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CLASSIFICATION AND STELLAR CONTENT OF GALAXIES OBTAINED FROM DIRECT PHOTOGRAPHY

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1. INTRODUCTION

The first step in the development of most sciences is a classification of the objects under study. Its purpose is to look for patterns from which hypotheses that connect things and events can be formulated by a method proposed and used by Bacon (1620). If the classification is useful, the hypotheses lead to predictions which, if verified, help to form the theoretical foundations of a subject.

Simple description, although not sufficient as a final system, is often an important first step. In the study of galaxies, Wolf's (1908) and Vorontsov-Velyaminov's (1962, 1963, 1964, 1968) descriptions are examples of a system of this first type. But as a classification develops, a next step is often to group the objects of a set into classes according to some continuously varying parameter. If the parameter proves to be physically important, then the classification itself becomes fundamental, and often leads quite directly to the theoretical concepts.

It is too early to judge if the classification of galaxies has reached this stage because no theory of their origin and evolution is yet certain. But the systems of Hubble (1926) (as extended by Holmberg 1958; de Vaucouleurs 1956, 1959a; van den Bergh 1960a, b; and others) and of Morgan (1958, 1959) are based on continuously varying parameters and therefore constitute classifications of the second kind.

The classification criteria for the Hubble system are (1) the size of the nuclear bulge relative to the flattened disk, (2) the character of the spiral arms, and (3) the degree of resolution into stars and H II regions of the arms and/or disk. Item (1) is likely to be related to the angular-momentum distribution of the original protogalaxy, and to the timing of earliest star formation relative to the collapse time. The other two criteria are probably related to the present rate of conversion of gas into stars in a rotating galaxy.

Both the Hubble and the Morgan systems appear to be more than simple descriptions because many galaxian properties such as the integrated color, the composite spectral type, and the density of free H I gas vary systematically along the sequence of forms. These classifications may therefore be fundamental in the above sense because they provide connective relations, based on form alone, that may be related to the initial conditions of formation and subsequent temporal change.

2. EARLY CLASSIFICATION OF GALAXIES

The most extensive all-sky surveys before the introduction of photography were made by the Herschels from about 1780 to 1860 by visual methods. Star clusters, galactic nebulae, and galaxies were catalogued, and moderately extensive descriptions were given. The *General Catalogue of Nebulae*, incorporating the observations of 5079 objects, of which 4630 were discovered by the Herschels, was published by Sir John Herschel in 1864 in the *Philosophical Transactions*. This forms the largest single base for the *New General Catalogue* (NGC) of Dreyer which, together with the two *Index Catologues*, incorporates most discoveries of nebulae to 1908. The descriptive symbols used by the Herschels are summarized by Dreyer in the Introduction to the NGC, and by Curtis (1933) in his view of galaxian research to 1934. Although the descriptions do not constitute a classification in the formal sense, they are still valuable as a supplement to the current systems, and have been used as recently as 1956 by de Vaucouleurs (1956) in his survey of southern galaxies.

The faintest structural features of galaxies could be detected only when photographic surveys came into general use about 1890. These features proved to be decisive in the classification problem because the presence or absence of spiral arms is what divides galaxies into the two major groups (E and S), and separates the spirals along a linear sequence by the character of the arm structure.

Wolf's (1908) system was a classification based on photographs taken at Heidelberg in which letters were used for various forms, and in which no distinction was made between galactic planetary nebulae and galaxies. Although the system is not now in general use, it was the first to use a linear sequence which proceeds from amorphous forms with no spiral patterns (type *d* to *k*), to fully developed spirals (types *r* to *w*). Extensive use of the Wolf classification was made as late as the 1940s. Because of this, and because it provides a more detailed description of the many variations of spiral patterns than does Hubble's, Wolf's sequence is shown in figure 1.

