolated objects exhibit well-developed spiral structure, compared to 67 $\pm$ 6% of members of binary pairs or groups. These results show that the formation of 'grand design' spiral structure is strongly favored by tidal interactions. Not unexpectedly Elmegreen & Elmegreen find a significant correlation between their spiral arm classification types and the luminosity classes of van den Bergh (1960a,b,c). Galaxies with patchy, fragmentary arms of Type 1 are all of low luminosity, whereas spirals with grand design spiral arms of Type 12 are, without exception, objects of high luminosity. The fact that spirals with very late Hubble types (Sd, Sdm, Sm) all have chaotic fragmentary arms of Types 1 and 2 is, no doubt, due to the low intrinsic luminosities of many very late-type spirals. These results strongly suggest that Elmegreen & Elmegreen's galactic arm morphology differences are produced by effects that depend on *both* galaxy luminosity *and* some other factor. Table 6 shows the frequency distribution of Elmegreen & Elmegreen (1982) spiral arm type classifications versus the Hubble stages from Sandage & Tammann (1981). Over the Hubble type range Sa–Sc the table shows no obvious relationship between arm type and parent galaxy Hubble stage. In particular, a Kolmogorov–Smirnov test shows no significant difference between the frequency of different arm types among spirals of Hubble stages Sa and Sc. In other words *Hubble stage and arm type appear to be unrelated (and hence orthogonal) classification parameters over the range Sa–Sb–Sc.* Thornley (1996) has noted that a small number of flocculent spirals exhibit 'grand design' spiral arms in K′ (2.1 μm) images. Kormendy (1982, p. 142) suspects that flocculent spirals contain fewer massive young stars than do 'grand design' spiral arms produced by density waves.

Fourier analysis (Elmegreen, Elmegreen & Montenegro 1992) shows that many galaxies exhibit an $m = 3$ component in addition to the $m = 2$ component that is so dominant

Table 6. *Elmegreen's arm classification versus parent galaxy type*

Type	Sa	Sab	Sb	Sbc	Sc
1–3	1	1	4	1	1
4–6	4	2	6	1	6
7–9	1	1	5	11	25
10–12	3	1	3	4	4

in most two-arm spirals. A good example of a spiral with a strong $m = 3$ component is NGC 4254, which is shown as panel [224] of *The Carnegie Atlas of Galaxies* by Sandage & Bedke (1994). Elmegreen *et al.* point out that galaxies such as NGC 3031 (= M81) and NGC 5194 (= M51), which appear to have been exposed to tidal forces recently, exhibit particularly weak $m = 3$ components. Another fine example of a spiral with particularly well-developed arms that appears to have suffered a recent tidal interaction, is NGC 5364. This object is shown in Figure 6. The companion to the peculiar Sb^+ I spiral NGC 5364 is the $S0_3$ galaxy NGC 5363. This unusually dusty S0 might have picked up gas and dust

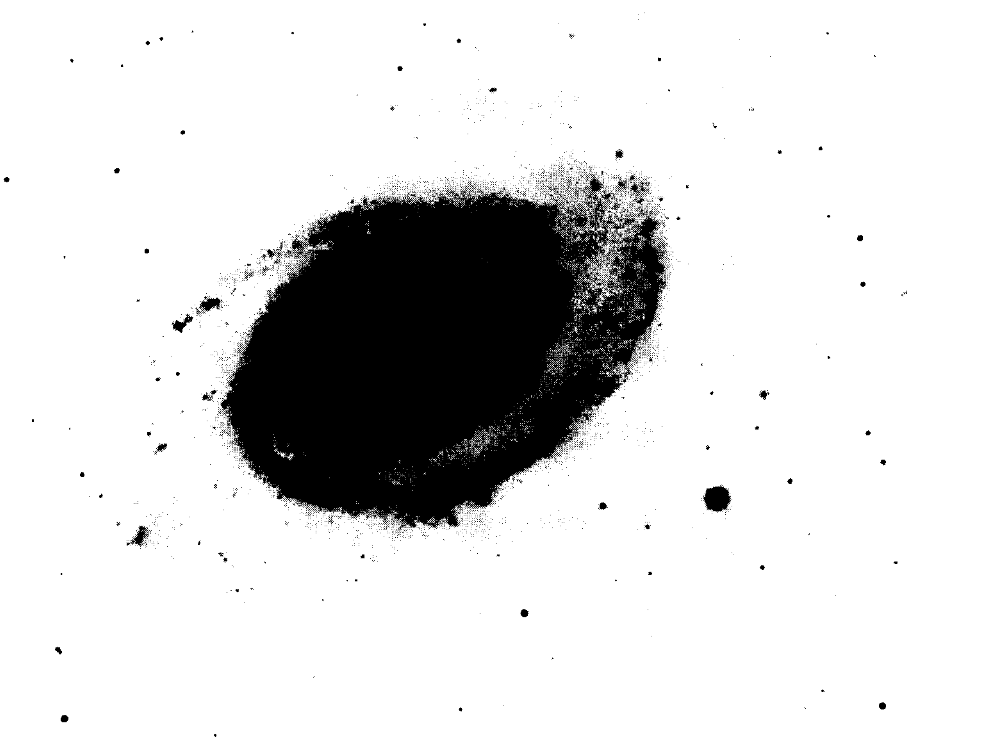

Fig. 6 The late Sb spiral NGC 5364 from a blue (IIIaJ + GG385) 4-m Mayall telescope plate. The particularly well-developed spiral arms of this object may have been enhanced by a recent encounter with the $S0_3$ galaxy NGC 5363.

during a close tidal encounter with NGC 5364. Holmberg (1958) assigned NGC 5363 to his Ir II class, which comprises non-magellanic irregular galaxies. A second close physical companion to NGC 5364 is NGC 5360, which according to Krienke & Hodge (1974), is also an Ir II galaxy. In this respect the NGC 5364 group resembles the M81 group which also contains two Ir II galaxies: M82 (= NGC 3034) and NGC 3077. Krienke & Hodge divide the Ir II class into 'dusty' and 'explosive' sub-groups. The proto-type of the dusty sub-group of Ir II galaxies is NGC 5195, which is the companion of the Whirlpool nebula M51 (= NGC 5194). Among the explosive sub-type of Ir II galaxies Krienke & Hodge recognize three sub-classes: (1) E/S0-like [NGC 3077], (2) spiral-like [M82 = NGC 3034] and (3) tidally interacting [NGC 520].

Reshetnikov & Combes (1996) find that the mean ratio of scale-height z_0 to radial scale-length r_0 is about twice as large in interacting edge-on galaxies as it is in isolated objects. This clearly shows that galaxy interactions can thicken stellar disks. Since the H I gas layer in spiral galaxies is usually thinner than the stellar disk one expects star formation eventually (i.e. over a period of a few Gyr) to reduce the ratio of vertical scale-height to radial scale-length.

4.2 Theory of spiral arms

Lin & Shu (1964) first showed that spiral structure in galactic disks can be explained in terms of density waves that rotate with a pattern speed which is slower than the rotation speed of the underlying galaxy. The formation of such density waves can be triggered by gravitational perturbations, such as those produced by an orbiting companion or a central bar. Interstellar gas in the disk of a galaxy will be strongly compressed by the slight density variations of the stellar spiral structure. This is so because the gas flow relative to the spiral arms is supersonic. This compression produces small-scale gravitational instabilities that can lead to a high rate of star formation.

Additional theoretical insight into problems of spiral arm formation was provided by Roberts, Roberts & Shu (1975). These authors found that the morphology of spiral structure can be understood in terms of two fundamental galactic parameters: (1) the total mass of a galaxy divided by a characteristic dimension, and (2) the degree of mass concentration toward the galactic center. They showed that these two parameters determine both the strength of galactic shocks in the interstellar gas, and the geometry of the spiral wave pattern. In other words one would expect the morphology of isolated galaxies to be determined by (1) their total mass, and (2) by their central mass concentration. These parameters are closely correlated with total luminosity and Yerkes concentration class. On the picture proposed by Roberts *et al.* (1975) galaxies of Yerkes class *k*, which have a high central concentration of light, are expected to show a tightly coiled spiral pattern with small pitch angles. Conversely one would predict objects of low central concentration, which are assigned to Yerkes class *a*, to exhibit wide-open spiral structure and large pitch angles. Wakamatsu (1976) has also found that the centrifugal force at the peak of the rotation curve, which is proportional to V_{max}^2/R_{max}, increases with a rising bulge/disk luminosity ratio. Kormendy & Norman (1979) show that global spiral patterns are either maintained by nearly solid-body rotation throughout the region which exhibit the spiral pattern, or they are driven by a bar or a nearby companion.

Strom (1980) has emphasized that the critical parameter determining the degree of compression of gas in a spiral arm is W_n, the velocity of the gas normal to the spiral arm. If $W_n \gg a$, in which a is the acoustic speed (which is typically ~ 8 km s^{-1}), then star formation should proceed vigorously along the arm. For $W_n \lesssim a$ the compression is weak and the pattern of star formation is expected to be ill defined. Under such conditions (Gerola & Seiden 1978) flocculent spiral arms might be produced by self-propagating star formation.

4.3 Dwarf spirals

As one proceeds to disk systems of ever lower luminosity the compression in spiral arms will eventually become so low that spiral structure is no longer generated. One therefore expects the fraction of all disk systems that are spirals to shrink with decreasing luminosity (mass). This expectation is confirmed by the data on Shapley–Ames galaxies in Table 3 and Figure 1 which show that most disk galaxies brighter than $M_B = -17.5$ are spirals of types Sa–Scd, whereas those fainter than this are mainly of types Sm and Im. From the survey of dwarf galaxies on the Palomar Sky Survey (van den Bergh (1966) and Table 7) one finds that this trend continues towards fainter luminosities. In van den Bergh's luminosity class IV–V spirals and irregulars occur with equal frequency, whereas in luminosity class V irregulars out-number spirals by almost two to one. The claim by Schombert *et al.* (1995) to have discovered dwarf spirals is spurious, since such galaxies were first mentioned by Reaves (1956) and constitute about half of the objects listed in the catalogs of dwarf galaxies by van den Bergh (1959, 1966). Furthermore Baade (1963, p. 225) concluded that NGC 2366, which has $M_B = -16.7$, was 'probably not an irregular but an Sc'. In any case the six objects discussed by Schombert *et al.* have $-17.0 < M_V < -16.0$ which, strictly speaking, makes them sub-giants (luminosity class IV) rather than dwarfs (luminosity class V). The galaxies discussed by Schombert *et al.* (1995) have moderately dense core regions. In this respect they do not differ from some of the S/SB IV galaxies in the field (van den Bergh 1960c) and in the Virgo region (van den Bergh, Pierce & Tully 1990).

4.4 Pitch angles of spiral arms

Figure 7 shows a plot of the pitch angle ψ (Kennicutt 1981) of spiral galaxies in *A Revised Shapley–Ames Catalog of Bright Galaxies* (Sandage & Tammann 1981) versus their central concentration of light (Morgan 1959a). (Pitch angles published by Danver (1942) were *not* used because of evidence (Kennicutt 1981) which suggests that he erred in connecting unrelated arm segments into single arms). Figure 7 shows a loose correlation, in the sense that the most centrally concentrated spirals have the most tightly coiled spiral structure. Figure 8 shows a plot of pitch angle ψ versus absolute magnitude M_B (taken from Sandage & Tammann 1981) for spirals with Morgan (1959a) concentration classes

Table 7. *Apparent frequency of low-luminosity galaxies*[a]

Luminosity class	Spiral	Irregular
IV–V	27	27
V	38	64

[a] From van den Bergh (1966).

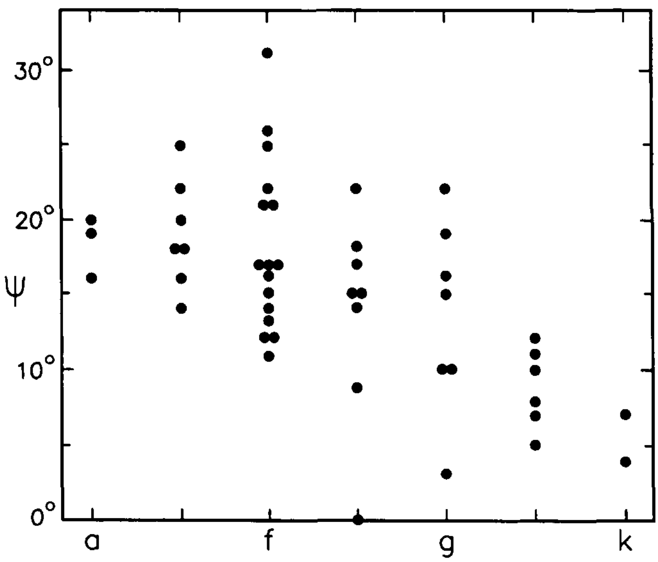

Fig. 7 Pitch angle ψ of spiral galaxies versus Morgan concentration class. The figure shows that galaxies with a low central concentration of light tend to have the most open spiral structure.

a–af–f. This plot shows a correlation between the spiral arm pitch angle ψ and galaxy luminosity in the sense that the least-luminous spirals have the most open spiral structure. This implies that part of the scatter between ψ and galaxy concentration class that is seen in Figure 1 was introduced by the luminosity (mass) dispersion among spiral galaxies. This conclusion is confirmed by Kennicutt & Hodge (1982) who find a strong correlation between the rotational velocities of spirals and the pitch angles of their spiral arms. This correlation is in the sense that slowly rotating (low-mass) galaxies have spiral arms that exhibit the largest pitch angles.

4.5 Summary

- The Hubble classification system does not capture the differences between 'flocculent' and 'grand design' spiral arms that have been noted by the Elmegreens and others.

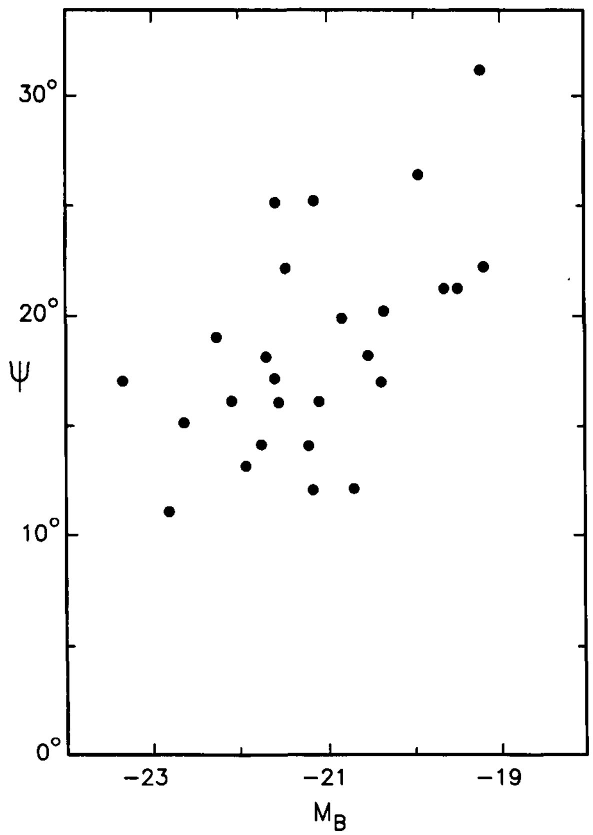

Fig. 8 Pitch angle ψ of arms versus luminosity for spirals of Morgan central concentration classes *a*, *af* and *f* versus M_B. This figure shows that the least-luminous objects have the most open spiral structure. This dependence of the pitch angle of spiral arms on luminosity (and hence on mass) contributes to the scatter seen in Figure 7.

- Over the range Sa–Sc no correlation is found between arm type and Hubble stage, i.e. arm type and Hubble stage appear to be independent classification parameters.
- The fraction of all galaxies that are spirals drops, and the fraction that are irregulars increases, with decreasing luminosity.
- Quickly-rotating and centrally condensed spirals are found to have the most tightly coiled arms.
- The Fourier $m = 2$ component is particularly pronounced in those galaxies in which spiral structure appears to have been stimulated by a recent tidal encounter.
- Most dusty Ir II galaxies (non-magellanic irregulars) probably result from galaxy collisions. Sub-types of Ir II are due to (1) gas and dust collection by E/S0 galaxies, (2) gas and dust collection by spiral galaxies, and (3) partial disruption of disk galaxies resulting from strong tidal interactions.

5 Van den Bergh's classification of galaxies

5.1 Luminosity effects on morphology

From a study of galaxies in the Virgo cluster Holmberg (1958, p. 69) noted that giant galaxies have a higher surface brightness than dwarfs. When the prints of the Palomar Sky Survey first became available in the late 1950s it was immediately obvious that this large, and very uniform, database of galaxy images enabled one to segregate low-luminosity dwarfs from the much more numerous galaxies of average luminosity. Based on inspection of the prints of the *Palomar Sky Survey*, van den Bergh (1959, 1966) was able to compile catalogs of 243 DDO dwarf galaxies north of $\delta = -27°$. The entries in these catalogs showed that the distribution of such dwarfs on the sky is broadly similar to that of nearby giant galaxies. This conclusion was confirmed for Virgo dwarfs by Reaves (1956, 1967). Furthermore, observations in the Local Group clearly show that dwarfs cluster around giants. Van den Bergh's data also showed that (1) the fraction of all galaxies classified as irregular increases dramatically with decreasing luminosity, and (2) the fraction of all spirals that are barred is much lower among giants than it is among dwarfs. In a subsequent study van den Bergh (1960a,b,c) was able to show that both the surface brightnesses of spiral galaxies and their morphologies are functions of luminosity. Supergiant spirals were found to have long and well-developed 'grand design' spiral arms, whereas low-luminosity spirals tend to have poorly developed 'scraggily' spiral arms.

5.2 The David Dunlap Observatory (DDO) system

By analogy with the system of stellar luminosity classification (Johnson & Morgan 1953) spiral galaxies were assigned to luminosity classes I (supergiants), II (bright giants), III (giants), IV (sub-giants) and V (dwarfs). Perhaps because the fraction of all galaxies that are irregular drops precipitously with increasing luminosity, there are no nearby examples of irregular galaxies of luminosity classes I and II. In actual practice, classifications of galaxies are made by comparisons with the standards illustrated in van den Bergh (1960a,b). The DDO luminosity classification system can be regarded as being defined by the classifications of northern Shapley–Ames galaxies listed in van den Bergh (1960c). The primary luminosity standards of the DDO system are listed below. Numbers in square brackets refer to the panel on which this object is shown in *The Carnegie Atlas of Galaxies* (Sandage & Bedke 1994):

Sb^- I	NGC 2841 [142]	Sb^+ I	NGC 5371 [126]	Sc I	NGC 4321 [213]
Sb^- II	NGC 3675 [139]	Sb^+ II	NGC 5055 [191]	Sc II	NGC 3184 [237]
Sb^- III	NGC 4064 [313]	Sb^+ III	NGC 4586 [76]	Sc III	NGC 2403 [273]
S^- IV	NGC 247 [285]				
S^- IV-V	NGC 45 [314]				
S V	DDO 122 [......]				

The Hubble stage assignments Sa, Sab, Sb, Sbc and Sc are only applicable to giant, bright giant and supergiant spirals. (Shapley's classification stage Sd was not used in the DDO classification system.) For sub-giants it is only possible to assign types S^- (early), S (intermediate) and S^+ (late) in which 'early' denotes spirals with a smooth structure and 'late' refers to highly resolved objects. Finally in class V no differentiation between early and late sub-types is possible. On the prints of the *Palomar Sky Survey* it is not even possible to distinguish spirals and irregulars among the least luminous objects of luminosity class V (van den Bergh 1966). A schematic diagram showing the distribution of galaxy classification types in a color-magnitude diagram is shown in Figure 9. This figure shows the following: (1) For the objects with the lowest luminosities ($M_V > -14$) one can only distinguish between (*a*) inactive dwarfs, such as the Ursa Minor dwarf spheroidal (dSph) system, (*b*) dwarfs exhibiting a low level of star forming activity like the dSph/dIr Phoenix system, and (*c*) active dwarfs, such as the dIr galaxy DDO 210. Among the inactive dwarfs there are some (Draco) that only contain very old stars, whereas others (Carina) were still forming some stars only a few Gyr ago. (2) At intermediate luminosities ($M_V \sim -16$) there are objects like (a) M32 (E2) which exhibit no present star formation activity, (b) NGC 205 (S0/E5 pec) that contain a relatively small fraction of recently formed stars, and (c) the Small Magellanic Cloud (Ir IV-V) which is presently in an active phase of star formation in which the integrated light is dominated by young stars. (3) The vast majority of luminous galaxies with $M_V < -19$ outside of rich clusters fit comfortably into the E, Sa, Sb and Sc classes defined by Hubble (1926,1936). This is so because Hubble's classification scheme was almost entirely defined by supergiant standards.

In the DDO system intermediate luminosity classes I–II, II–III, III–IV and IV–V are also recognized. It should, however, be noted that the intrinsic errors of classification, which are of order 0.4–0.7 mag, are such that the distinction between say II and II–III may not always be physically significant. The matrix of DDO types is shown in Table 8. A luminosity classification system very similar to that given above was adopted by Sandage and Tammann (1981). In the DDO system the presence of a strong bar is indicated by a B, and that of a weak bar by (B). The DDO types S, S(B) and SB correspond to the types SA, SAB and SB, respectively, of de Vaucouleurs (1959a). Patchy arms are denoted by * and smooth arms by *n*. Extreme cases of smooth armed objects are called 'anemic' by van den Bergh (1976b). For example, a galaxy of DDO type S(B)c* I is a supergiant of stage Sc exhibiting a mild bar-like structure and patchy spiral arms. On the other hand a galaxy of type Sb*n* III is a pure spiral giant of Hubble stage Sb that exhibits smooth spiral arms. Tidal distortions are indicated by a *t*. Extreme cases of the *, *n* and *t* phenomena are denoted by **, *nn* and *t*!

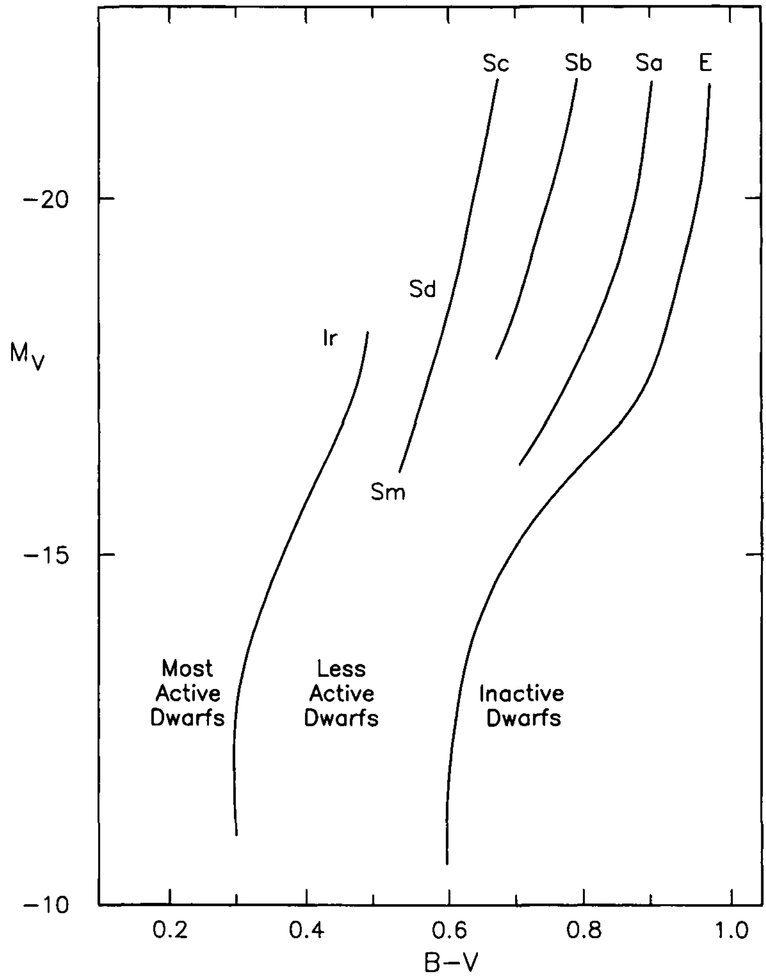

Fig. 9 Schematic color–magnitude diagram for galaxies. Hubble types E, Sa, Sb, Sc dominate the region with M_V brighter than —19. Fainter than $M_V = -14$ one can only distinguish between very active, less active and inactive dwarfs. Note that the line Sc–Sd–Sm represents a sequence of decreasing luminosity.