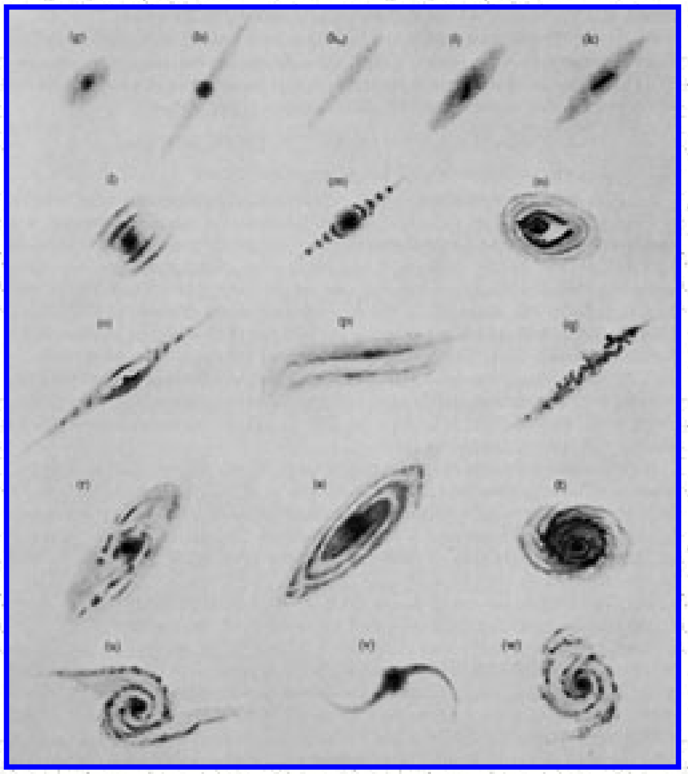

Figure 1. Wolf's 1908 descriptive classification system of galaxies. The top row of his original diagram, which showed galactic nebulae (mostly planetaries), is deleted here.

Although Hubble's system places galaxies in a physically significant linear sequence (or a series of such sequences as in de Vaucouleurs's extension) it is ``simple'' in that it gives no notational recognition to the great variety of spiral arms, as does Wolf`s. For this reason, Danver (1942) preferred the Wolf types and commented: ``As to the Hubble classes, these [appear to constitute] a division along a line of development. This is certainly a great advantage, but if a conception of the appearance of the object is desired, it is better to designate the types according to Wolf." It is quite possible that when the theory of spiral structure is more fully developed than at present, a new classification of the arm patterns *alone* may be needed, and the Wolf scheme might serve as a new point of departure. The modern work of of Vorontsov-Velyaminov (Section 8) may be a step in this direction.

Among the more complete discussions using the Wolf symbols are Reinmuth's (1926) study of the Herschel galaxies, Lundmark's (1927) summary of galaxian research to 1926, Holmberg's (1937) work on double galaxies, Reiz's (1941) study of the surface distribution of galaxies, and Danver's (1942) work on the forms of spiral arms. Danver gives a comparison of the Hubble types with those of Wolf, extending a similar discussion by Shapley and Ames (1932, pp. 68-69). [(1)]

Lundmark (1926, 1927) proposed a classification based on a major division of galaxies into three groups (amorphous ellipticals, true spirals, and Magellanic Cloud-type irregulars), further dividing the groups according to the concentration of light toward the center. The division into E and S classes is similar to that made by Hubble (1926), but the parameter which divides galaxies within the classes (concentration by Lundmark and the nature of the spiral arms by Hubble) is different. Curtis (1933, appendix 5G), summarizes Lundmark's system, and compares it with the Wolf symbols.

Shapley (1928) also proposed a classification based on concentration, but included the nonintrinsic properties of apparent magnitude and apparent flattening in his notation. The system was used at Harvard in the early stages of the survey of galaxian distribution to $m_{pg} = 17$ (e.g., *Harvard Annals*, **88**), but is not now in general use.

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[1] Hubble (1917) used Wolf's classification in his early work at Yerkes. Back

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3. DEVELOPMENT OF THE MODERN SYSTEM

3.1 Early Isolation of the Types

Reliable separation of galaxies into classes could successfully begin only after extensive photographic surveys were well underway, and the forms of galaxies discovered. This descriptive phase is not yet complete for the interacting galaxies (cf. Vorontsov-Velyaminov 1959; Zwicky 1959 and references therein), peculiar galaxies (Arp 1966), and perhaps even for the infinite detail of more regular systems (Vorontsov-Velyaminov, Krasnogorskaja, and Arkipova, in the four volumes of the *Morphological Catalog of Galaxies* 1962 - 1968). However, following the isolation of the S0 type by Hubble (cf. Spitzer and Baade 1951; Sandage 1961), of the dwarf ellipticals by Shapley (1938a, b) with the subsequent discovery of great numbers in the Local Group (cf. Harrington and Wilson 1950), and of dwarf spirals related to Magellanic Cloud-type Sm (cf. the *Hubble Atlas*, p. 40, for Dwf I and II in the NGC 1023 group), all the more common types of galaxies had been discovered by 1940.