It should, perhaps, be emphasized that the DDO classification system is based on inspection of images of galaxies in *blue* light. If the red image of a spiral were to be mistaken for a blue one the DDO luminosity classification might be underestimated by up to one luminosity class. This is so because the blue stars that outline spiral arms are more easily seen on blue images than they are on images obtained in red light. Spiral structure is particularly prominent in images of galaxies taken in the light of Hα. It would be interesting to establish a system of luminosity classification for spiral galaxies based entirely on Hα images. However, no sufficiently large and homogeneous database is presently available to undertake such an investigation.

Table 8. *Classification types in the DDO system.*

Sa I	Sab I	Sb I	Sbc I	Sc I	
Sa I–II	Sab I–II	Sb I–II	Sbc I–II	Sc I–II	
Sa II	Sab II	Sb II	Sbc II	Sc II	
Sa II–III	Sab II–III	Sb II–III	Sbc II–III	Sc II–III	Ir II–III
Sa III	Sab III	Sb III	Sbc III	Sc III	Ir III
Sa III–IV		Sb III–IV		Sc III–IV	Ir III–IV
	S^- IV	S IV	S^+ IV		Ir IV
	S^- IV–V	S IV–V	S^+ IV–V		Ir IV–V
	S V				Ir V
			V		

5.3 **Difference between spirals and irregulars**

In the literature there is some confusion regarding the distinction between late-type spirals and irregulars. Hubble (1926, 1936) defined his morphological classification system in terms of giant and supergiant prototypes. In particular he used the bright giant NGC 4449 as the prototype for irregular galaxies. Following in Hubble's footsteps Sandage (1961) classified NGC 4449 as Ir; however, Sandage & Tammann (1981) re-assign it to type Sm. In fact, there seems to be a systematic difference between the classifications of late-type galaxies by Sandage & Tammann and by other authors. Of the 17 northern Shapley–Ames galaxies which van den Bergh (1960c) assigns to type Ir only one (6%) is classified as an irregular by Sandage & Tammann. These authors call all of the remaining 16 objects spirals. By the same token, only one (9%) of the 11 galaxies called Ir by Humason, Mayall & Sandage (1956) are classified as irregular by Sandage & Tammann (1981).

The presence of spiral structure is the primary criterion for distinguishing between late-type spirals and irregular galaxies. However, in doubtful cases (Hubble 1936, van den Bergh 1995) the most objective way to distinguish irregulars and late-type spirals is by using the presence of a nucleus as a classification criterion. Hubble (1936, p. 47) writes 'Since their [Ir galaxies] stellar contents resemble those of very late-type spirals, they are sometimes considered as representing the last stage in the sequence of regular nebulae. Their status, however, is speculative, and the absence of conspicuous nuclei may be of more fundamental significance than the absence of rotational symmetry.' However, if NGC 4449 is classified as an irregular then the apparent presence of a nucleus in that object is an anomaly. Possibly this 'nucleus' is, in fact, a more-or-less centrally located enormous H II region and star forming complex. It would clearly be of great interest to obtain very high resolution imaging and spectroscopy of the central region of NGC 4449 to throw more light on this question.

5.4 Anemic galaxies

Inspection of the prints of the *Palomar Sky Survey* (van den Bergh 1960b) showed that spiral galaxies with nebulous arms (e.g. Sbn, or in extreme cases Snn) occurred more frequently in clusters than in the general field. Subsequently (van den Bergh 1976b) it was suggested that galaxies with fuzzy arms belong to a class of 'anemic' galaxies that are frequently located in clusters, in which star formation has been suppressed by ram pressure stripping of gas (Gunn & Gott 1972). The proto-type of such anemic cluster spirals is NGC 4921 (see Figure 10), which is the brightest spiral in the Coma cluster. Another good example of this class of object is the luminous spiral NGC 3312 in the Hydra I cluster (= A1060), which is shown in panel [114] of the Carnegie atlas. A fine

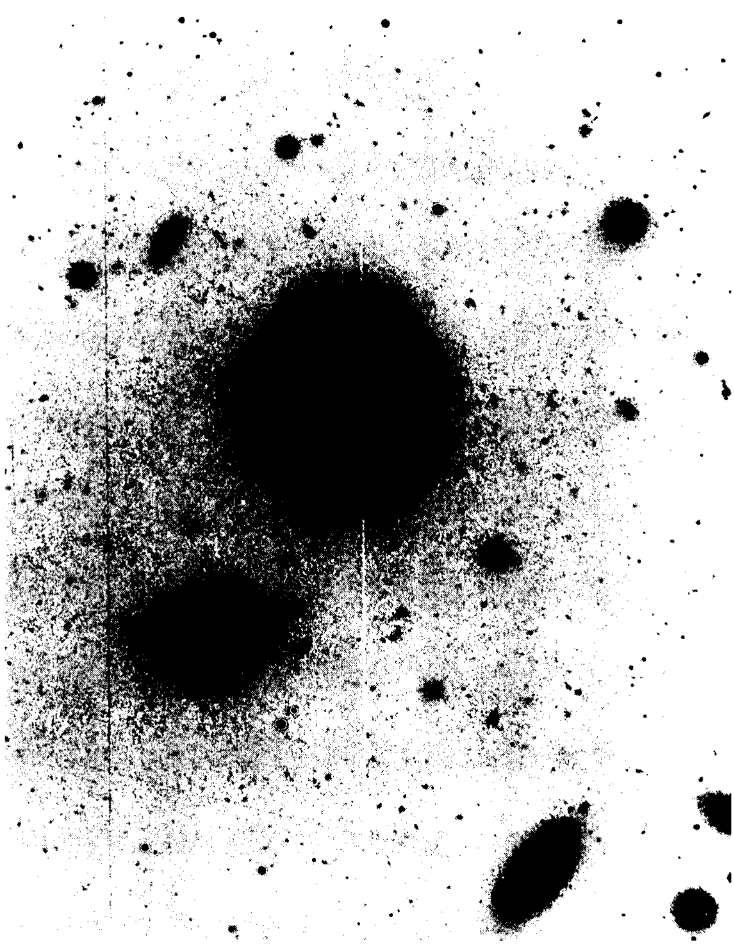

Fig. 10 Mayall 4-m telescope IIIaJ plate of the anemic galaxy NGC 4921 in the Coma cluster. This object has a classification A(B)b I on the system of van den Bergh (1976b). Note fuzzy arms and prominent dust lanes.

example of a luminous anemic galaxy is NGC 4569 (= M90) in the Virgo cluster, which is shown in the Hubble atlas and in panel [109] of the Carnegie atlas. The very prominent absorbing dust lanes seen in this class of galaxy might be due to the fact that ram pressure on the gas has lifted the dust above the equatorial plane of the stars. It is, however, somewhat puzzling that NGC 4826 (= M64), which is also illustrated in the Hubble atlas and which is shown in panel [110] of the Carnegie atlas, is a field galaxy, even though its morphological peculiarities are similar to those of the cluster spirals NGC 3312, NGC 4568 and NGC 4921. Probably the peculiar appearance of the 'black eye' galaxy NGC 4826 is due to a recent merger event which manifests itself by the presence of a counter-rotating inner disk (Braun, Walterbos & Kennicutt 1992). The observation (van Gorkom & Kotanyi 1985, Haynes & Giovanelli 1986, Cayette *et al.* 1994) that spirals in the core of the Virgo cluster are severely depleted in hydrogen strongly supports the hypothesis that ram-pressure stripping plays an important role in rich clusters.

In the late-type Virgo spiral NGC 4571, illustrated in panel [260] of the Carnegie atlas, the low gas density produced by gas stripping has resulted in an unusually low surface brightness for the outer spiral structure. (It was this low surface brightness which made it possible to discover Cepheids in this galaxy with the ground-based CFH Telescope (Pierce *et al.* 1994).) Following in the footsteps of Spitzer & Baade (1951) and Baade (1963, pp. 77–80), van den Bergh (1976b) proposed that anemic galaxies might form a sequence (see Figure 11) that is intermediate between that for normal spirals and lenticular (S0) galaxies. In other words he regarded normal spirals as gas-rich disks, anemics as gas-poor disk-like galaxies and S0 galaxies as disks from which most (or all) gas had been removed by ram pressure. Alternatively (Moore *et al.* 1996) some of the present characteristics of cluster galaxies may be due to past 'harassment' resulting from frequent high-speed tidal encounters.

In a plot of disk-to-bulge diameter ratio versus integrated color (see Figure 12) one would expect anemic galaxies, in which star formation is suppressed, to be redder than ordinary spirals but bluer than S0 galaxies. This expectation is confirmed in the case of NGC 4921, which is found to be redder than expected for its disk-to-bulge ratio (van den Bergh 1976c).

Plots of disk-to-bulge ratios for normal spirals show that the fraction of bulge light drops rapidly as one moves from early to late types along the sequence Sa–Sb–Sc–Sd–Sm. Galaxies of type Im (which contain no nuclei) also exhibit no central bulges. Kormendy (1993) has stated that 'By type Sc, I do not believe that any galaxies contain true bulges.' This hypothesis is best tested in very nearby Sc galaxies in which individual late-type stars can be observed. A review of available observations in M33 (van den Bergh 1991) shows that the existence of a small true bulge in this galaxy remains controversial.

5.5 Classification of central regions of galaxies

The DDO classification system is mainly based on the morphology of the outer regions of galaxies. Van den Bergh (1995) has made a tentative attempt to develop a complementary classification system for the inner regions of galaxies, which are often over-exposed

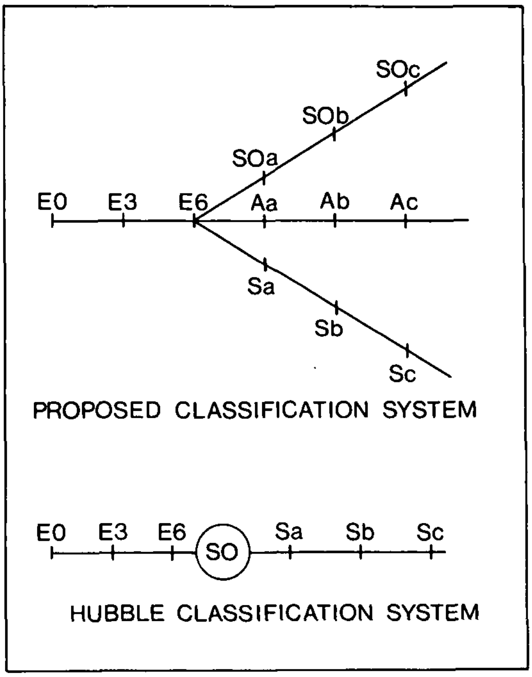

Fig. 11 Comparison between the Hubble (1936) classification system for ordinary spirals and for a system (van den Bergh 1976b,c) in which anemic galaxies are postulated to be intermediate between lenticular (S0) galaxies and ordinary spirals. The latter classification system has been called the 'trident diagram'.

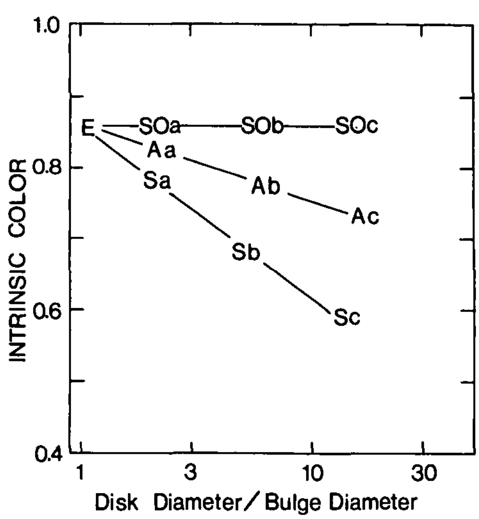

Fig. 12 Relation between intrinsic color and disk-to-bulge ratio. Since star formation in anemic galaxies is suppressed they are, at a given disk-to-bulge ratio, expected to be redder than ordinary spirals, but bluer than lenticulars.

on the prints of the *Palomar Sky Survey*. These classifications are based on inspection of the prints of intermediate- and late-type galaxies in Volume II of *The Carnegie Atlas of Galaxies* (Sandage & Bedke 1994). Most of these prints were made from plate material obtained with large reflectors. The following is a brief description of the adopted preliminary classification system for the inner regions of galaxies. (Numbers in square brackets refer to the panel number in *The Carnegie Atlas of Galaxies*)

NN (no nucleus)
Galaxy appears to contain no nucleus. The type example is NGC 2366 [327].

N (nucleus)
Object contains a star-like nucleus. Good examples are NGC 991 [245], NGC 5949 [270], NGC 6207 [274], and NGC 6508 [288].

SSN (semi-stellar nucleus)
Good examples of galaxies having semi-stellar nuclei are NGC 300 [261] and NGC 7793 [321].

CB (central bulge)
The galaxy is centered on a small bright central bulge or disk. The proto-type of this class is NGC 3726 [181]. Other good examples are NGC 1300 [154], NGC 1433 [158], NGC 2712 [165], NGC 3338 [173], NGC 4999 [159], and NGC 7038 [175]. In some cases (e.g. the Seyfert 1 galaxy NGC 4051 [180]), a semi-stellar nucleus is known to be present, but is not visible in the burned-out bulge of the image published by Sandage & Bedke (1994). In other cases (e.g. NGC 1097 [201] and NGC 2903 [226]), the bright central region appears to be produced by a disk of H II regions and young OB stars. In galaxies of types SBb and SBc, the central bulge may have a non-circular outline.

NB (nuclear bar)
In galaxies such as NGC 5112 [248], a nuclear bar-like structure is present in the galactic center. Other good examples of this type are NGC 672 [307], NGC 4116 [306], and NGC 5669 [299].

Tr (transitional)
These are objects that appear to be intermediate between spirals which have central bulges and objects with central regions that are resolved into stars and knots. Good examples are NGC 1313 [309] and NGC 4647 [278].

Van den Bergh (1995) shows that galaxies of type CB are, without exception, luminous and have Hubble type Sc or earlier. On the other hand galaxies of type NN are all intrinsically faint and have late Hubble types in the range Sc–Im. Among spheroidal galaxies (van den Bergh 1986) the fraction of objects with nuclei grows dramatically with increasing luminosity. A similar phenomenon is observed among late-type galaxies where objects with nuclei are, on average, much more luminous than those without nuclei.

5.6 Summary

- The degree to which spiral structure is developed is a strong function of galaxy luminosity. Pretty 'grand design' spirals are luminous, whereas low-luminosity spirals exhibit scraggily spiral structure.
- The Hubble stages Sa–Sb–Sc are only well defined for giant and supergiant galaxies. Among low-luminosity spirals only early and late sub-types can be distinguished.
- The distinction between very late-type spirals and magellanic irregulars should be based on whether a galaxy does, or does not, contain a nucleus.
- It would be interesting to classify spiral galaxies on the basis of their Hα images.

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- It would be interesting to classify spiral galaxies on the basis of their Hα images.

6 Morgan's classification system

6.1 Central concentration of light

The galaxy classification system proposed by Morgan (1958, 1959a), which is sometimes referred to as the Yerkes system, is a one-dimensional scheme based on central concentration of light. Morgan arranged galaxies in a sequence *a–f–g–k*, with objects of type *a* having the weakest central concentration of light and those of type *k* having the strongest central concentration. The Yerkes system also recognizes the intermediates types *af*, *fg* and *gk*. Abraham *et al.* (1996b) have shown that it is possible to measure a central concentration index *C*, determined from measurements of the intensity-weighted second-order moments of a galaxy image, which is closely related to the central concentration classification of the Yerkes system.

Galaxies with Morgan type *a* tend to have early-type (A) spectra, whereas galaxies of type *k* mostly exhibit late-type (K) integrated spectra. This linkage between morphology and spectral type shows that the dominant stellar population in centrally concentrated galaxies is old, whereas objects with a low central concentration of light tend to have a strong young population component. Probably this correlation between central concentration and integrated spectral type is largely due to the fact that regions of high gas density will usually collapse at earlier times than is the case for low density regions. This is so because the collapse time-scale $\tau \propto (G\rho)^{-1/2}$. As we shall see in Chapter 11 a puzzling exception is provided by the dwarf spheroidal galaxies, most of which are dominated by an old stellar population, even though they are of low density. Mirabel, Dottori & Lutz (1992) have attempted to overcome this conundrum by postulating that dSph galaxies condensed from tidal arms that had been torn from interacting dense massive galaxies. However, a difficulty with this suggestion (Kormendy 1990a) is that some Local Group dSph galaxies are observed to contain a large amount of dark matter (e.g. Hargraves *et al.* (1996)). Such dark matter is not expected to be stripped from the dark coronae of massive galaxies during tidal interactions (Barnes & Hernquist 1992). It is therefore concluded that the majority of dSph galaxies were probably formed individually when the Universe was still young. However, a minority of them may have condensed later from tidal arms.

6.2 Morgan's form families

In addition to the primary central concentration parameter, Morgan's classification system also recognizes the following 'form families': E (elliptical), S (spiral), B (barred spiral), I (irregular), L (low surface brightness), and N (objects with bright nuclei superposed on a considerably fainter background). Galaxies of type N might be quasars (which were not yet known in 1958), objects with active nuclei, or centrally concentrated starburst galaxies. Finally, Morgan introduced a class D comprising rotationally symmetrical galaxies without pronounced spiral or elliptical structure. Many of the galaxies that Hubble and Sandage place into the S0 class, or which de Vaucouleurs calls 'lenticulars', are assigned to the D form family by Morgan. Regarding the nature of the S0 class Baade (1963, p. 78) writes: 'In the end I think it is quite clear that, if we introduce the class S0, we should define it as the class of galaxies in which from their general form we should expect to find spiral structure, but which, contrary to our expectation, do not show it. I think that Hubble finally accepted this view.' In both the Hubble/Sandage and Morgan (1958) systems a problem arises in making the somewhat artificial distinction between ellipticals and 'systems showing rotational symmetry without pronounced spiral on elliptical structure.' Particularly sharp criticism of Morgan's D classification is presented by Kormendy (1987a) who points out that this form family is a heterogeneous combination of S0s, tidally distended Es and probably also some very luminous ellipticals that exhibit shallow outer brightness profiles. Both Morgan's D and Hubble's S0 classification types have become repositories for a rather diverse population of early-type galaxies that are (mostly) not normal ellipticals.

Morgan adds a numerical index, similar to that which Hubble used to describe the flattening of E galaxies, to each classification type. A complete Morgan classification might, for example, be *k*E6 for a highly flattened centrally concentrated elliptical, or *af*S1 for an almost face-on spiral with a low central concentration. A slight modification of the original Yerkes classification was given by Morgan (1962) in his Henry Norris Russell lecture.

6.3 cD galaxies

Matthews, Morgan & Schmidt (1964) and Morgan & Lesh (1965) have added a sub-class of particularly luminous D galaxies, which they dubbed cD, to the Yerkes classification system. (The 'c' derives from the notation used by early spectroscopists to denote narrow-lined supergiant stars.) Such cD galaxies have elliptical-like $r^{1/4}$-law cores that are surrounded by an extensive power-law luminous envelope (see Figure 13). With few possible exceptions all cD galaxies are located close to the centers of rich clusters.

Inspection of images of clusters of galaxies shows that the surface brightnesses of the luminous central cD galaxies in such clusters are dramatically lower than are those of the less luminous normal cluster ellipticals. In fact Kormendy (1980) finds that cD galaxies fall at the extreme low surface brightness (and large radius) end of the linear σ_e versus log r_e relation for elliptical galaxies, in which r_e is the effective radius within which is contained 50% of the galactic light *in projection*, and σ_e is the surface brightness at r_e. (It is noted in passing (cf. Kormendy 1982, p. 193)) that most central bulges of spirals fall below the σ_e versus r_e relation for ellipticals, i.e. bulges are, at any value of r_e, fainter than ellipticals.) Hudson & Ebeling (1996) find that the luminosities of cD galaxies are related

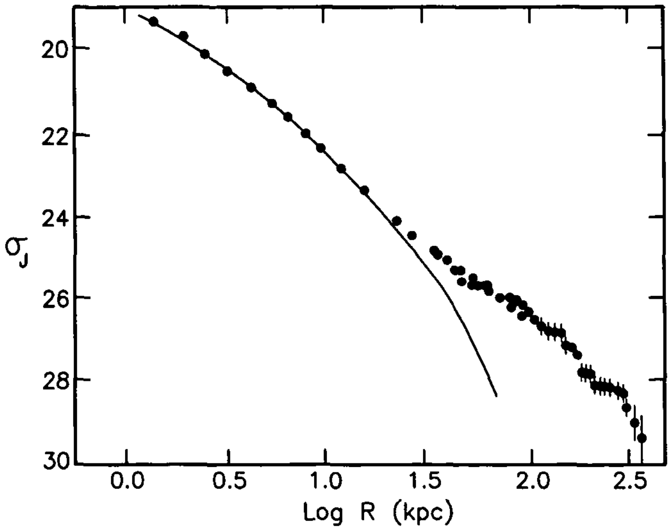

Fig. 13 Surface brightness distribution σ_J in the J-band (Oemler 1973) of the central cD galaxy in the rich cluster A2670. The smooth curve shows a schematic luminosity profile for a normal elliptical. The observed excess luminosity at large radii is diagnostic of cD galaxies.

to the x-ray luminosities/temperatures of their host clusters. This suggests that the baryonic masses of cD galaxies may depend on the depth (or structure) of their dark matter halos.

The envelopes of cD galaxies are enormous in size and rival the dimensions of their parent clusters. It might have been expected that tidal friction would have allowed some compact ellipticals (such as M32) to spiral into the low density cores of cD galaxies without being destroyed by tidal forces. The fact that such compact objects are, in fact, rare or absent in (or near) the nuclei of cD galaxies is puzzling (Faber *et al.* 1996). Possibly such compact galaxies were torn up and sliced apart by the massive black holes that are believed to be lurking in the centers of cD galaxies (Kormendy & Richstone 1995).

For a detailed discussion of various scenarios that have been proposed for the formation of cD envelopes the reader is referred to White (1982, pp. 365–75), Schombert (1988), and Kormendy & Djorgovski (1989). Schombert (1986) finds that the cluster environment is a prerequisite for the formation of cD envelopes. Furthermore he (Schombert 1988) notes that cD envelopes do not appear to exhibit strong color gradients. These observations suggest a picture in which cD envelopes represent an accumulation of tidal debris around massive ellipticals located at (or near) the dynamical centers of rich clusters of galaxies. However, such a scenario does not account for the high specific frequency of globular clusters that is observed in some (but not all) central cD galaxies in rich clusters (West *et al.* 1995). Furthermore, (Richstone 1990, Tremaine 1990) it is not yet clear if the rate of accretion of other galaxies is large enough to account for either the high luminosities of cD galaxies, or for the high frequency with which they occur near the centers of rich clusters. Merritt (1984) has pointed out that the velocity dispersion in rich clusters is so large that only galaxies that were already gravitationally bound to the central cD galaxies at the time of their formation could have merged with them. A quite different scenario for the formation of cD envelopes has been proposed by López-Cruz *et al.* (1997) who suggest that the flat luminosity functions of the faint dwarf (mainly dSph) galaxies in many cD dominated rich clusters is due to the fact that a large fraction of the cluster dwarfs were disrupted during the early stages of cluster formation. On their picture the stars from these disrupted dwarfs were re-distributed throughout the cluster potential well during violent relaxation, resulting in the formation of the extended cD envelope. In the López-Cruz *et al.* scenario the core of the central cD (and its metals!) were formed from dense merging proto-ellipticals, whereas the cD envelope was derived from disrupted dwarfs. A possible problem with this scenario is that the Coma cluster contains a central cD galaxy, even though it cannot be classified as a cluster with a flat luminosity function. However, Lobo *et al.* (1997) do find that the luminosity function of the Coma cluster may indeed contain a deficit of faint galaxies near the luminous objects NGC 4874 and NGC 4889.