If 1940 marks the end of the major survey for types, the beginning occurred in 1845 when spiral structure was first discovered visually in M51 by Lord Rosse with the 72- inch reflector at Burr Castle. According to Curtis (1933) spiral structure was subsequently identified by Rosse in perhaps 20 additional galaxies. The classical photographic work of Isaac Roberts from 1885 to 1904 confirmed the spiral types, and increased their number to about 40.

The photographic surveys of Keeler (1898-1900), Perrine (1901-1903), and Curtis (1909-1918; *Lick Pub*., **13**, 1918) with the Lick Crossley reflector marks the beginning of research which led to the present classification. Mount Wilson survey's by Ritchey and by Pease (1917, 1920) with the 60-inch added to the material, as did the early systematic work of Knox-Shaw, Gregory, and Madwar with the Reynolds reflector at Helwan (Vols. **1** and **2** of *Helwan Observatory Bulletins*). Knox-Shaw (1915) and Reynolds (1920a) were among the first to call attention to amorphous galaxies with no trace of spiral arms (E systems). Curtis (1918) first isolated the barred spirals (called by him ϕ type), and Lundmark (1926, 1927) emphasized the highly resolved Magellanic Cloud types, incorporating them as a separate group in his classification system.

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3.2 The Early Hubble System

From these data, supplemented by plates taken by Hubble, Humason, and Duncan with the Mount Wilson 60- and 100-inch reflectors, and building on the earlier proposals (Section 2), Hubble (1926) formulated the linear classification system which has evolved into the present standard systems. Galaxies are divided into three major classes (ellipticals, spirals, and irregulars). The spirals are separated into two families, the ``normal" spirals and the barred; and are separated along each family into types a, b, and c according to the three criteria listed in Section 1, which generally (but not always) vary together along the form sequence from early Sa (SBa) to late Sc (SBc). The system has been described in many places (e.g., Hubble 1926, 1936; de Vaucouleurs 1959a; Sandage 1961; Baade 1963, chap. 2; Hodge 1966) and need not be repeated here.

Soon after publication of Hubble's 1926 paper, Reynolds (1927a, b) criticized the system because of a supposed inadequate number of classification bins. Impressed by the enormous variety of galaxian structures, Reynolds wrote: ``The problem I have always found in attempting a general classification of spiral nebulae is that one meets case after case where a special class is required for the individual object. Spectral classification of stars is a simple and straightforward matter compared with this." [2]

Wolf had earlier commented similarly in the first sentence of his 1908 paper ``Es gibt kein zwei Nebelflecken am Himmel, die sich gleichen." But it is precisely because Hubble's system specifically ignores the multitude of superficial details of arm structure (for example), and concentrates on the gross characteristics of pattern according to broad criteria, that the system has such merit. Nearly all galaxies can be put into a specific classification bin (in the revised system) without forcing, because the bins are large. This is true even for most of the interacting and peculiar galaxies discussed by Vorontsov-Velyaminov (1959), Arp (1966), Burbidge, Burbidge, and Hoyle (1963), and others. The underlying Hubble type is usually visible, albeit with peculiar features denoted by pec or p after the basic type. Baade's comment (1963, chap. 2) that the Hubble system has great merit is shared by most classifiers, but not all would agree with his belief that the logical extensions by de Vaucouleurs are unnecessary-extensions which retain the simplicity of the scheme, but narrow the class sizes and give notational recognition to the transition cases between ordinary and barred spirals.

Genuinely peculiar objects do exist, such as M82, NGC 3077, NGC 520, NGC 2685, NGC 3718 (illustrated in the *Hubble Atlas* 1961). These fall outside the system, but constitute only a few percent of any random sample.

An example of the universality of Hubble's system is given by a trial classification of galaxies in the *Atlas of Peculiar Galaxies* (Arp 1966). Of the 338 illustrated galaxies, 45 are so abnormal that they could be given no underlying basic Hubble type (except peculiar), but this is only 13 percent of the total sample, which itself is already highly selected as regards peculiarity.