6.4 **Automatic classifications on the Yerkes system**

The two principal advantages of computer-driven classifications, such as those of Abraham *et al.* (1994), are that: (1) the central concentration index C is continuous, whereas galaxies are placed in discrete bins in the Yerkes system, and (2) a computer-driven morphological classification system can be used to mass-produce galaxy classifications from digital images. A more detailed discussion of the relative advantages and disadvantages of 'hand-crafted' and mass-produced galaxy classifications will be given in Chapter 15.

Two lines of evidence show that the central concentration index C provides a very robust way to classify galaxies:

(1) Observations of galaxies in the Hubble Deep Field (e.g. van den Bergh *et al.* (1996)), which were obtained with the *Hubble Space Telescope* (HST), suggest that many spiral galaxies had not yet been assembled from their ancestral objects at large look-back times. As a result, it is often difficult to 'shoehorn' individual young galaxies into the Hubble classification scheme. Nevertheless, it is possible (Abraham *et al.* 1996a,b) to classify these objects using the A (asymmetry) and C (central concentration) parameters. It is not yet clear how the C parameter will evolve with time. However, it does seem likely that a decrease in the frequency of galaxy interactions, and dynamical evolution of individual galaxies, will result in a systematic decrease in the numerical value of the average asymmetry parameter A of galaxies with time.

(2) The Hubble classification scheme was designed to describe galaxies in our immediate neighborhood. It therefore provides a natural way to sort the galaxy types that occur among field galaxies and in small clusters. However, the Hubble classification system does *not* provide a natural framework for classifying galaxies

in the cores of very rich clusters of galaxies (Abraham *et al.* 1994). In such rich cluster environments the vast majority of galaxies belong to types E, S0 and SB0, or to types intermediate between these classifications. However, central concentration of light, i.e. Morgan's sequence *a–f–g–k*, still provides a convenient way to classify the galaxian populations in such rich clusters of galaxies.

6.5 Comparison between the Morgan and Hubble systems

Table 9 and Figure 14 show a comparison between the classifications of 463 galaxies using the Yerkes system (Morgan 1959a), and the Hubble system (Sandage & Tammann 1981). Uncertain classifications were excluded from this comparison. Inspection of the

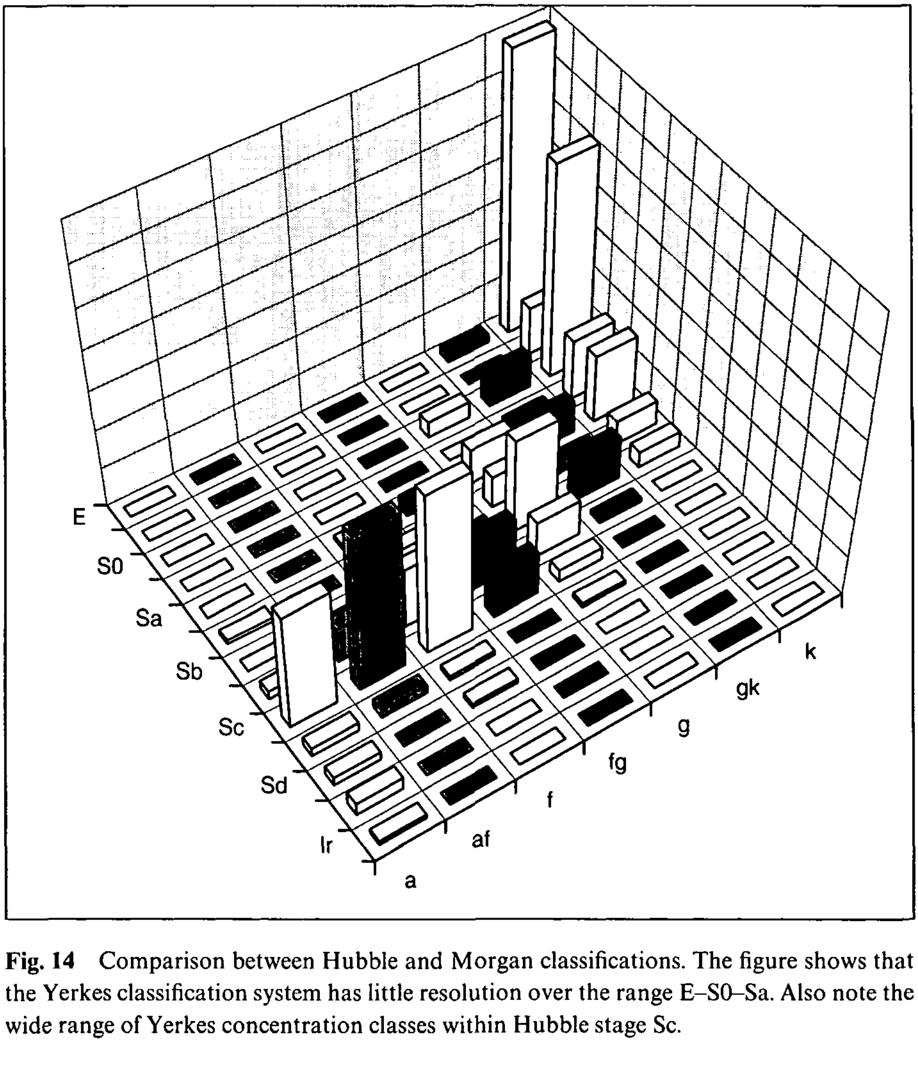

Fig. 14 Comparison between Hubble and Morgan classifications. The figure shows that the Yerkes classification system has little resolution over the range E–S0–Sa. Also note the wide range of Yerkes concentration classes within Hubble stage Sc.

Table 9. *Comparison between Morgan and Hubble classifications*

	E	E/S0	S0	S0/Sa	Sa	Sab	Sb	Sbc	Sc	Scd	Sd	Sm	Ir
k	69	12	53	15	17	6	4	0	0	0	0	0	0
gk	2	0	8	1	8	3	11	1	0	0	0	0	0
g	0	0	4	0	9	8	24	9	3	1	0	0	0
fg	0	0	0	0	3	1	5	13	11	0	0	0	0
f	0	0	0	0	1	1	11	15	41	1	1	0	0
af	0	0	0	0	0	0	0	9	40	2	0	0	0
a	0	0	0	0	0	1	0	2	29	2	2	3	1

table and figure shows that the Morgan system has little resolution for galaxies of Hubble types E, E/S0, S0 and S0/Sa; almost all of which are classified as being of type *k* by Morgan. The largest dispersion in Yerkes types is seen to occur among galaxies of Hubble type Sc. Perhaps surprisingly, no systematic luminosity difference is found between compact Sc galaxies of types *fg* and *g* and more diffuse Sc galaxies of types *a* and *af*. Furthermore, the relationship between the Hubble and Yerkes types appears to be no different for Virgo cluster galaxies than it is in the field. The most striking discrepancy between the Hubble and Morgan classifications occurs for the very peculiar Virgo cluster member NGC 4569 (= M90) which is of type Sab, yet has Morgan type *a*. A good photograph of this very peculiar object is shown in plate 13 of *The Hubble Atlas of Galaxies* (Sandage 1961) and in panel 109 of *The Carnegie Atlas of Galaxies* (Sandage & Bedke 1994).

6.6 Summary

The Yerkes system captures most of the correlation between stellar population type and Hubble stage by using central concentration of light as a classification parameter.

- The Yerkes system has the advantage that its main feature may be expressed using a single parameter that can easily be measured on CCD images.
- This central concentration parameter can be measured for galaxies located in the cores of rich clusters, and for objects located at large look-back times. Such objects are often difficult to shoehorn into the Hubble classification scheme.
- A problem with the Yerkes classification system is that the distinction between the E and D form families appears to be somewhat artificial and ill defined.

7 Galactic bars

Most spiral galaxies are, to a good approximation, oblate spheroids that can be arranged on the sequence Sa–Sb–Sc. However, a significant minority exhibit bar-like structures and may be placed on the SBa–SBb–SBc tine of Hubble's 'tuning fork' diagram. Objects, with less pronounced bars, can be arranged on the intermediate sequence S(B)a–S(B)b–S(B)c between normal and barred spirals. Some disks appear to be globally oval (Kormendy 1982, p. 135). Such oval disks are of interest because, like bars, they represent non-axisymmetric distortions of the gravitational potential. An excellent review on the dynamics of barred galaxies has been given by Sellwood & Wilkinson (1993). Infrared imaging shows that some galaxies contain *small* IR bars (Frogel, Quillen & Pogge 1996). When such small inner bars are found in galaxies with large outer bars there is no correlation between the position angles of the large and small bars.

Bars are important to the dynamical evolution of galaxies (Kormendy 1982, 1993) because they can (*a*) lose angular momentum to cold disks and dark halos, and (*b*) gain angular momentum from rapidly rotating bulges. Furthermore, transfer of significant amounts of gas by bars to the nuclear regions of galaxies will increase the central galactic mass concentration, which in turn will make the galactic disk less prone to the development of bar-like distortions. In other words stellar bars can self-destruct (or transform themselves into lenses[1]) by transporting too much gas to the nuclear regions of their parent galaxies.

7.1 Differences between normal and barred spirals

De Vaucouleurs (1961) finds that the mean integrated colors of normal and barred spirals of a given Hubble stage are not significantly different. This shows that the differences between normal and barred objects do not reflect deep differences in their stellar populations. Using the pitch angles of galaxies tabulated by Kennicutt (1981), and the Hubble types of Sandage & Tammann (1981), it is found (see Figures 15 and 16 and Table 10) that there is no significant difference between the spiral arm pitch angle versus Hubble stage relations for ordinary spirals and for barred spirals. The relatively large dispersion among the pitch angles for objects of types Sc and SBc is, at least in part, due to luminosity (mass) differences. It is also noted in passing that there appears to be no significant difference between the Hubble stage versus arm pitch angle relations for field spirals and for spiral galaxies in the Virgo cluster.

[1] A lens is an elliptical shelf in the brightness distribution between the bulge and the exponential disk of a galaxy.

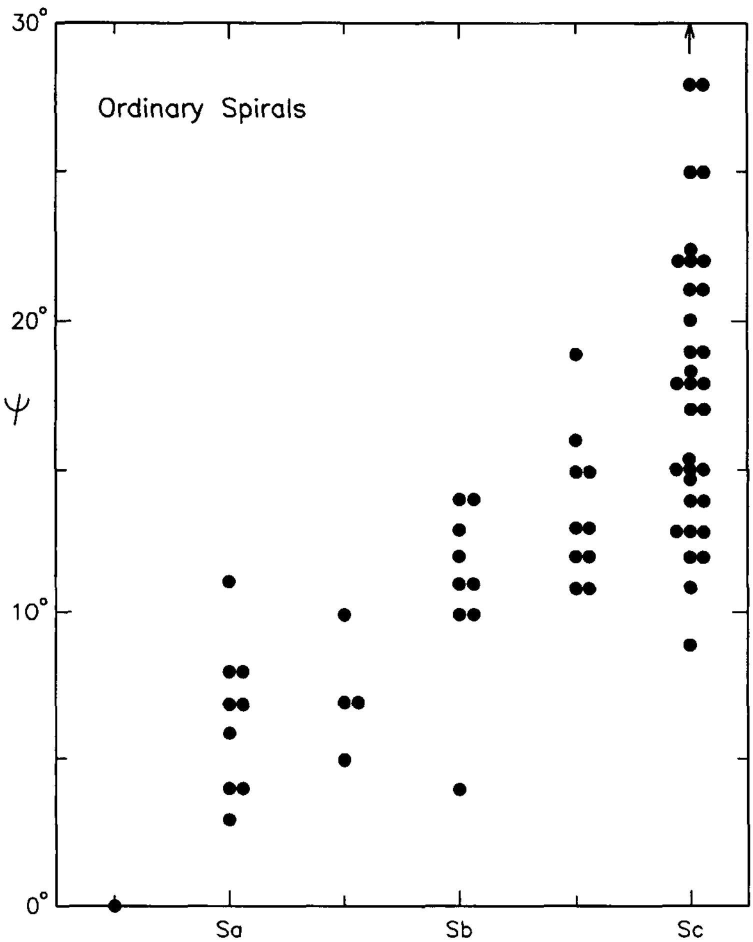

Fig. 15 Relation between Hubble stage and arm pitch angle for ordinary spirals.

7.2 Bars as conduits for gas

Gas orbiting in a bar potential will exhibit large deviations from circular motion resulting in strong shocks. Such shocks will produce both loss of energy and loss of angular momentum. As a consequence of this bar-like structures in galaxies might serve as catalysts for the transfer of gas into the nuclear regions of spiral galaxies. As a result one expects galaxies with active nuclear 'hotspots' consisting of OB stars and/or H II regions to occur preferentially in barred spirals. Of the galaxies studied by Morgan (1958, 1959a), 19 are noted as exhibiting such hotspots. Among these galaxies containing hotspots seven are of types SBb–SBc and ten are of types Sb–Sc, i.e. 41 ± 16% of hotspot galaxies are barred spirals. For comparison *A Revised Shapley–Ames Catalog of Bright Galaxies* (Sandage & Tammann 1981) contains 480 objects of types Sb–Sc and 173 of types SBb–SBbc, i.e. barred spirals comprise only 26 ± 5% of the entire sample. In other words hotspots do not occur, at a respectable level of statistical significance, more frequently in

Table 10. *Mean arm pitch angle (in degrees) versus Hubble stage for ordinary and barred spirals*

	Type				
	a	ab	b	bc	c
S	6.4 ± 0.8	7.2 ± 1.0	11.0 ± 1.0	13.7 ± 0.8	18.1 ± 0.9
SB	4.4 ± 1.2	6.0:	14.6 ± 1.7	16.6 ± 1.5	19.3 ± 1.4

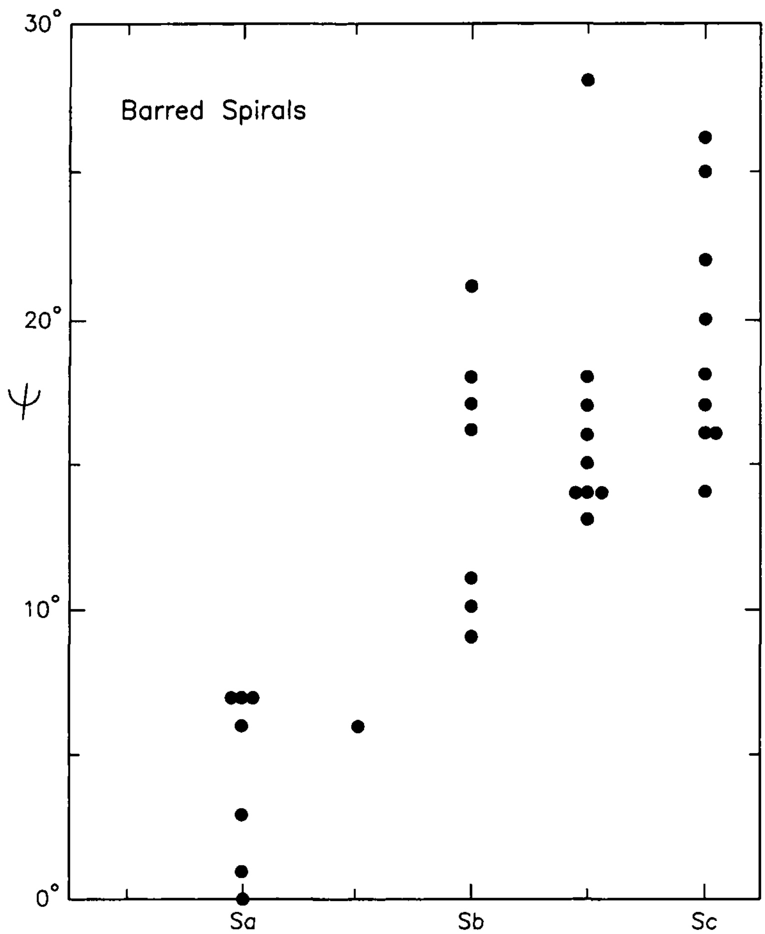

Fig. 16 Relation between Hubble stage and arm pitch angle for barred spirals. No systematic difference is seen between the increase of pitch angle with advancing Hubble stage relations for ordinary and barred spirals. The large scatter among objects of types Sc and SBc is, at least in part, due to the great luminosity (mass) range of these objects.

barred spirals than they do in normal spirals. A similar conclusion had previously been reached by Heckman (1978). This conclusion is supported by a more recent investigation undertaken by Ho, Filippenko & Sargent (1997). These authors find that the presence of a bar seems to have no noticeable impact on the likelihood that a galaxy will host either nuclear star formation or an active galactic nucleus.

Perhaps surprisingly, McLeod & Rieke (1995) find that Seyfert galaxies do *not* exhibit bars more frequently than do normal spirals. This suggests that the Seyfert phenomenon is triggered by violent *external* perturbations of galaxies, or perhaps by oval distortions (Kormendy 1982). Moles, Márquez & Pérez (1995) find that active galaxies 'without exception either have a close companion or present a distorted morphology.'

Mulchaey & Regan (1997) find that a significant fraction of Seyfert galaxies (even in the infrared) show no evidence for the presence of a bar. This suggests that either: (1) large-scale kiloparsec bars are not a universal fueling mechanism, or, perhaps less plausibly, (2) the bars in the non-barred Seyferts were recently destroyed (perhaps by the formation of a central black hole). Mulchaey, Regan & Kundu (1997) find that many galaxies that appear unbarred in the optical, display evidence for bars in the infrared.

The presence of a bar may affect the radial abundance gradient in a galaxy in two ways (Friedli, Benz & Kennicutt 1994): (1) A bar can stir up the gas in the disk of a galaxy, and will therefore reduce, or eliminate, a pre-existing gradient. Such an effect might, for example, account for the lack of any observable abundance gradient in the Large Magellanic Cloud. (2) If a bar funnels gas towards a galactic nucleus, a starburst might be triggered which will, in its turn, generate supernovae that create heavy elements. As a result the next generation of stars will exhibit an enhanced radial metallicity gradient. A detailed study of the correlation between metallicity gradients and the presence, or absence, of a bar, would clearly be of considerable interest.

7.3 Why do some galaxies develop bars?

The fraction of all galaxies that are barred spirals was taken from Sandage & Tammann (1981) and is given in Table 11. The data in this table appear to show no significant trend with Hubble type.

The classifications by Sandage & Tammann (1981) were used to determine the fraction of galaxies of various Morgan (1959a) types that are barred spirals. The presence of bars is often difficult to establish in nearly edge-on systems. Such objects were therefore omitted from the statistics. Also excluded were galaxies of types S0 and SB0. Theoretically one would expect galaxies with the strongest central concentration of light (i.e. Morgan's classes *gk* and *k*) to be most stable against bar-like disk instabilities. The data in Table 12 do, indeed, suggest that the percentage of barred objects may be lowest among galaxies of Morgan types *gk* and *k*. However, a Kolmogorov–Smirnov test shows that the distribution of normal and barred objects does not differ, at a statistically significant level, along the Morgan classification sequence.

Figure 17 and Table 13 show a comparison between the luminosity distributions of ordinary Sc and barred SBc spirals in the *Shapley–Ames Catalog* (Sandage & Tammann

Table 11. *Frequency of barred spirals*

Hubble type	No. galaxies	% Barred
S0 + S0/a	190	25 ± 4
Sa + Sab	165	25 ± 4
Sb + Sbc	283	34 ± 4
Sc	370	21 ± 3
Sd − Im	56	30 ± 8

Table 12. *Frequency of bars as a function of Morgan type*

Type	Normal spiral	Barred spiral	% Barred
a	47	21	31
af	43	18	30
f	62	31	33
fg	27	15	36
g	50	21	30
gk	26	2	7:
k	30	10	25

1981). The figure demonstrates that late-type *barred spirals are, on average, significantly fainter than ordinary spirals.* A Kolmogorov–Smirnov test shows that there is only ~ 0.2% probability that the Sc and SBc spirals in the Shapley–Ames sample were drawn from the same parent population. Since SBcd galaxies are, on average, less luminous than SBc galaxies the observed excess of faint SBc galaxies *might* have been caused by a systematic mis-classification of SBcd galaxies as SBc by Sandage & Tammann (1981). However, this seems unlikely because the excess of ~ 23 SBc galaxies fainter than $M_B = -20$ is larger than the *total* number of Scd + SBcd galaxies in *A Revised Shapley–Ames Catalog*! Furthermore there is no evidence that SBcds have, as a result of such mis-classification, been depleted relative to objects of type Scd. From the data in the *Shapley–Ames Catalog* one finds that N(SBcd)/N(Scd) = 5/13 = 0.39 ± 0.20, which does not differ significantly from N(SBc)/N(Sc) = 73/285 = 0.26 ± 0.03. A *low* N(SBcd)/N(Scd) ratio would have been expected if a significant number of SBcd galaxies had been mis-classified as SBc. It is therefore concluded that the observed excess of SBc galaxies fainter than $M_B = -20.0$ is *not* due to a systematic mis-classification of SBcd galaxies as objects of type SBc.

How might the striking difference between the luminosity distributions of Sc and SBc galaxies be accounted for? Possibly massive luminous late-type spirals collapsed more rapidly than faint low-mass ones because the collapse time-scale $\tau \propto (G\,\rho)^{-1/2}$. Noguchi (1996) suggests that slow infall from a protogalactic halo will keep the gas mass in the disk low resulting in a low star formation rate, and hence a cold disk that can develop a bar instability. On the other hand the halo of a massive protogalaxy might collapse rapidly leading to a pile-up of disk gas, in which massive clumps arising from gravitational

Table 13. *Luminosity distributions for ordinary and barred spirals of type Sc in the Shapley–Ames Catalog*

M_B	$N(M_B)^a$	$N(M_B)^b$
−23.25	4	0
−22.75	8	1
−22.25	15	3
−21.75	48	4
−21.25	45	12
−20.75	58	9
−20.25	43	10
−19.75	34	21
−19.25	18	8
−18.75	8	3
−18.25	4	2

[a] Ordinary spirals
[b] Barred spirals

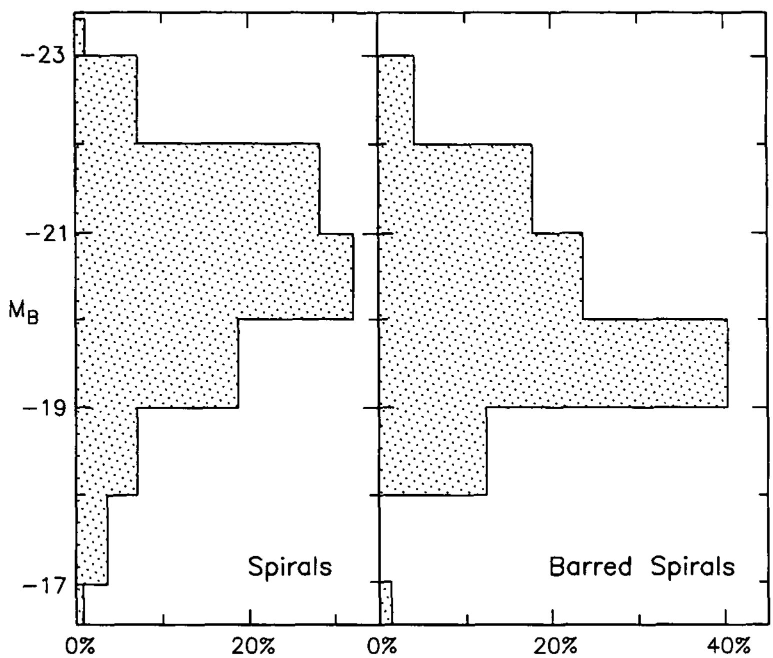

Fig. 17 Normalized luminosity distribution of ordinary Sc spirals and of barred SBc spirals in the Shapley–Ames Catalog (Sandage & Tammann 1981). The figure shows that barred SBc spirals are, in the mean, significantly fainter than ordinary Sc spirals.

instability in the gas disk heat the stellar disk component dynamically, thus acquiring enough random motion to suppress bar instabilities. It is noted in passing that gravitational perturbations produced by such massive disk clumps might scatter thin-disk stars into a thick disk. A possible test of the scenario proposed by Noguchi might be provided by a spectroscopic comparison between the [O/Fe] values in the disks of ordinary and barred spirals of the same luminosity. On the picture proposed by Noguchi (1996) one would (other things being equal) expect fast-collapsing ordinary spirals to be mainly enriched by fast-evolving supernovae of Type II, resulting in relatively high disk [O/Fe] values. On the other hand slowly collapsing objects that produce barred spirals would be expected to be enriched in heavy elements by supernovae of both Type II and Type Ia, resulting in a relatively low disk [O/Fe] ratio. Unfortunately presently available data (Jablonka, Martin & Arimoto 1996) are not yet suitable for performing such a test. For spirals of types Sa, Sab and Sb no significant difference is found between the luminosity distributions of ordinary and barred objects. This result is consistent with the conjecture by Noguchi that the bars in early-type galaxies, whose disks are likely to have grown quickly, were formed as a result of tidal interactions with other galaxies. Beauchamp & Hardy (1997) have recently shown that interference filters can provide stellar spectral indices, which could be used to measure Mg/Fe in large numbers of galaxies. Such measurements could provide huge samples of data to search for possible systematic Mg/Fe differences between normal and barred galaxies.

Van den Bergh *et al.* (1996) found that barred spirals are very rare in the Hubble Deep Field. Using simulations these authors are able to show that the *HST* would have been able to distinguish remote barred spirals from ordinary spirals in the Hubble Deep Field. The almost complete absence of barred spirals in the Hubble Deep Field may indicate that the stellar populations in the disks of the first spiral galaxies formed at this remote epoch had enough random motion to suppress bar instabilities. Such a situation might have arisen if early disks were dynamically heated by frequent infall and capture of massive ancestral gas clumps. A massive central starburst occurring at a more recent epoch might have formed an inner stellar disk. If this disk is unstable to bar modes it could thicken into a bulge (Pfenniger & Norman 1990, Merritt & Sellwood 1994).

7.4 Summary

Normal and barred galaxies of the same Hubble stage exhibit very similar colors. This suggests that they contain broadly similar stellar populations. However, late-type barred spirals are found to be significantly less luminous than normal galaxies of the same Hubble stage. Possibly (Noguchi 1996) this difference is due to the fact that slow infall from a low-mass protogalactic halo will produce a cold disk that can develop a bar instability. On the other hand rapid infall of material from a massive halo might result in a hot disk that is stable against bar-like deformations. If this hypothesis is correct then one might expect the logarithmic α-element to iron ratio [α/Fe] to be higher in normal spirals than it is in barred spirals. It is also tentatively suggested that the low frequency of barred spirals in the Hubble Deep Field might be due to the fast collapse (resulting in hot disks) of the spiral galaxies that are presently being viewed at large look-back times.

There is presently only marginal observational evidence in favor of the view that bars serve as conduits for transporting disk gas into the nuclear regions of spirals.

8 Elliptical galaxies

The visual light of elliptical galaxies is dominated by old metal-rich stars (Morgan 1959b). To a first approximation the isophotes of an E galaxy may be represented by ellipses with a major axis a and a minor axis b. Following Hubble (1936, p. 41) the flattening of an elliptical is defined as $(a - b)/a$. The observed range of ellipticities extends from $\epsilon = 0.0$ to $\epsilon = 0.7$, corresponding to types E0–E7. The relationship between the projected isophote shapes of galaxies and their intrinsic shapes (which may be triaxial) has been studied by many authors, including Hubble (1926), de Vaucouleurs (1959a), Sandage, Freeman & Stokes (1970), Binney (1978), Binney & de Vaucouleurs (1981), Franx, Illingworth & de Zeeuw (1991), Tremblay & Merritt (1995), and Ryden (1996).

8.1 Radial profiles of elliptical galaxies

Sérsic (1968) was able to show that the surface brightnesses of galaxies may be conveniently represented by the relation

$$I(r) = I_0 \exp\left[-(r/r_0)^{1/n}\right], \tag{1}$$

in which I_0 is the central surface brightness, r is the reduced radius defined as $r = [r_{min}\ r_{max}]^{1/2}$, r_0 is the scale-length, and n is a free variable. For $n = 1$ this is the exponential radial surface brightness distribution that provides a good description of the brightness profile for many spiral disks. As n becomes large, the Sérsic profile approaches a power law. Broeils & Courteau (1996) have found that the central regions of spirals are also best fit by exponential profiles. In other words *two* exponentials may be used to provide a satisfactory fit to the light profiles of a significant fraction of all spiral galaxies. Broeils & Courteau find that the ratio of bulge/disk scale lengths is typically ≈ 0.1. It is not yet clear why Nature appears to be so inordinately fond of exponential disks! The case $n = 4$ corresponds to the 'r to the quarter' law, which de Vaucouleurs (1948, 1953, 1959b) found to give a good representation of the surface brightness distribution of many ellipticals that are more luminous than $M_B = -18$. For fainter dE and dSph galaxies Young & Currie (1994) find that the radial surface brightness distribution is related to absolute magnitude by the relation

$$M_B = (3.9 \pm 0.3)/n - 18.8 \pm 0.3, \tag{2}$$

in which M_B was calculated by *assuming* $H_0 = 50$ km s^{-1} Mpc^{-1}. Using more extensive data Jerjen & Binggeli (1997) find

$$M_B \simeq -10 \log n - 14. \quad (3)$$

Young & Currie suggest that the n-values of dE galaxies are a strong function of the gravitational potential well constraining their constituent stars. In the M_B versus n plane dE galaxies lie on a linear relation that branches off from the ellipticals with $n = 4$ that are brighter than $M_B = -18$. Equation (2) can be used to determine the relative distances of clusters of galaxies. Furthermore, using NGC 147, NGC 185, NGC 205 and the Fornax dwarf as calibrators, it can be employed to estimate the value of the Hubble parameter. However, Jerjen & Binggeli (1997) caution that the intrinsic dispersion in Equation (3) may be too large for this approach to carry much weight. Some of this dispersion may be due to the fact that elliptical and dwarf spheroidal galaxies might belong to physically distinct families (Wirth & Gallager 1984, Kormendy 1985, Gorgas *et al.* 1997).

A quite different approach has been taken by Saglia *et al.* (1997) who suggest that (for $n \lesssim 8$) the profiles of elliptical galaxies may be thought of as consisting of an $r^{1/4}$ component, on which an exponential disk with the appropriate scale-length and disk-to-bulge ratio has been superposed. In other words Saglia *et al.* propose that the variety of luminosity profiles exhibited by early-type galaxies may be due to the presence of disk components of various strengths.

The structure of the envelopes of luminous E and cD galaxies has been discussed in great detail by Schombert (1986, 1987, 1988). He finds that their structure is well correlated with, and a smooth function of, luminosity. For the brightest cluster galaxies Graham *et al.* (1996) find a large scatter in n values. As expected (Caon, Capaccioli & D'Onofrio 1993) brightest cluster galaxies with the largest values of the radial scale-length r_0 are, on average, also observed to exhibit the highest values of n. A nice plot of the relationship between n and the half-light radii of cD, S0/E and dSph galaxies is shown by Courteau (1996a). His plot shows that the brightest galaxies in rich clusters have both the largest values of n and the largest effective radii. Courteau, de Jong & Broeils (1996) note that a significant fraction of early-type (Sa–Sab) galaxies are best represented by an $n = 2$ brightness profile. These authors also find that only a small fraction of the galactic bulges are best represented by an $r^{1/4}$ profile.

8.2 Boxy and disky ellipticals

The first evidence suggesting that elliptical galaxies might constitute a composite population was obtained by Davies *et al.* (1983), who discovered that intrinsically faint ellipticals rotate more rapidly than luminous ones. The next piece of evidence to support this view was obtained independently by Bender (1988) and by Nieto, Capaccioli & Held (1988) who found that some ellipticals appear to contain inner disks. The present view on this question has been summarized as follows by Kormendy & Bender (1996): 'there is a dichotomy between (1) normal- and low-luminosity ellipticals that rotate rapidly, that are nearly isotropic and oblate-spheroidals, that are coreless, and that have disky-distorted isophotes, and (2) giant ellipticals that are essentially non-rotating, that are anisotropic and moderately tri-axial, and that have cuspy cores, that are boxy-distorted.' Recent high-resolution observations of 61 early-type galaxies (Faber *et al.* 1996), which are plotted in Figure 18, suggest that the true situation may be a bit more complex. Bender (private communication, (see also Nieto & Bender 1989)) points out that the four boxy low-luminosity objects in Figure 18 are all special in the sense that they are rotationally flattened compact companions to bright galaxies. In this figure global isophote shapes have been expressed as a Fourier series expansion of deviations from pure ellipses. A convenient recipe for first finding the best fitting ellipse to the digital image of an elliptical galaxy, and then the third and fourth order Fourier co-efficients that describe the deviations of the image from this ellipse, is given by Ferrarese (1996, pp. 17–18). Such an expansion is usually dominated by the $a(4)$ co-efficient, which is negative for 'boxy' isophotes, while pointed 'disky' isophotes have $a(4) > 0$. A convenient non-dimensional parameter is $a(4)/a$. Bender *et al.* (1989) find that $a(4)/a$ changes only slightly from

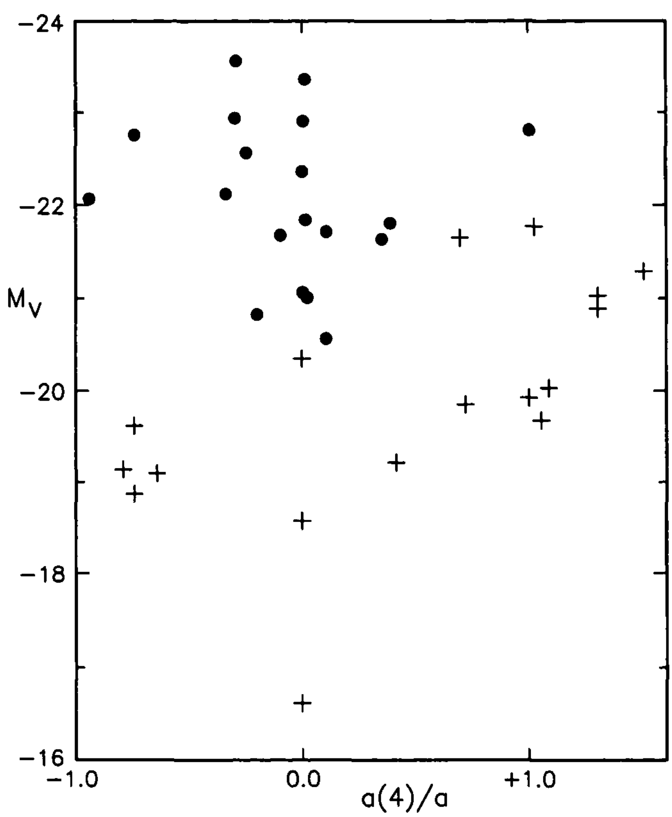

Fig. 18 Dependence of $a(4)/a$ on luminosity ($H_0 = 80$ km s^{-1} Mpc^{-1} assumed) for galaxies with inner power-law profiles (crosses), and for those which contain a central core (filled circles). For $M_V < -20$ power-law galaxies are seen to have mainly disky profiles with $a(4)/a > 0.0$, while galaxies with cores mostly exhibit boxy isophotes with $a(4)/a \lesssim 0.0$. However, no such correlation between the core/power-law type and the global isophote shape appears to exist for fainter galaxies with $M_V > -20$.

isophote to isophote. Inspection of Figure 18 shows that for luminous ellipticals with $M_V < -20$ the boxy objects with $a(4)/a < 0.0$ do indeed (mainly) have cores, whereas the disky galaxies with $a(4)/a > 0.0$ mostly exhibit power-law radial profiles. However, the figure also shows that *the fainter power-law galaxies with* $M_V > -20$ can have either boxy or disky global isophotes. Kormendy & Bender (1996) suggest that faint rapidly rotating boxy ellipticals might be related to the boxy bulges observed in some spirals. These authors also note that many of these objects are companions of much more luminous objects, which suggests that their box structure is due to interactions.

A plot of $a(4)/a$ from Bender *et al.* versus Hubble type taken from Sandage & Tammann (1981) is shown in Figure 19. This figure shows that almost all E0–E4 galaxies have $-0.01 < a(4)/a < +0.01$. However, the majority of E5$-$S0_3 galaxies are seen to have pointed isophotes, i.e. $a(4)/a > 0$. The relationship between Hubble type and isophote shape is seen to be similar for galaxies more luminous than Sandage & Tammann magnitude $M_B = -21.0$ (open circles) and galaxies fainter than this value (filled circles). A plot of $a(4)/a$ versus M_B is shown in Figure 20. Perhaps unexpectedly, this figure shows no clear correlation between M_B and the isophote shape parameter $a(4)/a$. Independent of luminosity the E0–E4 galaxies (plotted as + signs) are again seen to mostly fall in the range $-0.01 < a(4)/a < +0.01$, while the more flattened objects (plotted as filled circles) of all luminosities include a significant fraction with pointed isophotes having

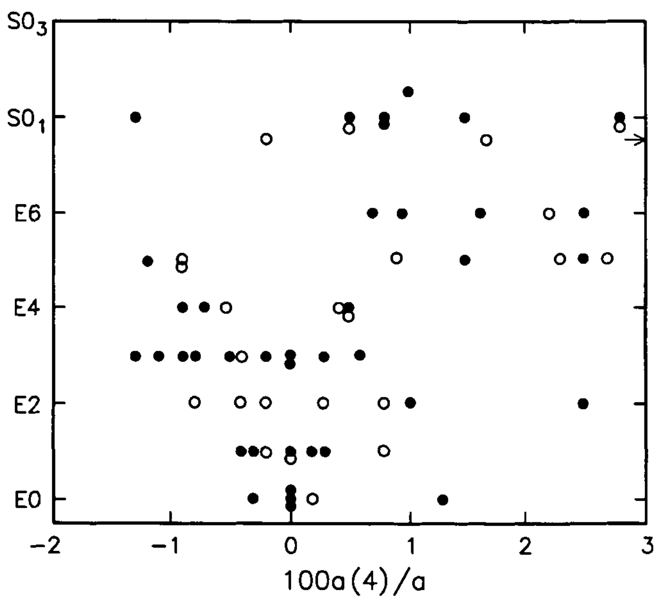

Fig. 19 Boxyness/diskiness parameter $a(4)/a$ versus Hubble type (Sandage & Tammann 1981) for early-type galaxies. Objects of with mixed classifications, such as E4/S0_1, were *not* plotted. High luminosity (open circles) objects with $M_B < -21$ and less luminous (filled circles) galaxies with $M_B > -21$ are seen to have similar distributions. Most of the E0–E4 galaxies have $-0.01 < a(4)/a < +0.01$. More flattened early-type galaxies mostly have larger $a(4)/a$ indices.

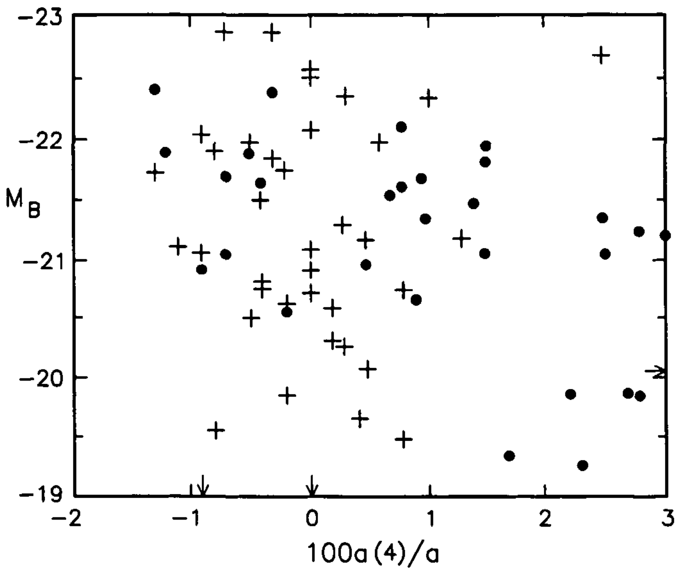

Fig. 20 Galaxy luminosity versus the global isophote shape parameter $a(4)/a$ (taken from Bender *et al.* (1989)). Little luminosity dependence is seen for galaxies of types E0–E4, which are plotted as crosses. The most 'disky' galaxies, which are plotted as filled circles, all appear to be fainter than $M_B = -21.5$.

$a(4)/a > +0.01$. The conclusion that $a(4)$ is not a function of luminosity for ellipticals has been confirmed by Andreon (1996). Using a complete sample of Coma cluster galaxies he finds that boxy and disky ellipticals have similar luminosity functions. However, this conclusion differs from that of Bender (1997) who postulates that the role of gaseous processes and dissipation decreases with increasing mass preferentially creating rotationally flattened disky ellipticals (and S0s) at lower luminosities, and boxy anisotropic ellipticals at higher luminosities. Bender believes that gas and dissipational processes must still have played some part in the formation of even the most luminous ellipticals.

In a beautiful investigation of the disk-like sub-structures within elliptical galaxies Scorza (1993) was able to show that such structures lie on an extension of the relation between scale-length and central surface brightness for S0 and Sa galaxies. This clearly shows that there is a continuity between spiral galaxies and the disk-like sub-systems in ellipticals.

De Jong & Davies (1996, 1997) find that disky ellipticals have systematically stronger Hβ absorption lines than do boxy ones. This suggests that a relatively young stellar population may be associated with the disky structures in elliptical galaxies. Such a conclusion is consistent with the work of Caon & Einasto (1995) who shows that early-type galaxies with disky isophotes in the Virgo cluster lie in regions of lower mean density than do those having boxy isophotes. A more detailed discussion of the relation between galactic populations and the density in their environments will be given in Chapter 9.

8.3 Formation of ellipticals

Nieto, Bender & Surma (1991) and Faber *et al.* (1996) speculate that luminous early-type galaxies with cores and boxy isophotes were formed by dissipationless mergers (Binney 1976) of mainly stellar ancestral objects. Figure 21 shows a possible example of such a merger in the Hubble Deep Field (van den Bergh *et al.* 1996). Such a dissipationless merger might account for the high luminosity, triaxiality, velocity anisotropies and the low rotational velocity of such objects. On the other hand Faber *et al.* argue that the early-type galaxies with power-law profiles were probably formed by dissipational mergers of gas-rich ancestral objects. The importance of dissipational processes for the formation of some ellipticals is strongly supported by phase space arguments (Carlberg 1986) and by arguments derived from cooling diagrams (Kormendy 1990a). Alternatively

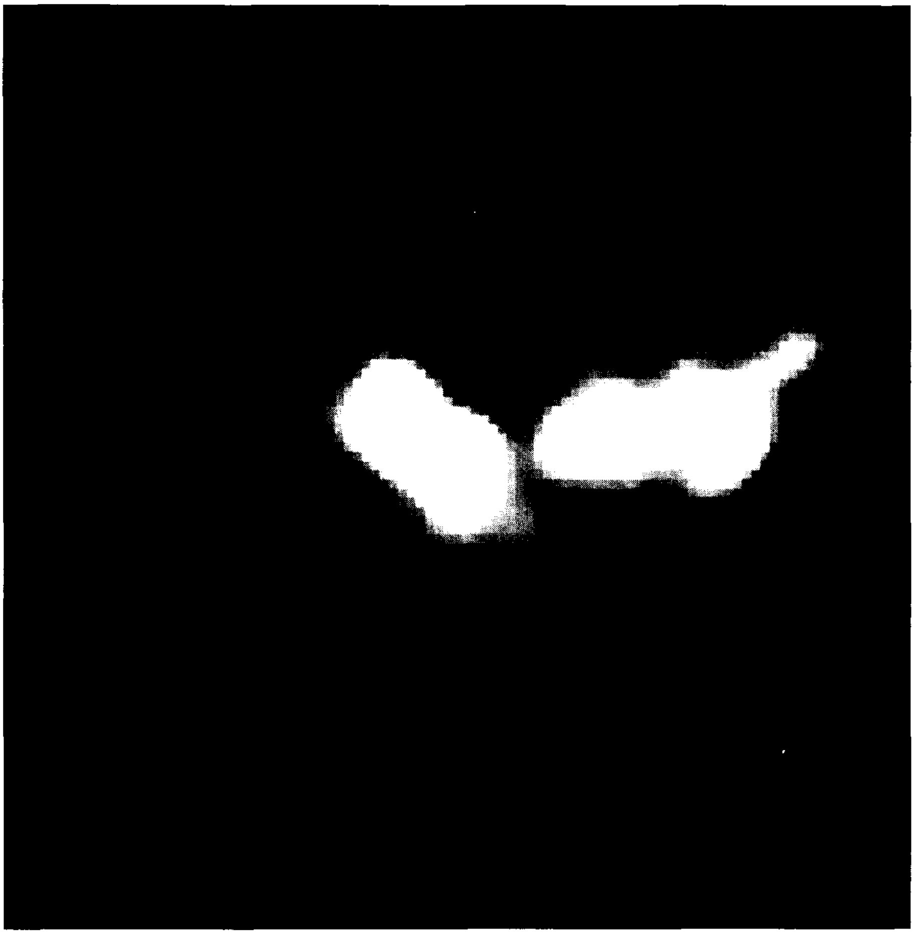

Fig. 21 Compact clustering of blue knots and fragments in the Hubble Deep Field. This object (HDF 2-403) may be a rather rare example of an elliptical galaxy forming at a relatively late epoch.

one could, of course, assume that such disky galaxies formed *à la* Eggen, Lynden-Bell and Sandage (1962 = ELS), by rapid dissipational collapse of a single gas-rich protogalaxy. One might also think in terms of an ELS + noise (Sandage 1990) model in which some late-time capture of smaller ancestral fragments is superposed on a more general collapse. A possible problem with the attractive scenario proposed by Faber *et al.* is that it does not explain why faint ($M_V > -20$) early-type galaxies can have either disky or boxy global isophotes. Perhaps tidal distortions (Kormendy 1980) of isophotes are more important for such low-mass, faint, early-type galaxies than they are for more massive luminous ones. Since global isophotes may be affected by environmental factors (which do not influence galaxy cores) it seems likely that the bulge/power-law dichotomy of galaxy cores is more fundamental than the boxy/disky one for the global profiles of early-type galaxies. Possibly boxy low-luminosity objects are tidally truncated boxy bulges (Nieto & Bender 1989).

Indirect evidence on the early evolutionary history of elliptical galaxies may be provided by the color (metallicity) distribution of their globular clusters. Objects that experienced a simple monolithic collapse might be expected to have a globular cluster system that exhibits a single maximum in its color distribution. On the other hand early-type galaxies that underwent a complex evolutionary history are expected (Ashman & Zepf 1992) to exhibit a multi-peaked frequency distribution of globular cluster colors. Forbes (1996) provides V–I color distributions for globular cluster systems associated with four of the early-type galaxies for which Faber *et al.* (1996) provide bulge/power-law classifications. Three of these objects (NGC 3608, NGC 4365 and NGC 5813) have cores and single-peaked color distributions. The galaxy (NGC 1700), which exhibits a power-law density distribution, does not contain a sufficiently large number of globular clusters with color information to establish the nature of their color distribution. Studies of the color distributions of globular clusters surrounding some of the other galaxies studied by Faber *et al.* might throw significant light on the nature of the early evolution of elliptical and S0 galaxies. Kissler-Patig (1997) finds that boxy ellipticals tend to have higher specific globular cluster frequencies S than do disky ones. However the Virgo galaxies NGC 4472 [$a(4)/a = -0.3, S = 6$] and NGC 4486 [$a(4)/a = 0.0, S = 14$] are counterexamples to this trend.