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[2] Although Reynolds criticized Hubble's 1926 system as too ``simple," he had himself, seven years earlier, proposed a classification (Reynolds 1920b) that was similar enough to Hubble's E, Sa, Sb, Sc, and Irr types (but called classes I-V), that, in the absence of his 1927 repudiation, Reynolds would now have been considered as an early originator of part of the modern classification. Back.

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3.3 Hubble's Major Modification Between 1936 and 1950

The S0 class was not isolated observationally until after 1936, although Hubble had earlier come to believe such a class was necessary. In *The Realm of the Nebulae* he wrote, ``The junction [between E and S types] may be represented by the more or less hypothetical class S0. Observations suggest a smooth transition between E7 and SBa [on the barred side of the tuning-fork diagram], but indicate a discontinuity between E7 and Sa (on the spiral side] in the sense that Sa spirals are always found with arms fully developed [whereas SBa in the 1936 system had no arms, by definition]." The difference, then, was primarily a matter of definition (cf. plate II of *Realm*), but it did represent an asymmetry between the ordinary and barred spiral families because no ``armless ordinary spirals" had been found whereas armless barred spirals did exist (cf. NGC 2859, *Hubble Atlas*, p. 42; NGC 2950, p. 42; and NGC 4643, p. 42, all originally classed as SBa but now classed as SBO).

Because of this asymmetry, Hubble undertook a special search for nonbarred examples of ``armless spirals" (the modern S0 class). They were subsequently found on long-exposure plates taken in the Mount Wilson survey of the Shapley-Ames galaxies north of δ = - 15°, carried out by Hubble between 1936 and 1950 with the 60- and 100-inch reflectors.

Elliptical and S0 galaxies are easily confused on small-scale plates, which explains why the S0 class remained unrecognized for so long. Neither class has arms, and both show smooth intensity distributions with no resolution into bright supergiant stars. The criterion that distinguishes the two classes is a difference in the radial intensity distribution *I(r)*. E galaxies have a steep intensity gradient (Hubble 1930, de Vaucouleurs 1948, 1953, 1959a), whereas S0 galaxies have an extensive exponential outer envelope, superposed on a central E-like distribution (cf. de Vaucouleurs 1956, 1959a; Liller 1960; Johnson 1961; Hodge and Webb 1964; Hodge and Merchant 1966). This envelope is similar to the underlying exponential disks of spirals (cf. de Vaucouleurs 1958, 1959b, 1962, 1963a, 1964; Freeman 1970).

Although it is clear that Hubble discovered the S0 class and studied some of its members, he published no discussion of the important phenomenon. The first literature references were made by Spitzer and Baade (1951), based on Baade's conversations with Hubble. Summaries were given by de Vaucouleurs (1956, 1959a) based on prepublication notes from the *Hubble Atlas*, and by Sandage (1961) where the class is discussed and illustrated.

A description of Hubble's revised system as it existed in 1950, written by Hubble between 1947 and 1950, is useful, and is reproduced from the *Hubble Atlas:*

> The sequence of classification, as originally presented, consisted of a series of elliptical

nebulae ranging from globular (E0) to lenticular (E7) forms, and two parallel series of unwinding spirals, normal (S) and barred (SB). Each of the latter series was subdivided into three sections, termed early, intermediate, and late, and designated by the letters a, b, and c, respectively. Thus the early, normal spirals were represented by the symbol Sa, and the early barred spirals by SBa.

The data available in 1936 seemed to indicate a smooth and continuous transition from elliptical nebulae to barred spirals, and, in fact, the first section of the latter series, SBa, exhibited no spiral arms. The corresponding section of the normal series, Sa, contained so many nebulae with fully developed spiral arms, that, where arms could not be definitely recognized, their presence was assumed, and the failure to detect them was attributed to effects of orientation or other causes. The procedure was unsatisfactory because it introduced subdivisions in the parallel series of spirals that were clearly out of step. Moreover, the transition from E7 to Sa appeared so abrupt that, if real, it might be regarded as cataclysmic.

With accumulating data, and especially with the increasing number of good photographs with the 100-inch reflector, the situation has clarified. Numerous systems are now recognized which are later than E7 but which show neither bars nor spiral structure. These nebulae fill the supposed gap between E7 and Sa and remove the excuse for postulating a cataclysmic transition. [These transition galaxies are designated S0. They are actually found in nature and are no longer a hypothetical class, as was once believed; see *The Realm of the Nebulae*, pages 45-46, and the legend to figure 1, page 45, of the Yale University Press edition of 1936. A.S.]

A similar group of objects corresponds to the section [called SBa in the 1936 classification]. This situation emphasizes the desirability of redefining the sections of both series in a more comparable manner.

The revision might be made in various ways but only that actually adopted will be described. First, two new types, S0 and SB0, have been introduced to include objects later than E7 but with no trace of spiral structure. Second, the series of true spirals, as before, are subdivided into the three sections Sa, Sb, Sc, and SBa, SBb, SBc. In the case of the normal spirals, the change amounts to a subdivision of the former section Sa into the two sections S0 and Sa. In the case of the barred spirals the entire former section, SBa, is now termed SB0, and the former section SBb is subdivided into the two sections SBa and SBb. The revisions are summarized in the following table:

Old Class	New Class	Old Class	New Class
Sa	{ S0 { Sa	SBa	SBO

		SBb	{SBa SBb
Sb	Sb		
Sc	Sc	SBc	SBc

The introduction of the new types leads to a revision of the original assignment of symbols. The original SBa nebulae are now described as SB0, and the original SBb nebulae are redistributed between SBa and SBb. Among the normal spirals, the Sa objects are redistributed between S0 and Sa. Otherwise the system remains unchanged.

The transition stages, S0 and SB0, are firmly established. In both sequences, the nebulae may be described as systems definitely later than E7 but showing no spiral structure. The next stages, Sa and SBa, are represented by nebulae which show incipient spiral structure. Fully developed spirals are distributed over the two later stages of each sequence according to the relative extent of the unresolved central region, and the degree to which the arms are resolved and unwound.

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3.4 Finer Subdivision Along the Sequence

Hubble's bin sizes among the spirals were large, and inspection of survey plates showed that they could usefully be narrowed. At various times, the Mount Wilson observers have used combination symbols S0, S0/a, S0a, S0ab, S0b, S0bc, S0c, S0c/Irr, and Irr to divide the linear sequence into nine groups instead of three along both the ordinary [(3)] and barred families.

Holmberg (1958) has used + and - symbols with the notation a, b-, b+, c-, c+, Irr I to divide the spirals into six groups.

De Vaucouleurs has used both notations in his revised classification by dividing the E's and S0's into early, intermediate, and late bins as E, E+, $S0^{-}$, $S0^{0}$, $S0^{+}$, and by using the mixed notation along the spiral sequences as a, ab, b, bc, c.

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[3] Nonbarred spirals were called ``normal'' by Hubble. De Vaucouleurs (1959a) has emphasized that barred and nonbarred spirals are equally normal because both appear with about the same frequency (de Vaucouleurs 1963b, table 5) if the transition types are neglected. He suggested use of the term ``ordinary'' rather than ``normal,'' and we follow this notation in the remainder of this chapter. Back.

4. REVISION BY DE VAUCOULEURS

4.1. Extensions of the Sequence Beyond Sc

Galaxies originally classed Sc on the Hubble system cover a large interval along the sequence, ranging from regular well-developed arms in the early Sc to nearly chaotic structures in the very late Sc. de Vaucouleurs has made a division and extension of the Sc and SBc families by introducing the cd, d, dm, m, and Im subdivisions. This important addition extends the Sd class of Shapley and Paraskevopoulos (1940) and Shapley (1950) toward even later types. The Sd type-example is NGC 7793 (photograph in Shapley 1961, p. 22), which would have been classed as a very late Sc on the Hubble system.

The further extension beyond Sd by inclusion of Magellanic Cloud types (Sm or SBm, or SAm and SBm in the revised notation) follows from the discovery of weak but definite spiral structure in the Large Magellanic Cloud (LMC) (de Vaucouleurs 1954, 1955a). Closely related galaxies, collectively denoted Irr by Hubble (as were the Sm types) but clearly following linearly beyond the Sm stages, are the dwarf Population I systems such as IC 1613, NGC 2366, Holmberg I and II, and IC 2574 (*Atlas*, pp. 39, 40). de Vaucouleurs's symbols I(m) and IB(m) replace Hubble's Irr class and show the connection with the Magellanic Cloud types. The revision brings the type back into the formal sequence as suggested by Lundmark (1927).