Faber *et al.* (1996) make the interesting suggestion that the cores of luminous early-type galaxies might have formed when massive black holes at the centers of two merging ancestral galaxies spiralled together, while transferring their orbital energy to (and hence heating up) the stars that were originally present. If this hypothesis is correct then *the absence of cores in disky power-law galaxies might be due to the fact that such objects (mainly) formed by collapse of a single proto-galaxy.*

8.4 The fundamental plane

Casual inspection of the images of elliptical galaxies might seem to suggest that they are all very similar, i.e. if you have seen one elliptical you have seen them all. However, plots relating pairs of parameters describing elliptical galaxies are found to exhibit considerable intrinsic scatter (Faber & Jackson 1976, Kormendy 1977, Binggeli, Sandage & Tarenghi 1984). This induced Djorgovski & Davis (1987) and Dressler *et al.* (1987) to propose independently that early-type galaxies populate a plane in the parameter space defined by r_e, μ_e, and σ, in which μ_e is the surface brightness at r_e, and σ is the velocity dispersion. By taking advantage of this relationship it is possible to determine the luminosities of galaxies with greater precision than would be possible from the relation between M_V and μ_e or between M_V and σ.

8.5 Summary

Luminous elliptical galaxies appear to be either boxy objects that contain cores, or disky power-law structures that do not contain such cores. Possibly boxy ellipticals formed by mergers of (mostly stellar) ancestral objects. On the other hand disky ellipticals may have formed *à la* Eggen, Lynden-Bell and Sandage, from a single proto-galaxy, or from the merger of mainly gaseous ancestral objects. If this view is correct then the strength of the disk-like component in a galaxy depends on the gas fraction that remained in its ancestral objects at the time of their merger(s). The presence of cores might be due to ejection of stars resulting from heating by merging massive black holes that originated in the nuclei of ancestral galaxies. The apparent lack of correlation between the bulge/power-law dichotomy, and the boxy/disky one for the least luminous galaxies, which is seen in Figure 18, might be due to the effects of tidal distortions on the global isophote shapes of lower-luminosity ellipticals. Detailed studies of the frequency distribution of metallicities within globular cluster systems should help to throw light on the early evolutionary history of elliptical galaxies.

9 The S0 class

9.1 Introduction

It is surprising that Hubble (1936, p. 55, pp. 79–81) makes only a few passing references to the fact that early-type (E–S0–Sa) galaxies predominate in rich clusters, whereas the field is dominated by galaxies of late type (Sc–Ir). Spitzer & Baade (1951) were the first to emphasize the physical importance of the fact that the frequency of S0 galaxies is greatest in rich clusters of galaxies. Van den Bergh (1962) subsequently used the difference between the galactic populations in rich clusters and in the field to show that rich clusters must be stable over periods comparable to the age of the Universe. In particular the difference in the galactic populations of clusters and field provided a powerful argument against the tentative speculation by Hubble (1936, p. 81) 'that the disintegration of clusters may populate the general field.' The possible physical significance of the relation between galaxy morphology and environmental density was first discussed in great detail by Dressler (1980), who stressed that elliptical galaxies are most frequent in the regions of highest density, whereas late-type spirals predominate in low-density regions. A somewhat different approach was taken by Whitmore & Gilmore (1991) who found that galaxy morphology was strongly correlated with distance from the cluster center. It is, of course, difficult to disentangle these effects because local density and distance from the cluster center are closely correlated. Sanromà & Salvador-Solé (1990) found that galaxy morphology does not appear to be affected by sub-clumpings within rich clusters. Finally Dressler *et al.* (1994) have used *HST* images of a distant rich cluster to show that blue (Butcher-Oemler (1978)) cluster galaxies appear to be normal late-type spirals. This contrasts with the situation at low redshifts, where the flattened disk-like objects in rich clusters are mostly of type S0. Such observations suggest that significant numbers of spirals may have become transformed into lenticulars during the last 5–7 Gyr.

9.2 Definition of the S0 class

The S0 classification type was introduced by Hubble (1936, p. 44). He wrote that 'nebulae intermediate between E7 and Sa are occasionally designated as S0.' Furthermore, he (Hubble 1936, p. 45) emphasized that 'The transitional stage, S0, is more or less hypothetical.' Whereas Hubble (1936) regarded S0 galaxies as being transitional *between* ellipticals and spirals, Spitzer & Baade (1951) suggested that they might, in fact, form a dustless sequence that *parallels* the Sa–Sb–Sc tine of the Hubble tuning fork diagram (cf. Figures

11 and 12). Specifically Spitzer & Baade proposed that S0 galaxies were flattened objects from which gas had been removed by collisions between spirals. Regarding the nature of S0 galaxies Morgan (Matthews, Morgan & Schmidt 1964) writes that 'the class S0, as used by Hubble, applies to galaxies having a variety of superficial appearances; that is, a mental picture of a unique galaxy form could not be derived from the class S0.' Sandage (1961) states that the existence of S0 galaxies was established empirically by data accumulated during a photographic survey of nearby galaxies carried out between 1936 and 1950. He divided S0 galaxies into three subclasses $S0_1$, $S0_2$ and $S0_3$. The distribution of light across $S0_1$ galaxies is continuous with no traces of structure or of dust. A weak dust lane is seen projected on the central bulges of $S0_2$ galaxies that are viewed almost edge-on. A sharp, narrow, absorption lane is seen to be embedded in the lens component of $S0_3$ galaxies. These sub-types of the S0 class are illustrated in *The Hubble Atlas of Galaxies* (Sandage 1961).

9.3 Luminosity of S0 galaxies

The different sub-types of the S0 class are found to have luminosity distributions that are indistinguishable from each other. Furthermore no dependence of luminosity on (projected) galaxy flattening is found among members of the S0 class. The latter result is unexpected because the luminosity distribution of ellipticals peaks ~ 1.5 mag brighter than that of S0 galaxies (van den Bergh 1990). One might, perhaps, have expected round S0s to have luminosities similar to ellipticals.

Hubble (1936, p. 42) wrote that 'The transition from E7 to SBa is smooth and continuous but that from E7 to Sa may be cataclysmic – all known examples of Sa have fully developed arms.' This question has more recently been studied by Sandage (1961). He speculated that Sa galaxies with spiral arms (Sa(*s*)) are a continuation of type $S0_2$, whereas he hypothesized that Sa galaxies with rings (Sa(*r*)) branch off from type $S0_3$. However, the luminosity distribution of the $S0_2$ and Sa(*s*) galaxies in *A Revised Shapley–Ames Catalog of Bright Galaxies* (Sandage & Tammann 1981) argues against such a continuity. For the $S0_2$ galaxies in this sample $< M_B > = -20.56 \pm 0.27$ compared to $< M_B > = -21.35 \pm 0.18$ for the Sa(*s*) galaxies. A Kolmogorov–Smirnov test shows only a $\sim 1\%$ probability that the absolute magnitudes of the Shapley–Ames $S0_2$ and Sa(*s*) galaxies were drawn from the same distribution of parent galaxy luminosities. For the Shapley–Ames $S0_3$ galaxies $< M_B > = -20.40 \pm 0.22$, compared to $< M_B > = -21.08 \pm 0.17$ for objects of type Sa(*r*). In both cases the S0 galaxies are seen to be fainter than the corresponding subclass of Sa galaxies. *The luminosity difference between* $S0_2$ *and Sa(s), and that between the* $S0_3$ *and Sa(r), galaxies militates against the hypothesis that there is a smooth transition between these morphological classes of objects.*

From high signal-to-noise spectra Kuijken, Fisher & Merrifield (1996) find that probably only $\sim 1\%$ of all S0 galaxies exhibit a counterrotating stellar disk, whereas $24 \pm 8\%$ of the gaseous disks in S0 galaxies are counterrotating. This suggests that a significant fraction of the cases in which S0 galaxies contain gas is due to capture of H I clouds.

9.4 Summary

Objects of type S0 are, on average, fainter than Sa galaxies. Furthermore, no correlation is found between the luminosity and the (projected) flattening of S0 galaxies. Finally, no significant differences are found between the luminosity distributions of galaxies having sub-types $S0_1$, $S0_2$ and $S0_3$.

10 Early-type galaxies

10.1 Cores and power-law profiles

Lauer *et al.* (1995) have used the Planetary Camera of the *HST* to image the central regions of 57 early-type galaxies. They found that the radial surface brightness profiles of most of these fall into two distinct classes: (1) galaxies that have *cores*, and (2) galaxies that exhibit *power-law* profiles that continue down to radii near the resolution limit. Of the galaxies observed by Lauer *et al.* 15 have cores and 30 exhibit power-law profiles. Among the galaxies that have been classified as having either cores or power-law profiles 21 are contained in *A Revised Shapley–Ames Catalog of Bright Galaxies* (Sandage & Tammann 1981). Since the statistics of objects in this catalog are better understood than those of the entire sample, only the nine galaxies with cores and the 12 having power-law profiles that are in the *Shapley–Ames Catalog* will be considered below. The most striking feature of these data (which has already been commented on by Lauer *et al.* and others) is that the galaxies with cores tend to be more luminous than those with power-law profiles. For the Shapley–Ames sub-sample a Kolmogorov–Smirnov test rejects the hypothesis that the galaxies with bulges were drawn from the same luminosity distribution as those having power-law profiles at the 97% confidence level. Furthermore four out of nine (44%) of the galaxies with cores have types E0–E4, compared to only one out of 12 (8%) of the objects with power-law profiles. Many years ago van den Bergh (1962) inspected the *Palomar Sky Survey* to classify the environments of all northern Shapley–Ames galaxies into three types: (*a*) field, (*b*) (small) groups, and (*c*) clusters. For the present sample the numbers in these three groups are 1 : 0 : 7, respectively, for objects with cores compared to 4 : 1 : 7, respectively, for ones with power-law profiles. In other words the very scanty data that are available weakly suggest that early-type galaxies with power-law spectra are more common in the field than they are in clusters. One striking feature of the data of Lauer *et al.* is that galaxies with off-center nuclei are much more common (6 out of 15) among galaxies with cores than they are among galaxies with power-law profiles (1 out of 30). Possibly this difference is due to the fact that galaxies with cores formed during violent mergers, whereas disky galaxies may have formed in a more quiescent fashion.

The most plausible explanation for the dispersion that is observed in the correlation between classifications of early-type galaxies based on global isophotes, and those derived from the profiles in the central regions of galaxies is that: (1) tidal interactions can modify the outer structure of ellipticals (Kormendy 1977); and (2) that projection effects can affect the global isophote classifications (Gerhard & Binney 1996). Such projection effects should be least important in early-type galaxies that are viewed almost edge-on. In view of these problems it is probably safest to place more reliance on classifications of early-type galaxies that are based on either: (1) radial intensity profiles of the unperturbed inner regions, or (2) classifications that take advantage of the kinematical differences between galaxies with cores and ones that exhibit power-law intensity profiles.

10.2 Relation between E, S0 and Sa galaxies

Van den Bergh (1989a, 1990) finds that it is often difficult to distinguish objects that have been classified as ellipticals from those assigned to type S0 by Sandage & Tammann(1981), on the basis of their published surface photometry. However, the data do indicate that exponential disks occur more often in S0 galaxies than they do in ellipticals. Furthermore, ellipticals exhibit their maximum flattening at intermediate radii more often than do S0 galaxies. In the rather small sample of early-type galaxies that have both core-type classifications by Lauer *et al.* (1995) *and* global photometry in their outer regions one finds that: (1) objects with cores tend to have ellipticities that increase towards larger radii, and (2) galaxies with central power-law profiles also preferentially have power-law luminosity distributions in their outer regions.

Figure 22 shows a histogram of the luminosity distributions of galaxies of types E, S0, Sa and Sb in *A Revised Shapley–Ames Catalog of Bright Galaxies* (Sandage & Tammann 1981). This figure shows that objects classified as S0 are systematically fainter than those of types E and Sa. This clearly shows that S0 galaxies cannot be the 'missing link' between ellipticals and spirals. In view of the difficulty in distinguishing ellipticals from lenticulars it is, of course, quite possible that some of the brighter S0 galaxies are, in fact, mis-classified ellipticals. Such mis-classifications may be particularly common among S0s viewed nearly pole-on. By the same token it may well be that some of the fainter E galaxies are, in fact, mis-classified S0s. Two lines of evidence support this suggestion: (1) faint S0s are, on average, much more highly flattened than luminous S0s (see Figure 2 of van den Bergh (1990)), i.e. some faint S0s viewed pole-on might have been mis-classified as ellipticals, and (2) Davies *et al.* (1983) find that most faint ellipticals are spinning more rapidly than luminous ones and are therefore probably supported by rotation. Finally, some S0 galaxies with *very* luminous bulges may have been mis-classified as ellipticals because the light of their faint disks was swamped by the light of a bright spheroid.

Binggeli & Jerjen (1997) make the interesting point that the discontinuity in the surface brightness–luminosity relation around $M_B = -20$, which fostered the notion of a physical dichotomy between normal and dwarf ellipticals, is restricted to the very central parts of galaxies. Outside the central region ($r > 300$ pc) the radial surface brightness profile varies continuously between dwarf and giant ellipticals.

10.3 Summary

Available evidence favors a picture in which early-type galaxies, other than dwarf spheroidals, can be assigned to two (possibly overlapping) classes: (1) true ellipticals with

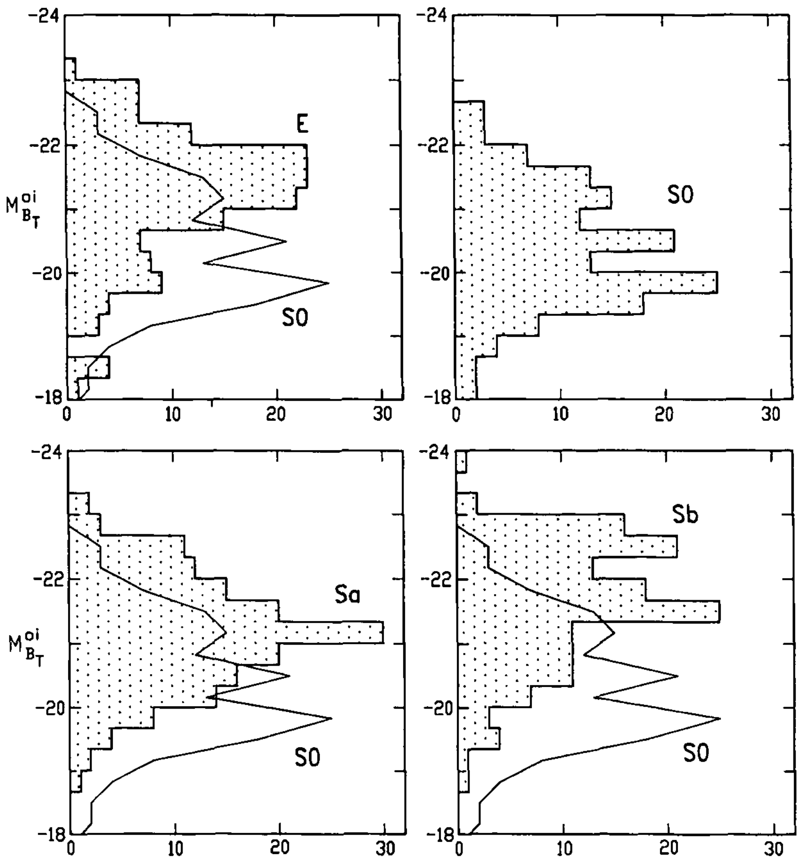

Fig. 22 Frequency distribution of luminosities for E, S0, Sa and Sb galaxies in the *Shapley–Ames Catalog*. The figure shows that S0 galaxies are, on average, less luminous than those of types E and Sa. This implies that not all S0 galaxies can be intermediate between types E and Sa.

cores that tend to be quite luminous and that may be triaxial, and (2) less luminous oblate and rotationally supported lenticular objects. The less-luminous lenticulars might have formed by collapse of a single (mostly gaseous) proto-galaxy *à la* ELS, whereas the more luminous true ellipticals may have formed by mergers of mainly stellar ancestral galaxies. On such a scenario the higher luminosity of true ellipticals would be due to the fact that they formed from mergers of two (or more) proto-galaxies. It is not yet clear why such merger products should have 'cores' whereas proto-galaxies that evolved into single power-law galaxies do not. One might, however, speculate that the interactions between massive black holes in the nuclei of merging ancestral objects and the stars in their vicinity gave rise to such cores. In other words orbital energy might have been transferred from a pair of merging black holes to the stars near the center of the merger remnant, causing them to expand to greater galactocentric distances. Objects with characteristics that are intermediate between those of true ellipticals and lenticular galaxies could have arisen from mergers between ancestral objects that were still partly gaseous.

Interesting hints about the differences in the evolutionary histories of ellipticals and spheroidal galaxies are provided by recent observations of central line-strength indices for Mg_2, $\langle Fe \rangle$, and $H\beta$ by Gorgas *et al.* (1997). These authors find that, for a given $\langle Fe \rangle$, ellipticals have systematically stronger Mg_2 than do S0 galaxies. This strongly suggests that ellipticals collapsed more rapidly than spheroidal galaxies.

11 Dwarf spheroidal galaxies

11.1 Introduction

Dwarf spheroidals are the most common type of galaxy in the Universe. The fact that they were not discovered until 1938 is entirely due to their feeble luminosity and low surface brightness. Of the 29 galaxies that are known to be located within 1.0 Mpc, approximately half are dwarf spheroidals (dSph). A listing of these Local Group dSph galaxies is given in Table 14. For the sake of completeness the dSph/dE galaxies NGC 147 and NGC 185, which are both brighter than $M_V = -15.0$, have been included in the table. Since most of the faintest known Local Group members are dwarf spheroidals it is almost certain that additional very faint dSph galaxies remain to be discovered in the Local Group. In particular it seems probable that more dSph companions to M31 will eventually be found. Only three such objects (And I, And II and And III) are presently known (van den Bergh 1972), whereas seven dSph companions (Sgr, UMi, Dra, Scl, Sex, Car, For) are known to be located within 150 kpc of the Galaxy – even though the Milky Way system is less luminous than the Andromeda nebula. It is, of course, possible that the small number of M31 dSph satellites is due to the fact that some dwarf companions to M31 were destroyed by tidal interactions with M32 and NGC 205. For reviews on dwarf spheroidal galaxies the reader is referred to Da Costa (1992), Gallagher & Wyse (1994) and Ferguson & Binggeli (1994).

11.2 Population content

A compilation of the mean metallicities of dwarf spheroidal galaxies has been given by Armandroff *et al.* (1993). These data show a loose correlation between the integrated magnitudes M_V, and the mean metallicities $< [Fe/H] >$ of dSph galaxies, in the sense that the least luminous objects have the lowest metallicities. This trend is strengthened by the observations of Mateo *et al.* (1995) which show that the Sagittarius dSph galaxy (which may originally have been much more luminous than its present value $M_V \sim -13$::) has $< [Fe/H] > \sim -1.1 \pm 0.3$, which is higher than that of any of the other dSph galaxies fainter than $M_V = -15.0$.

Color–magnitude diagrams of dSph galaxies show that many of these objects have had quite complex evolutionary histories. Some of them, like the Draco and Ursa Minor systems, appear to contain an almost pure old stellar population. Others, such as Fornax and Carina, have a stellar population that is predominantly of intermediate age. In fact

Table 14. *Dwarf spheroidal members of the Local Group*

Name	α (1950)	δ (1950)	Type	M_V	R_{GC} (kpc)
NGC 185	$00^h\ 36^m.1$	$+48^\circ\ 04'$	dSph/dE3p	−15.3	620
NGC 147	00 30.4	+48 14	dSph/dE5	−15.1	660
Fornax	02 37.5	−34 44	dSph	−13.7	131
Sagittarius	18 52.0	−30 32	dSph	−13::	18
And I	00 43.0	+37 44	dSph	−11.8	725
And II	01 13.5	+33 09	dSph	−11.8	725
Leo I (Regulus)	10 05.8	+12 33	dSph	−11.7	273
Sculptor	00 57.5	−33 58	dSph	−10.7	78
And III	00 32.6	+36 14	dSph	−10.3	725
Psc = LGS3	01 01.2	+21 37	dIr/dSph	−10.2	760
Sextans	10 10.5	−01 22	dSph	−10.0	79
Phoenix	01 49.0	−44 42	dIr/dSph	−9.9	390
Leo II	11 10.8	+22 26	dSph	−9.9	215
Tucana	22 38.5	−64 41	dSph	−9.5	870
Ursa Minor	15 08.2	+67 18	dSph	−8.9	63
Carina	06 40.4	−50 55	dSph	−8.9	87
Draco	17 19.4	+57 58	dSph	−8.6	76

observations (Stetson 1997) appear to show that Fornax contains a small population of objects with ages of only a few $\times\ 10^8$ years. Finally objects like the Pisces dwarf (= LGS3) are found (Lee 1995, Mould 1997) to contain a strong old evolved population, on which a weaker young blue population component is superposed. The Pisces galaxy is therefore intermediate between normal dwarf irregulars (which exhibit a strong young component), and dSph galaxies that only contain old and intermediate-age stars. The Phoenix system (Ortolani & Graton 1988) is another example of a dSph/dIr galaxy that contains both old and young population components. The existence of such galaxies with intermediate population characteristics supports the notion (Kormendy & Bender 1994) that faint dwarf irregulars and dwarf spheroidals are basically similar types of objects that are viewed at different evolutionary stages. In other words, it does not seem necessary to hypothesize (Lin & Faber 1983) that all dSph galaxies were originally dwarf irregulars from which the gas was stripped by ram pressure.

It was first noted by Einasto, Saar & Kaasik (1974) that dSph satellites occur closer to their primaries than do dIr companions. More recently van den Bergh (1994) has drawn attention to a possible correlation between the stellar content and Galactocentric distances of dSph satellites of the Milky Way system, which might have been caused by such sweeping. The close Galactic satellites Dra and UMi have only an old stellar population, whereas the more distant Fornax and Carina systems also contain a strong intermediate-age population component. However, an argument against such a simple picture is that the very distant Tucana dwarf (Castellani, Marconi & Buonanno 1996) does not contain a young population component, even though it is far removed from both the Galaxy and

M31. Oosterloo, Da Costa & Staverley-Smith (1996) have found a cloud with a mass of $\sim 1.5 \times 10^6$ $M_\odot$ of H I that might be associated with the Tucana dwarf. They note that 'The presence of H I associated with Tucana would mean that the three isolated Local Group dwarfs with dominant old stellar populations, namely Tucana, Phoenix and LGS3, are all distinct from the dwarf spheroidal companions of the Galaxy and M31 in that they possess measurable amounts of H I.' Perhaps these three isolated systems have been able to retain some primordial H I, whereas dSph galaxies near M31 and the Galaxy may have been swept free of such gas. However, such a simple scenario does not appear to be consistent with the observation (Mateo *et al.* 1995) that the very nearby Sagittarius system, which would be expected to have been swept clean of gas early in its career, contains a significant ~ 10 Gyr old intermediate-age population. Only the rather *ad hoc* hypothesis that the Sgr system has fallen in from a very large distance, appears able to save the notion that the dwarfs near M31 and the Galaxy were stripped of gas by moving through the halos of these giant galaxies. The Pegasus dwarf irregular galaxy (Aparicio & Gallart 1995) is an example of an intrinsically faint dIr galaxy that contains a strong old red population component. Among more luminous dwarf irregulars the WLM galaxy (= DDO221) is found (Minniti & Zijlstra 1996) to be embedded in a strong old metal-poor halo, and the S0/dSph galaxy NGC 205 (Lee 1996) contains a minority population of relatively young blue stars near the centroid of a dominant old population. *In summary, it appears that available evidence strongly supports the view that dwarf spheroidals can have quite complex star forming histories.* In this respect they differ dramatically from globular clusters which, with only a few exceptions, only contain stars of a single age and metallicity. Another striking difference between globular clusters and dwarf spheroidals is that most dSph galaxies appear to contain dark matter (e.g. Mateo 1997), whereas globulars do not. This shows (Kormendy 1990a) that the majority of dSph galaxies in the Local Group were formed as individual objects, and that they were not produced as condensations from tidal arms (Mirabel *et al.* 1992) that had been drawn out during interactions between massive galaxies. This is so because significant amounts of dark matter would not have become entrained in such tidal arms (Barnes & Hernquist 1992).

An additional argument against the hypothesis that most dSph galaxies were formed from tidal tails is provided by their low metallicities. Inspection of the prints of *The Palomar Sky Survey* shows that long tidal tails are usually produced during strong interactions between *giant* spirals. Even in the outermost regions such giant spirals typically have $[Fe/H] > -1.0$, whereas all Local Group dSph galaxies fainter than $M_V = -15$ have $[Fe/H] < -1.0$.

Burkert & Ruiz-Lapuente (1997) have drawn attention to the fact that the complex star forming history of dSph galaxies is unexpected. Data suggest that star formation in most dSph galaxies took place on a time-scale of a few Gyr. This result is quite puzzling from a theoretical point of view. This is so because most processes that regulate star formation (such as heating by high-mass supernovae of Type II, and cooling and dynamical contraction) have time-scales of only a few $\times$ 10^7 years. Star formation could, of course, have been delayed for a longer time if the gas in dSph galaxies had enough angular momentum to form a rotationally supported H I disk. However, no evidence has ever been found for such rotating gas disks in dwarf spheroidal galaxies. To overcome these difficulties Burkert & Ruiz-Lapuente (1996) have suggested that the gas in dSph galaxies, which was originally heated by SNe II on a short time-scale, is prevented from collapsing and forming stars by supernovae of Type Ia. Such supernovae are expected to start occurring $\sim 1 \times 10^9$ years after the initial burst of star formation took place in dSph galaxies. *In low-mass dSph galaxies heating by* SNe Ia *might keep the gas in a hot, hydrostatic equilibrium state, in which energy losses by cooling are balanced by the energy input of exploding* SNe Ia.

11.3 Location of dwarf spheroidals

Inspection of Table 14 shows that the majority of Local Group dSph galaxies are associated with either M31 or the Galaxy. Andromeda II is probably situated in the potential well of the Andromeda nebula, even though (see Figure 23) it is located closer in the sky to M33 ($d = 11°$) than it is to M31 ($d = 20°$). The Pisces (= LGS 3) galaxy may be a distant companion to M33, or it might be a member of the M31/M33 sub-group of the Local Group. It is not clear (Byrd *et al.* 1994) if Leo I (which has a large radial velocity) is, or is not, a satellite of the Galaxy. If Leo I is physically associated with the Milky Way system then the Galactic mass inside 50 kpc is 5.1×10^{11} $M_\odot$, compared to only 3.9×10^{11} $M_\odot$ if it is not (Kochanek 1996). Among the dSph galaxies listed in Table 14 only Phoenix and Tucana, and perhaps Pisces and Leo I, appear *not* to be associated with

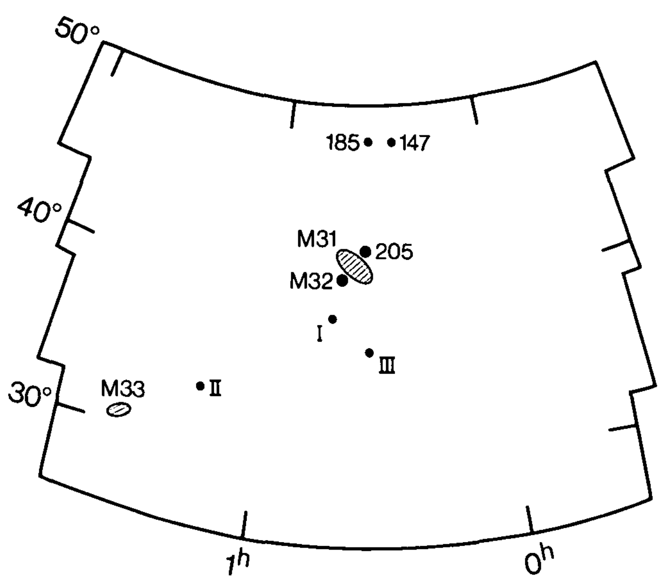

Fig. 23 This figure shows the location of the dwarf spheroidal galaxies And I, And II and And III. Note that And II is situated closer to M33 in the sky than it is to M31. However, it is still quite possible that it is actually located within the M31 potential well.

one of the three most massive Local Group members. This strongly suggests that the creation of dwarf spheroidal galaxies was intimately tied to the process that leads to the formation of giant spirals. This contrasts strongly with the situation for dIr galaxies fainter than $M_V = -15$ in the Local Group. All of these objects (IC 1613, DDO 210, WLM and Pegasus) are isolated.

11.4 Radial distribution of dwarf spheroidals

Among the dSph satellites of the Galaxy listed in Table 14 only one (Sgr) is located at $R_{GC} < 60$ kpc, while five (Car, Dra, Scl, Sex, UMi) have Galactocentric distances R_{GC} in the range 60–100 kpc. This suggests that some dSph galaxies that once existed at $R_{GC} < 60$ kpc, might have been destroyed by Galactic tidal forces, or captured via dynamical friction. Bellazzini, Fusi Pecci & Ferraro (1996) have noted that the dSph galaxies with the *lowest* surface brightnesses (which are the least able to resist tidal destruction) are situated closest to the Galaxy. Possibly this indicates that many low surface brightness dSph galaxies remain to be discovered at large distances from the Galaxy. However, this suggestion has been questioned by Kleyna *et al.* (1997) who used an adoptive kernal approach to search $\sim\frac{1}{4}$ of the sky without finding a single new dSph galaxy brighter than $M_V \simeq -9.5$.

The absence of any dSph galaxies with high surface brightness at $R_{GC} < 100$ kpc, which is noted by Bellazzini *et al.*, is not unexpected because only three such objects are known in the $26 \times$ larger volume with 100 kpc $< R_{GC} <$ 300 kpc. If the luminosity function of the Local Group does, indeed, contain more faint dSph galaxies than presently believed, then the apparent discrepancy between the shallow slope of the faint end of the Local Group luminosity function, and the steeper slope of the luminosity functions of rich clusters (Driver *et al.* 1994, Bernstein *et al.* 1995), might be reduced.

11.5 Summary

Dwarf spheroidals are the most common type of galaxy in the Universe. Some of them may have formed recently from condensations in tidal arms. However, the majority were probably formed $>$ 10 Gyr ago. The fact that many of these objects contain stellar populations which have a wide range of ages suggests that some dSph galaxies have had a complex evolutionary history. This may indicate that late-time heating by SNe Ia was able to keep the gas in dSph galaxies in hot hydrostatic equilibrium for periods of 1–10 Gyr. The radial distribution of the dSph companions of the Galaxy suggests that: (1) some dwarf spheroidals with $R_{GC} < 60$ kpc may have been destroyed by tidal forces, and (2) a number of low-density dSph galaxies with $R_{GC} > 100$ kpc still remain to be discovered.

The relationship between dSph, dE and S0 galaxies remains a subject of lively controversy. The most severe problems of galaxy taxonomy occur at $M_V \sim -16$ where different morphological classes appear to blend together. Is NGC 205 an elliptical or an S0; is NGC 185 a bright dSph, and is M32 a prototypical low-luminosity elliptical or the end product of an unusual evolutionary history?

12 Low surface brightness galaxies

12.1 Selection effects

The disks of galaxies on the Hubble sequence Sa–Sb–Sc have central surface brightnesses that appear to fall in a rather narrow range (Freeman 1970). Zwicky (1957, p. 113) and Disney (1976) were among the first to emphasize the fact that this might be the result of a selection effect which is due to the difficulty in discovering galaxies of very low surface brightness[1]. The fact that dwarf spheroidal galaxies, which are now known to be the most common type of extragalactic objects, were not discovered until the 1930s (Shapley 1939) supports this notion. It was originally thought (e.g. van den Bergh 1959) that all galaxies with a low surface brightness[2] were early or late-type dwarfs. However, radial velocity observations by Fisher & Tully (1975) showed that some galaxies with low surface brightnesses are actually quite large and luminous. This effect is clearly shown in Figure 24 which compares the surface brightnesses of the disks of normal and of low-luminosity galaxies. An interesting feature of Figure 24 (see also Figure 1 of Bothun, Impey & McGaugh (1997)), which is presently not well understood, is that disk galaxies with surface brightnesses that are significantly higher than those of normal spirals do not appear to exist. This is shown most clearly in Courteau (1996b), who finds that there is a rather well-defined upper cut-off at a red central surface brightness of ~ 17.5 mag arcsec^{-2}. Dalcanton, Spergel & Summers (1997) have speculated that disk instabilities might explain the observed lack of high surface-density disks.

By combining data from various surveys Bothun *et al.* (1997) find that the space density of galactic disks remains approximately constant between the Freeman (1970) peak at a blue central surface brightness of 21.5 mag arcsec^{-2} and an observational completeness limit at a blue central surface brightness of 24 mag arcsec^{-2}, i.e. over a range of ~ 10 in surface brightness. On the other hand Tully & Verheijen (1997) find that a complete sample of 62 galaxies in the nearby Ursa Major cluster exhibits a central surface brightness distribution with two well-separated peaks. These authors find that this separation is particularly clear-cut in the K′ band (in which absorption effects are

[1] A few galaxies will also be lost from surveys because they are hidden by bright quasars in their nuclei (e.g. Rönnback *et al.* (1996)), or because they are BL Lac objects (Falomo 1996) in which the parent galaxy is eclipsed by a bright central source of radiation.

[2] Low surface brightness galaxies may be defined as objects having a central blue surface brightness fainter than 22.0 mag arcsec^{-2}.

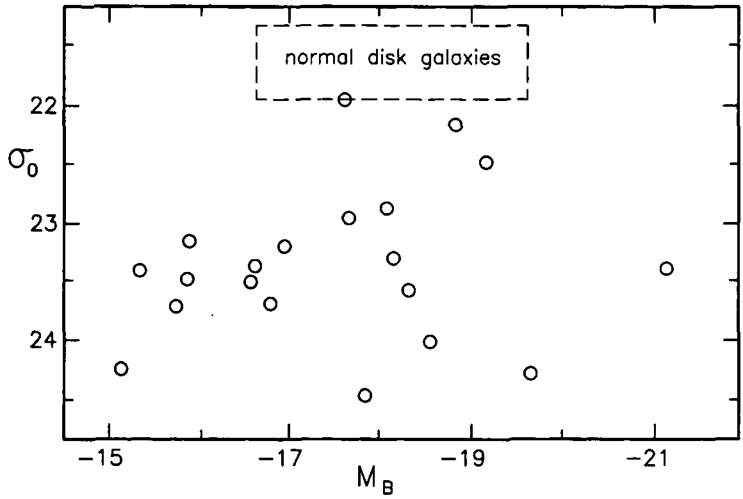

Fig. 24 The relation (McGaugh 1992) between disk surface brightness and integrated absolute magnitude M_B for (1) ordinary galaxies contained within one standard deviation of Freeman's (1970) mean central brightness $\sigma_0 = 21.65 \pm 0.3$ mag arcsec^{-2} (box), and (2) low surface brightness galaxies, which are plotted as open circles.

small), and when galaxies with close companions are excluded. The high surface brightness peak consists mainly of galaxies of Hubble stages Sa, Sb and Sc, whereas the low surface brightness peak mostly contains objects of types Sd, Sm and Im. Since high low surface brightness galaxies have similar scale lengths the division noted by Tully & Verheijen (1997) is also apparent in the Hubble stage versus M_B plot shown in Figure 1. However, from this plot it is not obvious that there is a real dichotomy between early- and late-type disk galaxies. De Jong (1996) also finds no dichotomy between early-type high surface brightness spirals and late-type objects having a low surface brightness. Taken at face value the result by Tully & Verheijen would suggest that normal and low surface brightness galaxies constitute physically distinct classes of objects. These authors suggest that the luminous material in low surface brightness galaxies has settled into a disk that is dominated by the halo potential, whereas the luminous material has become self-gravitating in the inner disk regions of high surface brightness galaxies. If the dichotomy between high and low surface brightness disks is confirmed by future work it might imply that galaxies with intermediate-density disks are unstable, i.e. disk galaxies must either have a 'maximum disk' or a 'minimum disk.' It is noted in passing that (1) both the high and the low surface brightness disk galaxies in the Ursa Major cluster lie on the same Fisher–Tully relation, and (2) the high surface brightness and LSM galaxies have similar disk scale lengths. It is noted in passing that global starbursts must be rare in any galaxian population that has a small luminosity dispersion around the Fisher–Tully relation.

12.2 A pair of low surface brightness galaxies

On the prints of the *Palomar Sky Survey* low surface brightness galaxies have a 'ghostly' appearance that clearly differentiates them from normal high surface brightness galaxies. A good example is provided by the pair NGC 4411A and NGC 4411B, that are shown in Figure 25. These objects are located 3°.66 from M87 and have redshifts of $V_{\odot} = 1277$ km s^{-1} and $V_{\odot} = 1266$ km s^{-1}, respectively. This indicates that: (1) they are probably members of the Virgo cluster, and (2) they form a close physical pair. Some of the parameters describing this pair (Binggeli, Sandage & Tammann 1985) are listed in Table 15. The classifications SBc II and Sc II, respectively, given by these authors are inconsistent with the low surface brightnesses of these objects. The B–V colors of NGC 4411AB indicate that most of the light of these low surface brightness galaxies is presently being contributed by moderately old stars. The fact that NGC 4411A is a barred spiral shows that bar instabilities do occur in LSB galaxies. It would be interesting to know if barred objects are more, or less frequent among low surface brightness galaxies than they are among normal galaxies. It seems rather probable that the low surface brightness of these two galaxies is due to ram-pressure stripping (Gunn & Gott 1972) of gas in their disks by intra-cluster material in the Virgo cluster.

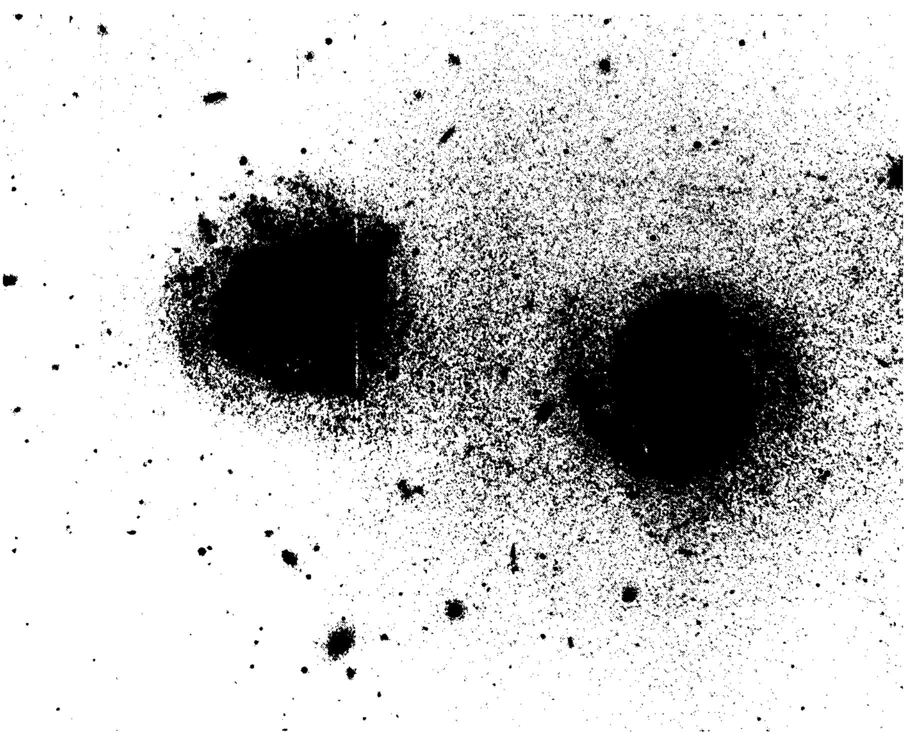

Fig. 25 The low surface brightness Virgo galaxies NGC 4411A (left) and NGC 4411B (right) from a 15 min blue (103aO emulsion + GG 385 filter) exposure at the prime focus of the CTIO 4-m Blanco telescope.

Table 15. *Properties of low surface brightness galaxies NGC 4411AB in the Virgo cluster*

NGC	DDO class.	B_T	$B-V$	M_B^a	$V_{\odot}$ (km s^{-1}1)
4411A	S(B)c III–V	13.4	0.72	−17.6	1217 ± 70
4411B	Sc III/III–IV	12.9	0.64	−18.1	1266 ± 73

[a] $(m - M)_0 = 31.0$ assumed

12.3 Three types of low surface brightness galaxies

For the sake of convenience LSB galaxies may be sorted into *at least* three classes. (1) monsters, such as Malin #1 (Bothun *et al.* 1987, Impey & Bothun 1989) and Malin #2 (Schombert & Bothun 1988), which have dimensions that are comparable to those of the cores of clusters of galaxies, (2) low surface brightness galaxies with luminosities similar to those of most normal spirals (McGaugh 1992, and references therein), and (3) dwarf irregular (Ir V), dwarf spiral (S V) and dwarf spheroidal (dSph) galaxies. The interrelationship between these three taxonomical classes of low surface brightness galaxies remains obscure. Possibly the Malin-type supergiants are remnants of some past cosmic catastrophe that have managed to survive because they occurred in low-density regions of the Universe. Alternatively Malin-type objects might be rare survivors of the class of Lyman α absorbers that are seen in the spectra of high-redshift quasars. The fact that the integrated colors of Malin-type objects are quite red suggests that they contain a significant old population and were therefore not formed recently. The low present rate of star formation in Malin-type objects is, no doubt, due to their small H I column density.

12.4 Physical characteristics of low surface brightness galaxies

This section deals with low surface brightness galaxies having luminosities comparable to ordinary spirals, i.e. not with dIr and dSph galaxies. Such objects exhibit a wide range in physical characteristics. Perhaps the most striking feature of these objects is that almost all of them contain disks that are well described by exponential luminosity profiles. However, a significant number of them also contain central bulges. Integrated color observations by McGaugh show that it is usually the reddest low surface brightness objects that have bulges. The super-giant galaxies Malin #1 and #2 appear to be redder than the majority of low surface brightness galaxies with luminosities that are comparable to those of normal spirals. Bothun, Impey & Malin (1991) find that some low surface brightness galaxies have a central surface brightness fainter than $\sigma_0 = 26$ mag arcsec^{-2}. Existing surveys of such extremely dim objects must be exceedingly incomplete. Most low surface brightness galaxies are quite blue. McGaugh (1992) points out that *this immediately rules out the hypothesis that the low surface brightness of such objects is due to fading.* This is so because disks will become redder as young blue stars fade away. McGaugh finds median colors $B - V = 0.44$ and $U - B = -0.12$ for his sample of low surface brightness galaxies. These colors are close to those expected for systems that are forming stars at a constant rate. However, a survey of low surface brightness galaxies by O'Neil, Bothun & Cornell (1997) suggests that the number of red low surface brightness galaxies may have been under-estimated in previous surveys. It might be speculated that some of these faint red objects are the remnants of the mysterious excess population of blue galaxies (Glazebrook *et al.* 1995) that is seen at large redshifts. On the other hand Guzmán *et al.* (1997) suggest that the remnants of high redshift blue galaxies are brighter spheroidal galaxies like NGC 205.

The spread in the observed integrated colors of low surface brightness galaxies is large. This shows that such objects have had a wide range of evolutionary histories. This conclusion is supported by the observation that the oxygen abundances in low surface brightness galaxies range from near-solar values of log (O/H) $= -3.13 \pm 0.07$ (Grevesse & Noels 1993), to log(O/H) $= -4.8$ in I Zw 18. (The distribution of O/H values in *compact* dwarfs is similar to that in low surface brightness galaxies.) The fact that typical low surface brightness galaxies have O/H abundance ratios that are a few times lower than those in the Sun suggests that most of these objects are relatively unevolved. Alternatively the mass spectrum of star formation in low surface brightness galaxies might contain fewer massive stars than it does in normal high surface brightness spirals. Most low surface brightness galaxies contain a large gas mass fraction (McGaugh & de Blok 1997). This tends to support the hypothesis that they are relatively unevolved objects, i.e. galaxies that have not changed as much over a Hubble time as normal high surface brightness galaxies. Low surface brightness galaxies that have a high gas content, and which exhibit a high rate of star formation, probably became active quite recently.

De Blok, McGaugh & van der Hulst (1996) have shown that the H I surface density distribution of ordinary low surface brightness galaxies differs from that of their cousins resembling Malin #1, which have a doughnut-like distribution of neutral hydrogen gas. The rotation curves of low surface-brightness galaxies rise more slowly than those of ordinary disk galaxies. This suggests that not only the light but also the mass are distributed more diffusely in low surface brightness galaxies than they are in normal disk systems. This result indicates that mass distribution was probably one of the factors that caused the systematic differences between the evolutionary histories of normal and low surface brightness galaxies.

One expects low-density galaxies, which are thought to have arisen from low-density peaks in the initial fluctuation spectrum, to start forming rather late in the evolutionary history of the Universe. This suggests that low surface brightness galaxies should be less clustered than galaxies of higher surface brightness. This expectation is confirmed by Mo, McGaugh & Bothun (1994) who find that low surface brightness galaxies, although embedded in the same large-scale structures as high surface brightness galaxies, are less strongly clustered. In fact most low surface brightness galaxies are extremely isolated on scales of less than 2 Mpc. However, there are exceptions such as the low surface brightness pair NGC 4411AB, which was discussed in Section 12.2, which appears to be situated in the core of the Virgo cluster. Possibly this is an example of a different type of low surface brightness galaxy, in which the present low surface brightness is due to recent sweeping by intra-cluster gas.

Zwaan *et al.* (1995) have drawn attention to the surprising fact that low surface brightness galaxies obey the same Fisher–Tully relation between their maximum rotational velocity and blue luminosity M_B as do normal spirals. This suggests that low surface brightness galaxies also have a low surface mass density σ_m, so that the product $\sigma_m M/L$ remains constant.

The disk scale-lengths of low surface brightness galaxies are typically 2–3 kpc. These values are quite similar to those of normal spiral galaxies. (However, at a fixed maximum rotational velocity the dimensions of low surface brightness galaxies are approximately twice as large as those of normal disk galaxies.) It is, perhaps, surprising that there appears to be no correlation between the scale-length of low surface brightness disks and their central surface brightness σ_o. This is so, even though the central surface brightnesses of the disks of such low surface brightness galaxies are typically a couple of magnitudes lower than those of normal spirals.

Dalcanton, Spergel & Summers (1997) point out that galaxies with low surface brightness disks will be extremely good tracers of the properties of dark matter halos. This is so because (1) the rotation curve of a galaxy with a low surface density will be closer to that of a pure halo than that of a galaxy with a massive disk, and (2) the rotation curves of low surface brightness disks will tend to reflect any deviations from axisymmetry within their halos much more clearly than would be the case for galaxies with massive disks.

Knezek (1993) has studied the properties of a matched set of UGC (*Uppsala General Catalogue*) galaxies that exhibit high (HSB), intermediate (ISB), and low (LSB) surface brightnesses. These data, which are shown in Table 16, suggest that these three classes of objects differ in their surface brightnesses, but not in their total, and H I, gas masses. Furthermore Knezek found that high surface brightness galaxies are much more likely to have close companions than low surface brightness galaxies. This suggests that either (1) interactions between close companions stimulates star formation, or (2) galaxies with close companions are more likely to have captured gas from companions.

Mihos, McGaugh & de Blok (1997) find that bars are relatively rare in low surface brightness galaxies. Despite their seemingly fragile nature low surface brightness galaxies are quite stable against the growth of bar instabilities. This is so because their low disk surface density and high dark matter content deprives them of the disk self-gravity necessary to amplify non-axisymmetric dynamical seeds.