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4.2 Transitions Between Ordinary and Barred Spirals

Many galaxies combine features of pure ordinary spirals (such as NGC 628, *Atlas*, p. 29) and pure barred systems (e.g., NGC 1300, *Atlas*, p. 45). Examples are NGC 4579 (*Atlas*, p. 13), 5236 (*Atlas*, p. 28), and 3504 (*Atlas*, p. 46), which Hubble and Sandage denoted by the mixed symbols Sb/SBb, Sc/SBb, and SBb/Sb, respectively, where the leading symbol gives the dominant type. De Vaucouleurs uses a more convenient and symmetrical notation by (1) adding a type-symbol A to the ordinary spirals, (2) retaining the symbol B for the barred spirals, and (3) adding the mixed symbol AB for the transition cases. De Vaucouleurs's notation for the three examples quoted are SABb (4579), SABc (5236), and SABab (3504), where the dominant type is underlined.

4.3 The r and s Varieties

Barred spirals are of two dominant varieties: the r type in which the arms begin tangent to the external ring upon which the bar terminates (the purest example may be NGC 2523, *Atlas*, p. 48, and plate 6 of this chapter), and the s type in which the arms begin from the end of the bar (e.g., NGC 1300, *Atlas*, p. 45, and plate 6 here).

Recognition of the r and s varieties was made in the *Hubble Atlas* for all barred spirals by the notation SBb(r) for 2523, or SBb(s) for 1300. Mixed types such as 1073 (*Atlas*, p. 49, plate 6 here) were called sr or rs according to which variety dominates.

The same phenomenon is present in ordinary spirals, although it is somewhat more difficult to detect. Examples are 4274 Sa(r) (*Atlas*, p. 12), and 309 Sc(r) (*Atlas*, p. 32), and 5457 (M101) Sc(s) (*Atlas*, pp. 27 and 31), and especially 4321 (M100) Sc(s) (*Atlas*, pp. 28 and 31). The r-type spirals had previously been noted by Shapley and Paraskevopoulos (1940), by Randers (1940), by Vorontsov-Velyaminov (1965), and undoubtedly by many others.

De Vaucouleurs adopted the r and s distinction for all non-E galaxies, underlining the r or s symbol in the mixed variety according to the dominant form. For example, the transition galaxy NGC 5236 is classified as SAB (s)c in the revised system, while NGC 4579 (*Atlas*, p. 13; plate 5 here) is SAB(rs)b [classed Sb/SBb(rs) in the *Hubble Atlas*].

4.4 Graphical Representation of the Classification

Visualization of the classification system has always been useful. The 1936 Hubble system is illustrated in the well-known tuning-fork diagram shown in Figure 2, taken from *The Realm of the Nebulae*. [(4)]

A more complicated diagram is needed to illustrate the separation of each branch of the tuning fork into the r and s varieties. A useful representation proved to be a three-dimensional figure such as Figure 3, which is taken from Hodge's (1966) version of a less complete diagram given in the *Hubble Atlas* (p. 26). Mixed varieties rs and transition types SAB are not readily accommodated in this representation, but could form the other sides of the figure for the rs and sr varieties, and would fill the interior of the volume for the mixed SAB types if this representation were carried further.

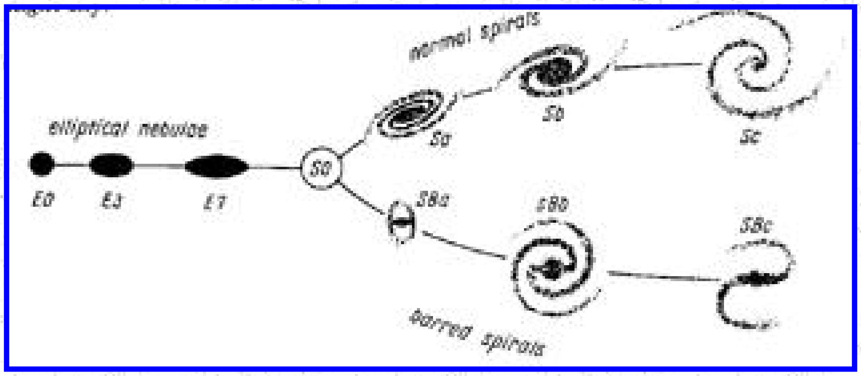

Figure 2. Hubble's original tuning-fork diagram as published in 1936 in his *Realm of the Nebulae*.