12.5 Was the Large Magellenic Cloud (LMC) once a low surface brightness galaxy?

Butcher (1977) discovered a break in the slope of the main sequence luminosity function of stars in the LMC. This break is located about 1 mag above the main sequence turnoff point of Population II stars. From this observation Butcher concluded that a major burst of star formation took place in the LMC 3–5 Gyr ago, and that the rate of star formation had been quite low before this burst occurred. This unexpected conclusion was subse-

Table 16. *Mean surface brightness, mass and gas content of UGC galaxies*[a]

	Surface brightness (mag arcsec^{-2})		
Parameter	$\sigma_B < 24$ HSB	$24 \leq \sigma_B \leq 25.5$ ISB	$\sigma_B > 25.5$ LSB
$< B >$	13.6	14.6	16.0
$< \log L_B (L_\odot) >$	10.7	10.3	9.8
$< \log M_{HI} (M_\odot) >$	10.3	10.3	10.2
$< \log M_{dyn} (M_\odot) >$	11.2	11.2	11.1
$< V >$ (km s^{-1})	4892	5043	5058

[a] From Knezek (1993).

quently confirmed by Stryker (1983) and by Hardy *et al.* (1984). For a discussion of this subject the reader is referred to the reviews by Olszewski, Suntzeff & Mateo (1996) and Elson, Gilmore & Santiago (1997).From an investigation of three starfields in the LMC Bertelli *et al.* (1992) estimate that the mean rate of star formation in the LMC was as much as ten times lower before this burst, than it has been since then. A rather different conclusion was reached by Holtzman *et al.* (1997) who, from the study of a single field in the outer region of the LMC, conclude that the best fit to the observed stellar luminosity function is provided by a model in which the rate of star formation in the LMC was, during most of its lifetime, only about three times lower than it has been since the LMC entered its present high state of star forming activity that started a few Gyr ago. Stappers *et al.* (1997) have found that the rate of star formation near NGC 1866 increased by about a factor of 2 $\sim$ 3 Gyr ago. Caveats are that such calculations depend in a rather sensitive way on the assumed distance to the LMC, the adopted mass spectrum of star formation and, to a lesser extent, on details of the assumed heavy element enrichment history of the LMC. From their *HST* observations of a field located at 1°.3 from the center of the LMC Elson *et al.* (1997) conclude that only $\sim$5% of the stars in this field belong to the old disk and halo population that predates the great burst of star formation which started $\sim$5 Gyr ago.

Da Costa (1991) has shown that a similar break exists in the age distribution of clusters in the LMC. After an initial burst of cluster formation 13–15 Gyr ago (during which 13 globulars were formed) there was a hiatus that lasted $\sim$8 Gyr, which ended with the burst of open cluster formation that started 3–5 Gyr ago. During the 'dark ages' between 12 Gyr and 4 Gyr ago the rate of cluster formation in the LMC appears to have been at least an order of magnitude lower than it is at the present time. During the 'dark ages' the LMC might therefore have exhibited the characteristics of a typical low surface brightness galaxy. It is of interest to note that four or five populous clusters are known to have formed in the Small Magellanic Cloud (SMC) during the $\sim$8 Gyr period when the LMC was inactive and formed only a single cluster (ESO 121-SC03 (Mateo, Hodge & Schommer 1986)). This suggests that the SMC was actively forming stars and clusters during the long period when the LMC was an inactive low surface brightness galaxy. The observation that the SMC does not appear to have undergone a burst of star and cluster formation 3–5 Gyr ago suggests that the burst of star formation in the LMC was *not* triggered by a close tidal encounter between the LMC and the SMC. The cluster ESO 121-SC03 (which is located $10^{\circ}.1 = 8.8$ kpc from the center of the LMC) is estimated to have an age of 6.4 Gyr (Sarajedini, Lee & Lee 1995) and has a metallicity [Fe/H] = −0.9, which is intermediate between that of the open clusters and globular clusters in the LMC. This cluster might perhaps have been captured from the SMC.

The data presented above suggest that the LMC may be a nearby example of objects of the type that Babul & Ferguson (1996) have named '*boojums*' (blue objects just undergoing moderate starbursts).

The observations which have been described above appear to indicate that the LMC transformed itself from a low surface brightness galaxy into an active magellanic irregular ~4 Gyr ago. This suggests that galaxies can sometimes jump from one morphological classification type to another.

Da Costa (1991) has pointed out that there is a clear-cut dichotomy between the LMC globular clusters with ages of 13–15 Gyr, which have metallicities in the range $-2.1 < [\mathrm{Fe/H}] < -1.4$, and open clusters with ages <4 Gyr, which have $-1.0 < [\mathrm{Fe/H}] < 0.0$. It is presently not clear how the metallicity of the LMC could have increased by an order of magnitude during the 'dark ages' while the rate of heavy element producing supernova explosions was, presumably, low. The following hypotheses might be proposed to account for this large increase in metallicity during a period when the LMC appears to have been quite inactive:

- The LMC swept up enriched gas from the SMC during a close encounter 3–5 Gyr ago. Arguments against this idea are that (1) the LMC open clusters formed during the last ~4 Gyr are more metal-rich than the gas and stars in the SMC, and (2) it appears that there was no burst of cluster formation in the SMC ~4 Gyr ago. Such a burst of star formation would have been the signature of such a close tidal encounter between the LMC and SMC.
- The LMC captured a massive metal-rich gas cloud 3–5 Gyr ago. A problem with this idea is that the orbit of the LMC did not come close enough to the Galaxy (see, e.g., Murai & Fugimoto (1980)) at this time for it to have picked up significant amounts of such metal-rich gas from the Milky Way system. This conclusion is confirmed by Hipparcos observations (Kroupa & Bastian 1997), which show that the LMC is presently close to apogalacticon.

It is therefore concluded that the process that increased the metallicity of the LMC by an order of magnitude between 13 and 5 Gyr ago remains unknown.

During its first active phase 13–15 Gyr ago the LMC produced 13 globular clusters. In conjunction with $M_V \approx -18.5$ this yields a present specific globular cluster frequency $S \approx 0.5$. However, during the 'dark ages' the LMC might have been ~2 mag fainter than it is now yielding a value $S \sim 3$ while the LMC was a low surface brightness galaxy. It would be of interest to observe relatively nearby late-type low surface brightness galaxies to see if they exhibit such a relatively high specific globular cluster frequency.

12.6 Summary

The following types of low surface brightness galaxies are presently known:

(1) Monsters like Malin #1, which may have been formed during some cosmic catastrophe.
(2) Low surface brightness galaxies with total luminosities comparable to those of normal spirals.
(3) Low surface brightness dwarfs, which range from early-type (dSph) to late-type (Ir V).
(4) NGC 4411AB-like objects, from which gas may have been removed by ram-pressure stripping.

Available data suggest that the LMC transformed itself from a low surface brightness galaxy to a normal magellanic irregular ~4 Gyr ago. This provides a clear counter example to the claim by Linnaeus (1751) that *Natura non facit saltum.* Such changes in morphology might be triggered by tidal encounters or by capture of massive intergalactic gas clouds.

The reason why disk galaxies exhibit a sharp upper limit (Bothun *et al.* 1997) to their central surface brightness is presently not understood. It would be interesting to know if the frequency of bars is different in normal galaxies and in low surface brightness galaxies of similar Hubble stage. It is not yet clear if galaxy disks exhibit a continuous distribution of σ_0 values (Bothun *et al.* 1997), or if the distribution of σ_0 is bimodal (Tully & Verheijen 1997). In the latter case normal and low surface brightness galaxies would represent physically distinct classes of objects.

13 Morphology of active galaxies

13.1 Ground state and excited galaxies

Excited galaxies (see Figure 26), i.e. objects that are not in the 'ground state,' fall into two broad classes: (1) diffuse galaxies with a high rate of star formation, such as starburst galaxies, Markarian galaxies, amorphous galaxies, Haro galaxies, intergalactic H II regions; and (2) objects with active nuclei, such as quasars, BL Lac objects (= blazars) and Seyfert galaxies. Most quasars and galaxies with active nuclei are located at large distances. This makes it difficult to study their morphology in detail. The images of luminous IRAS sources, including Seyfert 1, Seyfert 2, LINER (= low ionization nuclear emission-line region) and QSO parent galaxies by Hutchings & Neff (1991) suggest that many of them have a highly disturbed morphology including (what appear to be) tidal tails. Bahcall *et al.* (1996) show that the host galaxies of nearby quasars are frequently disturbed and interacting objects.

Active nuclei of galaxies can be fuelled by inward transport of gas (Morris & Serabyn 1996) via any one of the following processes:

- Gas may lose angular momentum to a stellar bar or oval disk by gravitational torques. Gas orbiting in a bar potential will have non-circular orbits resulting in collisions that produce shocks, which in turn result in loss of energy and angular momentum. The effect of spiral density waves is similar to that of bars, provided that there is no inner Lindblad resonance.
- Very massive gas clouds will be subject to dynamical friction, which causes them to spiral inwards towards the galactic nucleus.
- Clouds moving through a strong magnetic field may suffer substantial friction and angular momentum loss due to magnetic viscous forces.
- Gas may also lose angular momentum by viscous drag in a differentially rotating galactic disk.
- A rapidly rotating gaseous disk might be slowed down if it incorporates material lost from stars in a slowly rotating stellar bulge.
- The tidal disturbances produced by a massive companion may introduce fresh gas into the vicinity of a central black hole on the galaxy encounter time-scale of $\sim 10^8$ years (Hernquist 1989). The observed correlation between active galactic nuclei and galaxy interactions (MacKentry 1989) attests to the importance of this process.

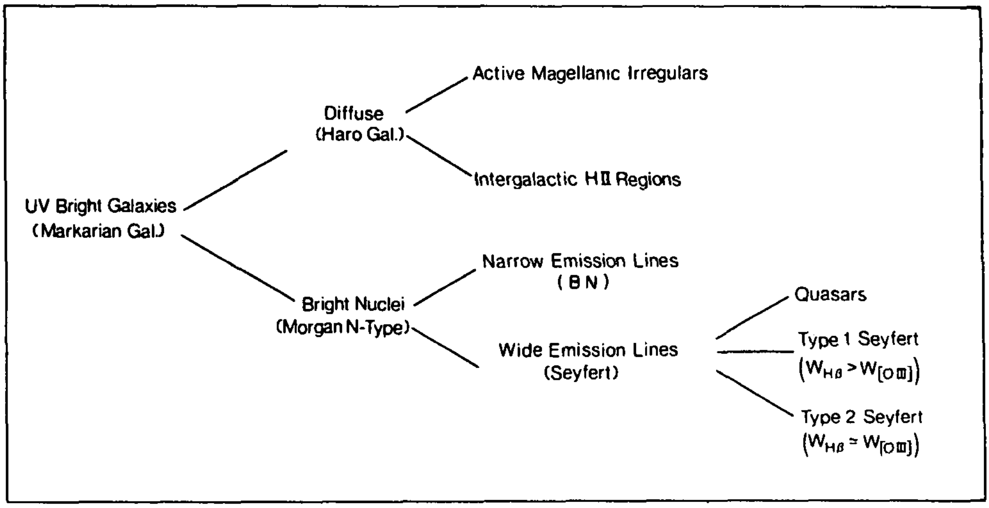

Fig. 26 Schematic illustration of various types of galaxies that are in excited states.

13.2 Seyfert galaxies

A listing of some relatively nearby Seyfert galaxies (Weedman 1977) that are illustrated in *The Carnegie Atlas of Galaxies* is given in Table 17. The data in this table show no striking morphological feature(s) that are shared by all of these objects. The Seyfert galaxies in Table 17 have Hubble types that range from E to Sbc. Four, or perhaps five, of the ten objects listed in the table are barred spirals. This is only marginally higher than the 22% of all Shapley–Ames galaxies (Sandage & Tammann 1981) that are barred. Some of the objects in Table 17 are definitely *not* barred spirals, so that the existence of a bar is not a necessary condition for transfer of gas into a galactic nucleus. However, a few of them may exhibit oval distortions. In particular Kormendy (1982) suggests that the nuclear activity in both NGC 1068 and NGC 4151 might have been facilitated by the presence of oval disks in these objects. In the case of NGC 3227 a violent interaction with NGC 3226 might have been responsible for dumping gas into the active nucleus. An above-average fraction (3 out of 10) of the galaxies in the table exhibit striking morphological peculiarities. Particularly compelling evidence to support the hypothesis that the Seyfert phenomenon is produced by gas dumped into nuclei during violent interactions is provided by the Seyfert ring galaxy NGC 985. Observations by Pérez Garcia & Rodríguez Espinosa (1996) show a second nucleus located only 4″ from the Seyfert nucleus of this object. The highly peculiar knots (see Figure 27) superimposed on the main body of NGC 4151 might perhaps be due to a direct interaction between the active nucleus and the gas in the galactic disk. One might also speculate that the unusually bright inner regions of NGC 1068 and NGC 1566 were produced by interactions with their nuclear energy sources.

Table 17. *Morphology and classification of some nearby Seyfert galaxies*

NGC	DDO class	Type	Atlas frame[a]	Remarks
1068	Sbc pec	Sy 2	[138]	Bright inner spiral superposed on faint outer spiral structure
1275	E0:pec	?	[24]	Hα filaments, dust patches, star clusters and associations
1566	Sbc I	Sy 1	[S5, 171]	Normal well-developed two-arm spiral with bright central region
3227	Sbcnt!	Sy 2	[26]	Has fuzzy patchy spiral arms. Violently interacting with the S0 galaxy NGC 3226
3516	SB0	Sy 1	[57]	Has faint outer ring or ansae
3783	SBab I	Sy 1	[98]	Normal multi-armed SB galaxy
4041	S(B)bc II	Sy 1	[180]	Multi-armed late-type spiral
4151	Sab:pec	Sy 1	[119]	Highly peculiar early-type galaxy with strings of resolved knots superposed
4507	S(B:)b II:	Sy 2	[123]	Two-armed spiral
6814	Sbc II	Sy 1	[175]	Multi-armed with bright bulge. Perhaps an S(B)bc galaxy

[a] Frame number from the atlas of Sandage & Bedke (1994).

13.3 Intergalactic H II regions

The nature of the active galaxies that have been described as 'intergalactic H II regions' is controversial. Taylor (1997) points out that low surface brightness dwarfs have dynamical masses similar to those of H II galaxies. This suggests the possibility that H II galaxies might, in fact, be low surface brightness galaxies in which a burst of star formation has recently occurred. Gerola, Seiden & Schulman (1980) have argued that star formation in dwarf galaxies is likely to proceed in bursts, whereas giant galaxies probably exhibit a more nearly constant rate of star formation. This is consistent with the observations of 'blue compact dwarf galaxies' reported by Fanelli, O'Connell & Thuan (1988). From observations with the *International Ultraviolet Explorer* (*IUE*) satellite these authors find that such objects (which typically have $M_B \gtrsim -18$) had star formation histories that were characterized by discrete bursts of star formation lasting for a few million years that were separated by tens, or hundreds, of millions of years. Basically this conclusion is based on the observation that the *IUE* spectra of galaxies such as Markarian 209, which shows evidence for the presence of main-sequence O3–O6 V stars and B2–B3 V stars, without a significant contribution by O7–B1 V stars. Telles, Melnick & Terlevich (1997) have obtained a uniform set of images of 39 H II galaxies, from which they conclude that these objects are, in fact, a very inhomogeneous morphological class. An extended component, which possibly represents an underlying galaxy, is found in about half of these objects.

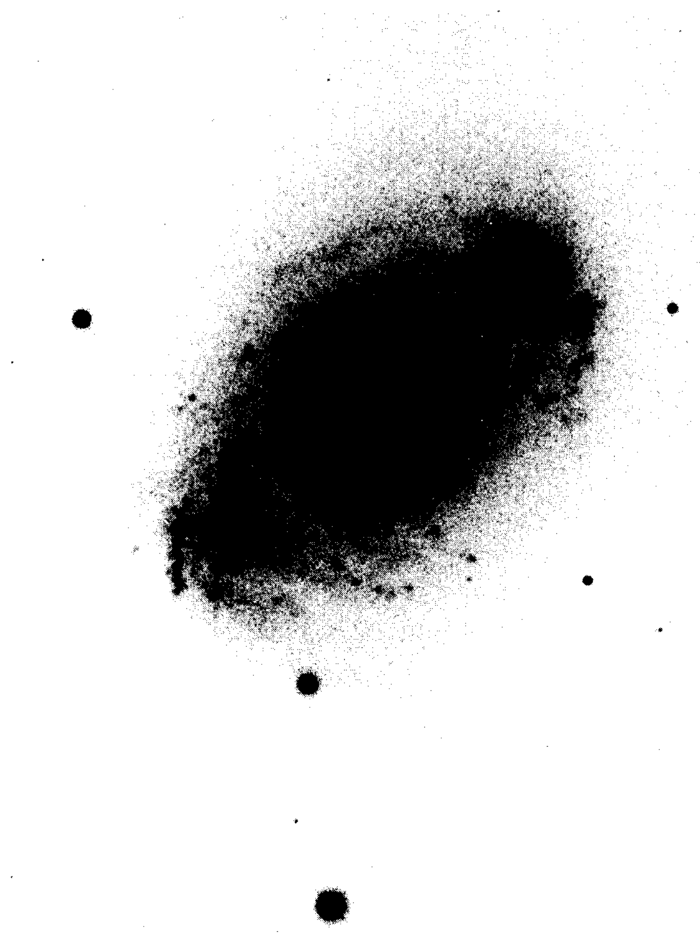

Fig. 27 Prime-focus 4-m Mayall telescope IIIaJ plate of the Seyfert I galaxy NGC 4151. The peculiar strings of knots visible in this image might have been produced by an interaction between the active nucleus and gas in the galactic disk/bulge.

Some H II galaxies also exhibit features such as wisps, tidal tails, or irregular fuzzy extensions, which suggest that they might be interacting or merging systems. On the basis of the shapes of their outer isophotes Telles *et al.* suggest that H II galaxies may be divided into two broad groups. Objects of Type I exhibit disturbed morphologies, irregular outer isophotes, fuzz or tails. On the other hand members of Type II are symmetric and regular objects, regardless of the multiplicity (i.e internal structure) of the starburst region. The H II galaxies of Type I are found to have higher velocity dispersions, and higher luminosities, than those of Type II. Telles *et al.* suggest that the starbursts in these types of objects might have been triggered by different mechanisms.

From an H I survey Taylor *et al.* (1996) find that H II galaxies have companions twice as often as do low surface brightness dwarfs. This suggests that differences in the frequency of nearby H I rich companions (which can be captured) might possibly account for some of the striking contrast between the star formation rates in low surface brightness galaxies and H II galaxies. Skillman (1996) finds that the radial H I profiles are more centrally peaked in H II galaxies than they are in typical dwarf irregulars. Haro 2 = Arp 233 is an example of a small class of low surface brightness non-star forming elliptical galaxies (Loose & Thuan 1986) that contain a single high surface brightness nuclear region.

13.4 Luminous infrared galaxies

At luminosities $> 10^{11}\ L_{\odot}$ infrared galaxies become the dominant population of nearby extragalactic objects (Sanders & Mirabel 1996). In most cases the intense infrared emission in these galaxies is thought to have been triggered by strong interactions of, or mergers between, gas-rich spirals. Observations obtained with the *ISO* short wavelength spectrometer (Lutz *et al.* 1996) show that such objects are mainly powered by recently formed massive stars that are embedded in dust clouds. The proto-typical object Arp 220 may contain a powerful nuclear starburst that is rapidly clearing out the obscuring dusty gas in the inner few kpc of this highly unusual galaxy. Lehnert & Heckman (1996) find that starbursts appear to have a limiting surface brightness of about $10^{11}\ L_{\odot}\ \mathrm{kpc}^{-2}$, corresponding to a maximum star formation rate of $\sim 20\ M_{\odot}\ \mathrm{yr}^{-1}\ \mathrm{kpc}^{-2}$. This suggests that starbursts are, in some way, self-regulating.

13.5 Summary

Active galaxies, which are not in the 'ground state' (Ozernoy 1974), belong to two main classes: (1) diffuse objects, such as Haro galaxies and Markarian galaxies, and (2) galaxies with active nuclei like quasars, Seyferts, blazars and LINERS. Activity in diffuse active galaxies may have been triggered by strong tidal interactions, collisions between gas-rich galaxies, or capture of large amounts of intergalactic gas. Active galactic nuclei appear to result from the capture of gas (and stars?) by massive central black holes.

14 Evolution of galaxy morphology

Butcher & Oemler (1978) discovered that distant rich clusters of galaxies contain more blue spiral galaxies than do similarly rich nearby clusters. This observation provided the first direct evidence for the evolution of galaxy morphology, i.e. that distant galaxies are (from an evolutionary point of view) younger than nearby galaxies. The limited resolution of ground-based telescopes made it difficult to follow this discovery up with more detailed studies of the evolution of galactic structure and morphology with increasing look-back time.

14.1 Galaxies viewed at large look-back times

A dramatic improvement of our ability to study distant galaxies is now provided by the *HST*. Abraham *et al.* (1996b) find that galaxies in the Medium Deep Survey (Driver, Windhorst & Griffiths 1995), which are typically located at $z \sim 0.5$, are basically still quite similar to those in the vicinity of the Milky Way, although the fraction of interacting galaxies (and objects that do not fit naturally within the Hubble classification scheme) is enhanced. Our deepest view into the past is provided by the *HST* observations in the Hubble Deep Field (Williams *et al.* 1996). These data are based on observations extending over 150 orbits in four colors of a field in Ursa Major. They provide images of 290 objects with $21 < I < 25$. Abraham *et al.* (1996a) find that the fraction of asymmetrical and distorted galaxies is larger in the Hubble Deep Field than it is in the Medium Deep Survey. A comparison between galaxy classifications on the DDO system in the *Shapley–Ames Catalog* (SAC) (van den Bergh 1960c), in the Medium Deep Survey (MDS) (Abraham *et al.* 1996b), and in the Hubble Deep Field (HDF) (van den Bergh *et al.* 1996) is shown in Table 18. A caveat is that galaxy classifications in the I band may have been systematically affected by the fact that distant galaxies in the Hubble Deep Field will, on average, be viewed at shorter rest frame wavelengths than they are in the less distant Medium Deep Survey. No significant systematic difference is, however, expected between the B observations of nearby galaxies and the I observations of Medium Deep Survey galaxies at $z \sim 0.5$.

A detailed study of cosmological bandshifting using pixel-by-pixel K corrections is discussed by Abraham, Freedman & Madore (1997). These authors conclude that 'the majority of peculiar/irregular/merging galaxies visible in the Hubble Deep Field are not simply bandshifted spiral galaxies, although some very late-type spirals will be misclassified as irregulars at high redshift.' The steep rise in the number count–magnitude

Table 18. *Frequency of galaxy classifications*

Type	SAC	MDS	HDF
E/S0	24%	20%	30%
S/Ir	69	63	31
Not classified	7	17	39

relation for such peculiar/irregular/merging galaxies continues to at least 25th magnitude in *I*. The increase in the number counts of such objects is much steeper than would be predicted by no-evolution models. This contrasts with the situation for E/S0 galaxies. The number counts for such early-type galaxies only slightly exceed the predictions obtained from no-evolution models.

The data in Table 18 show little change in the fraction of early-type galaxies as a function of look-back time. The most straightforward interpretation of this result is that elliptical galaxies formed at a very early epoch. However, uncertain corrections for evolutionary changes in galaxy luminosity leave this conclusion somewhat insecure. Nevertheless, the fact that the color–magnitude diagrams for elliptical galaxies in rich clusters like Coma show very little dispersion in color suggests that most E galaxies in such clusters had highly synchronous evolutionary histories. A firmer conclusion from the data in Table 18 is that the fraction of spiral galaxies decreases rapidly with increasing look-back time. The almost complete absence of 'grand design' spirals among the fainter galaxies in the Hubble Deep Field is particularly striking. The most likely interpretation of this result is that most spiral galaxies had not yet been assembled from their ancestral clumps at the time of the HDF era. Objects such as HDF 2-86 (Figure 28) and HDF 3-312 (Figure 29) (color images of these galaxies are shown in van den Bergh *et al.* (1996)) are examples of spiral galaxies that appear to be in the process of being assembled from ancestral fragments. A particularly striking feature of the galaxian population in the Hubble Deep Field (van den Bergh *et al.* 1996) is that barred spirals appear to be almost absent. Such barred spirals account for 22% of the nearby *Shapley–Ames Catalog* sample, 4% of the more distant Medium Deep Survey sample and only 0.3% of the very distant Hubble Distant Field sample. Perhaps young distant disk galaxies in the Hubble Deep Field have not yet had time to develop bar-like instabilities. Alternatively such disks might have been heated by rapid recent infall of ancestral fragments, thus preventing bar-like instabilities. Andreon, Davoust & Heim (1997) note that they find it to be much more difficult to see barred galaxies in *HST* post-refurbishment images of the cluster Abell 851 at $z = 0.407$ than it is to see such bars in the nearby Coma cluster. They therefore suggest that the almost complete lack of barred spirals in the Hubble Deep Field is due to the difficulty of recognizing bars at such large distances. However, it should be emphasized that the compact bars in the SB0 galaxies in rich clusters are much more difficult to recognize at large distances than are the larger bars that occur in the wide-open spirals that dominate in field galaxy samples. A small percentage of the

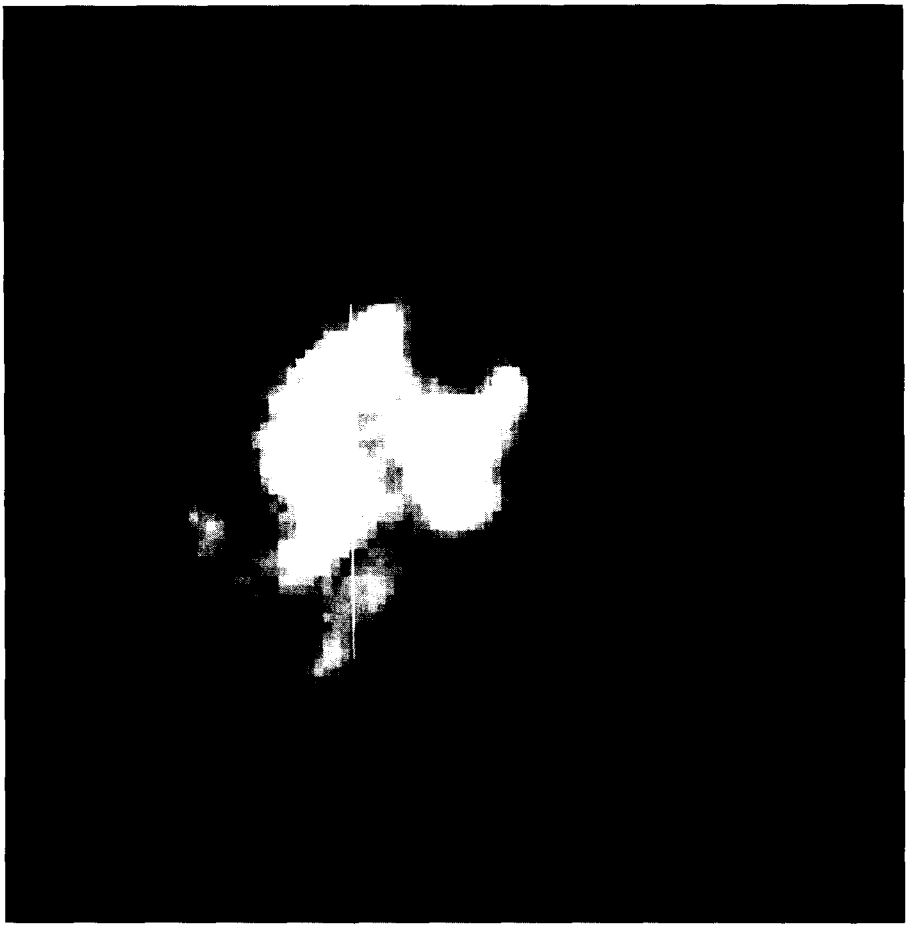

Fig. 28 Image of a chaotic object (HDF 2-86) in the Hubble Deep Field that may be a spiral galaxy that is in the process of being assembled.

galaxies in the Hubble Deep Field are head–tail galaxies resembling tadpoles (see Figure 30). Such objects have few, if any, low-redshift counterparts.

14.2 Galaxy interactions

As has been noted above the frequency of interactions between galaxies appears to grow rapidly with increasing redshift. The degree of interaction between galaxies may be rated by visual inspection on the following scale: ($w = 0$) no distortions or tidal tails visible, ($w = 1$) galaxies exhibit possible tidal distortions, ($w = 2$) galaxies exhibit tidal tails or probable distortions, ($w = 3$) galaxies strongly interacting and are possibly merging, ($w = 4$) galaxies almost certainly merger. These estimates can be used to calculate a normalized interaction index

Fig. 29 Possible example of a distant spiral galaxy (HDF 3-312) being assembled in the Hubble Deep Field. A color image of this object (van den Bergh et al. 1996) shows that the bright, slightly off-center, light concentration is reddish. This suggests that it is the intermediate-age nucleus of this object. On the color image the outer knots are all seen to be deep blue and hence, presumably, consist of young stars.

$$I_i = \sum_j w_{ij}/N_i, \tag{4}$$

in which w_{ij} is the value of w for the j^{th} galaxy in the i^{th} sample, and N_i is the number of galaxies in the sample. Values of I for the *Shapley–Ames Catalog* (van den Bergh 1960c), the Medium Deep Survey (Abraham *et al.* 1996b) and for the Hubble Deep Field (van den Bergh *et al.* 1996) are collected together in Table 19. Also given in this table are values of I for the sub-set of galaxies in van den Bergh *et al.* (1996) that have integrated colors indicating that they probably exhibit a Lyman break. I-values for a somewhat more restricted sample for which Steidel *et al.* (1996) found a Lyman break are also listed in the

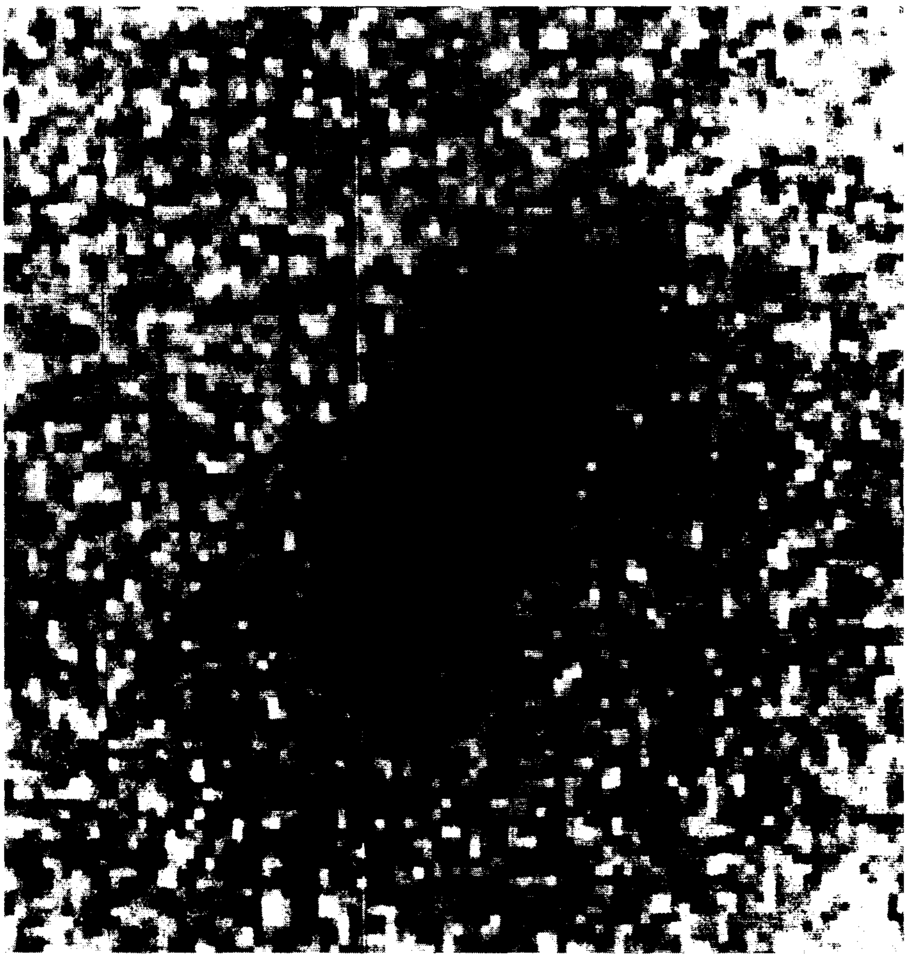

Fig. 30 Hubble Deep Field image (HDF 2-234) of a head–tail galaxy. Such objects have few (if any) counterparts at low redshifts.

table. The data compiled in Table 19 show strong evidence for an increase in the strength of the interaction index I with redshift. A possible caveat is that the very distant Lyman-break galaxies are viewed at a shorter rest-wavelength than the other objects in the table. Since the structure of galaxies in the far ultraviolet is more chaotic than it is at longer wavelengths there might be a tendency to over-estimate the fraction of such objects that are distorted by tidal interactions.

14.3 Lyman-break galaxies

High redshift 'Lyman-break' galaxies with $z \sim 3$ in the Hubble Deep Field can be identified by means of their very red U–B colors. This red color is due to the fact that the

Table 19. *Interaction index versus redshift*

Sample	Sample size	$< z >$	I
Shapley–Ames Catalog	936	0.0	0.18
Medium Deep Survey	508	$\sim$0.5	0.26
Hubble Deep Field	290	1 ?	0.96
HDF Lyman-break galaxies[a]	42	$\sim$3	2.05 ± 0.28
HDF Lyman-break galaxies[b]	21	$\sim$3	2.10 ± 0.38

[a] van den Bergh *et al.* (1996) sample.
[b] Steidel *et al.* (1996) sample.

Lyman continuum break at 912 Å shifts into the terrestrial U wavelength band. This Lyman break is produced by a combination of (1) the intrinsic break in the spectra of hot stars, (2) the opacity of a galaxy to its own ultraviolet radiation, and (3) H I absorption along the line-of-sight. Since the majority of spiral disks will not yet have formed at $z \sim 3$ it seems likely that most of the Lyman-break galaxies are young ellipticals, or precursors of present-day galactic bulges. Madau (1996) has pointed out that the Lyman-break systems in the Hubble Deep Field are under-luminous relative to the expectations for young spheroidal systems, i.e. dynamically relaxed pressure-supported portions of galaxies (including bulges and halos) and ellipticals. This may indicate that Lyman-break systems presently being observed in the Hubble Deep Field will eventually merge with other objects of similar type, to form the elliptical galaxies and galactic bulges that are observed at the present time. The high frequency of interactions among these systems, which has been noted above, is consistent with such a scenario. (However, see Colley *et al.* (1997) for a contrary opinion.) Alternatively small amounts of dust (which can produce significant absorption at far-ultraviolet wavelengths) may have resulted in an underestimate of the intrinsic luminosities of some Lyman-break galaxies.

14.4 **Summary**

Observations of galaxies at large look-back times provide unambiguous evidence for morphological evolution over time. Among galaxies with $z \lesssim 0.5$ such evolution manifests itself as the Butcher–Oemler effect, i.e. the presence of an excess of blue spirals in rich Coma-like clusters of galaxies. At larger redshifts the *HST* shows (1) an enhancement in the number of blue very late-type spirals, (2) an increase in the number of irregular and interacting galaxies, and (3) a decrease in the fraction of barred spirals. Very distant galaxies with $z \sim 3$ can be identified by means of their red U–B colors. Many of these 'Lyman-break' galaxies appear to be young ellipticals. The fact that they seem to be under-luminous compared to local spheroidal galaxies suggests that many of them will have to merge with their neighbors before they can evolve into the kinds of elliptical and spheroidal galaxies that are observed at lower redshifts.

15 Computer classification of galaxy images

The image of a galaxy can be characterized in an entirely objective and non-controversial way by (1) its total integrated magnitude (usually the Holmberg (1958) magnitude based on the total luminosity inside isophotes of 26.5 and 26.0 mag arcsec^{-2} in the photographic and photo visual regions, respectively), (2) its integrated colors, $U-B$, $B-V$, $V-R$ etc., (3) its isophotal radius r, in which $r = (a \times b)^{0.5}$, and where a and b are the semi-major and semi-minor axes to some specific isophote, (4) its effective radius r_e, defined as the radius within which half of the total galaxy light is emitted in projection, and (5) for many (but not all) galaxies the disk and bulge scale-lengths. More detailed characterizations, such as those provided by the Hubble, de Vaucouleurs and DDO type, are much more difficult (or perhaps impossible) to carry out in an entirely objective fashion.

Inspection of the images of the *SRC Southern Sky Survey* on IIIaJ emulsion (van den Bergh 1989b) show that it is just barely possible to recognize grand design spiral galaxies at redshifts of up to about 1×10^4 km s^{-1}. The images of such objects have diameters of $\sim$0.5 mm (corresponding to 34') and contain $\sim 1 \times 10^3$ picture elements. Experience shows that the images of galaxies with redshifts of 1000–2000 km s^{-1}, which typically contain 1×10^4–1×10^5 picture elements, can be classified with confidence on plates obtained with the SRC Schmidt telescope. The accuracy of galaxy classifications also depends on the dynamic range of images. It is, for example, not possible to distinguish E and S0 galaxies with confidence on the *prints* (which have a small dynamic range) of the *Palomar Sky Survey*. On the other hand van den Bergh *et al.* (1990) find that interactive inspection of CCD images (which have a large dynamic range) of Virgo galaxies often permits more accurate galaxy classification than is possible on photographic plates. The reason for this is that one can study both the faint outer structure and the bright inner regions of such galaxies in detail. It is also noted that it is easier to classify spiral galaxies on blue images than on images obtained in red light. The reason for this is that the contrast between disk and spiral arms is greater in blue light than it is in red.

15.1 Comparison between visual and computer classifications

The agreement between the 'eyeball' classifications of different 'expert' morphologists has been studied by Naim *et al.* (1995) and Lahav *et al.* (1995). In these papers classifications by each of the experts were transformed to the T system of de Vaucouleurs *et al.* (1976), in which $T = 1$ for Sa galaxies, $T = 3$ for Sb galaxies and $T = 5$ for Sc galaxies. Naim *et al.* found an rms difference of 1.8 'T units' between the classifications by different experts. This disappointingly large scatter is primarily due to the rather low dynamic range of the images, which were scanned from glass copies of the original pates of the Cambridge APM survey. Other contributing factors were the non-linear transformations of some classification systems (such as the DDO system) to the de Vaucouleurs T system, the small size of some of the APM images, and inclusion of edge-on galaxies (which are often difficult or impossible to classify) in the sample. Not surprisingly, Naim *et al.* find that classifiers who belong to the same 'school' (i.e. classify exactly on the same system) agree with each other better than others, who each classify galaxies on their own system.

15.2 **Artificial neural networks**

The advent of enormous databases, such as the *Sloan Digital Sky Survey*, will provide images of millions of galaxies. Complete analysis of such data samples will only be possible using computer-based techniques. Lahav *et al.* (1996) have made some preliminary attempts to apply artificial neural networks to this problem. Such neural networks may be thought of as non-linear minimizing machines that operate in a multi-dimensional space. Lahav *et al.* find an rms dispersion of ~ 2 T units between classification by humans and by artificial neural networks; i.e. a difference that is only marginally larger than that between human experts. The main advantage of artificial neural network classifications is that they can be defined objectively by use of a specific 'training set,' and that such classifications require orders of magnitude less time than do those by human experts. Obvious disadvantages of such mass-produced galaxy classifications are that artificial neural networks might be mis-led if: (1) two galaxies (or a galaxy and a star) are optically superposed; (2) galaxies are tidally interacting; (3) galaxies are viewed almost edge-on; (4) a galaxy has a peculiarity such as a 'jet', or dust patches; and (5) an artifact is superposed on the galaxy image.

15.3 **Objective classification parameters**

Quantities that are particularly suitable for the classification of digital images by computers have been discussed by Doi, Fukugita, & Okamura (1993) and by Abraham *et al.* (1994, 1996b). Abraham *et al.* parametrize a galaxy image by using the parameters C and A, in which C measures the central concentration of light and A describes the asymmetry of the image. The asymmetry parameter is determined by rotating an individual galaxy image about its center and then self subtracting it from the original image. The central concentration parameter C is measured from the second order moments of a galaxy image. Measurements of A and C have been reported for galaxies in the *HST* Medium Deep Survey (Abraham *et al.* 1996b) and in the Hubble Deep Field (Abraham *et al.* 1996a). These data show the following: (1) E/S0, spiral and Ir/merging galaxies are separated rather cleanly in the log A versus log C plane (see Figure 31); (2) with increasing

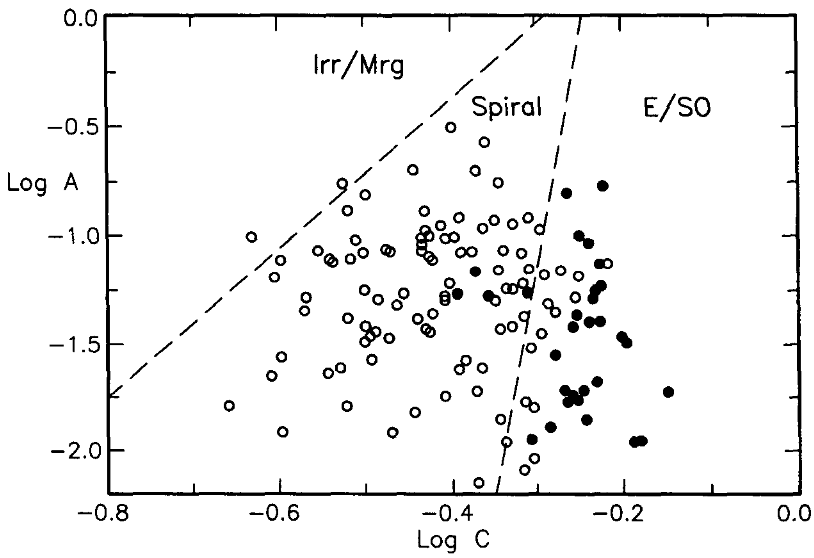

Fig. 31 Separation of spirals (circles) and E/S0 galaxies (dots) in the log A versus log C plane (adapted from Abraham *et al.* (1996b)).

look-back time galaxies are increasingly skewed towards highly asymmetric objects; and (3) number counts of concentrated (E/S0) galaxies increase roughly as expected from no-evolution models. However, the number of asymmetric objects with low central concentrations of light (Ir/peculiar galaxies/mergers) is found to increase much faster with look-back time than is predicted by no-evolution models. Naim, Ratnatunga & Griffiths (1997) have found that 'blobbiness' and filling factor of isophotes may also turn out to be useful classification parameters. Using six classification parameters these authors attempt to define peculiar galaxies in an objective way.

Lahav (1996) and Sodré & Cuevas (1997) have applied the artificial neural network approach to the classification of galaxy spectra. Lahav extracted ~8 principal components from such galaxy spectra. He finds that the first few principal components provide a useful new compact space to describe the spectroscopic characteristics of galaxies on the Hubble sequence. Such techniques are particularly well suited to the analysis of large samples of galaxy spectra. Eventually (Folkes, Lahav & Maddox 1996), principal component analysis should also be able to separate normal 'ground state' galaxies on the Hubble sequence from galaxies that are in excited states.

Rawson, Bailey & Francis (1996) have shown that artificial neural networks can also be used to classify the spectra of active galactic nuclei. A practical problem with such classifications is that both the spectral class and the redshift of each individual object need to be determined from the observations.

15.4 Summary

The experiments in computer assisted classification of galaxies, which have been described above, show that such techniques hold great promise for the study of large galaxy samples. However, visual classification of galaxy images by expert craftsmen will probably continue to play an important role in the study of particularly critical small samples, and for quality control of the automated classification of images in large databases.

16 Problems, challenges and conclusions

Morgan (1958) has said that 'The value of a system of classification depends on its usefulness.' Using this criterion the Hubble classification system has proved to be of outstanding value because it has provided deep insights into the relationships between galaxy morphology, galactic evolution and stellar populations. However, some classification parameters, such as the *r* and *s* varieties in the de Vaucouleurs system, have not yet been tied as firmly to physically significant differences between galaxies (cf. Kormendy (1982)). Furthermore, it is not yet clear if the dichotomy between ordinary and barred spirals allows one to draw any useful conclusions about the past evolutionary history of a particular galaxy.

The Hubble system was designed to provide a framework for the classification of galaxies in nearby regions of the Universe. It is therefore not surprising that it does not provide a useful reference frame for the classification of very distant galaxies (which are viewed at large look-back times), or for galaxies in unusual environments such as the cores of rich clusters. Furthermore, the existence of some classes of objects, such as (1) amorphous/Ir II galaxies, (2) anemic galaxies and (3) cD galaxies, which cannot be 'shoehorned' into the Hubble system, suggests that such galaxies have had an unusual evolutionary history. It has also become clear that the Hubble system, which is defined in terms of supergiant prototypes, does not provide a very useful framework for the classification of low-luminosity galaxies. Among such low luminosity objects a classification system based on the mean age of stellar populations appears to be more useful. In other words one might arrange such objects in a sequence from old dSph (Ursa Minor), through younger dSph (Carina), to inactive dSph/Ir (Phoenix), to dIr (DDO 210). Another problem with the Hubble system, and its extension by de Vaucouleurs, is that the effects of galaxy luminosity and of population type are interwoven over the range Sc–Sd–Sm. Furthermore, the Hubble system presently does not provide an objective way of distinguishing between very late-type spiral and irregular galaxies. Other major problems that still remain unresolved are: (1) how dSph galaxies are related to dE galaxies and dS0s (see Jerjen & Binggeli (1997) for a recent review); (2) how normal giant E galaxies and S0 galaxies are related; (3) what the relationship between boxy and disky E galaxies is, and how these relate to early-type spirals; (4) how cD galaxies form; and (5) what the relationship(s) between ordinary spirals and low surface-brightness disk galaxies is (or are).

A number of exciting challenges remain for future workers on galaxy classification and morphology:

- H II regions are the best tracers of spiral structure. It would therefore be of interest to try to classify arm structure from a large and homogeneous collection of Hα images of galaxies.
- The large mass-to-light ratios observed in many Local Group dwarf spheroidal galaxies suggests that these objects did not form by condensation of dense knots in tidal filaments. However, it would be interesting to search for dwarf spheroidals that *do* have low M/L-values to see if a significant fraction of the dSph galaxies in the Universe might have formed from tidal tails.
- What are the differences between the evolutionary histories of normal and barred spirals, and why are SBc galaxies, in the mean, fainter than objects of type Sc? Spectroscopic determinations of [α/Fe] might be used to see if there is a systematic difference between the collapse time-scales for these two types of objects.
- Is the apparent break down in the correlation between boxy/disky global isophotes and core/power-law radial profiles for galaxies fainter than $M_V = -20.5$ entirely due to the effects of past tidal interactions?
- What is the origin of the chasm between objects of types E/S0 and early-type spirals?
- Are gigantic Malin-type low surface brightness galaxies physically distinct from smaller low surface brightness galaxies?
- What can the morphology of young galaxies seen at large look-back times and the color distributions of globular clusters tell us about the early history of galaxy formation?

Future progress in the understanding of galaxy morphology and evolution will, no doubt, depend on both the acquisition of new data, and perhaps more importantly, on re-interpretation of what we already know. In the words of Yogi Berra: 'What gets us into trouble is not what we don't know, but what we know for sure that just ain't so.'

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