The extension was made by de Vaucouleurs (1959a) in a remarkable generalization of the entire scheme by filling the interior of the ``classification volume'' with both the r and s varieties and the A, B, and AB *families*. The basic linear sequence of *classes* is then separated *along* the axis of the volume. Figures 4 and 5 illustrate the revision, and are taken from de Vaucouleurs (1959a).

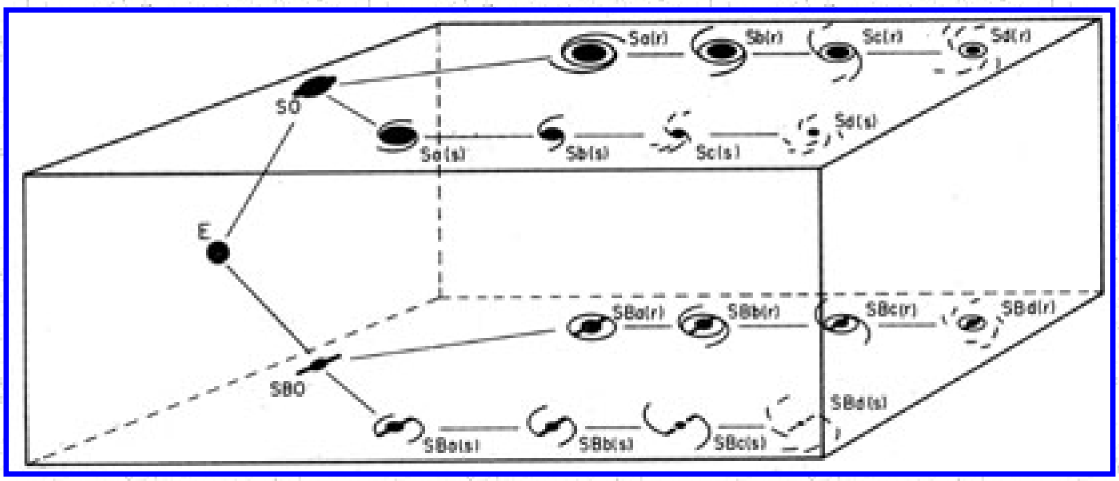

Figure 3. First stage of development of the concept of the *classification volume*. Here, the ordinary and barred families are separated onto opposite sides of a box. Within each family, a separation is made into the r and s strains, depending on whether the arms start from a ring or from the nucleus. Transition cases between the barred and ordinary families are not formally recognized in this visualization, but would fit in the interior of the box, a concept that leads into de Vaucouleurs's generalization shown in figs. 4 and 5. (Rendering of a diagram from Hodge 1966.)

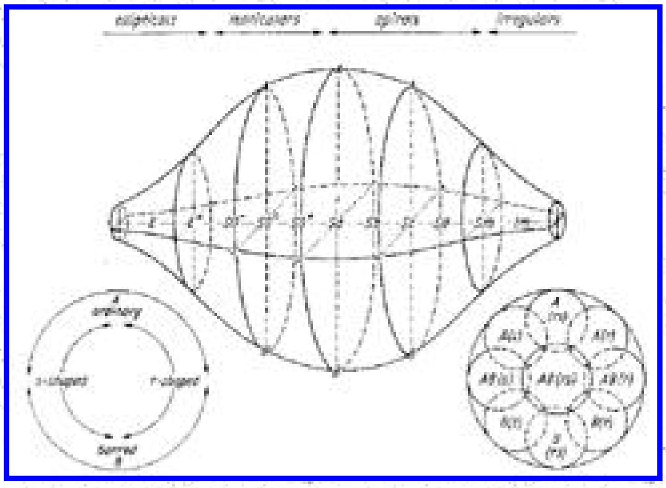

Figure 4. The *classification volume* of de Vaucouleurs. The division into gross types is made along the axis of the figure from left (E) to right (Sm),the division into the ordinary and the barred family is by position on the surface (from de Vaucouleurs 1959a).

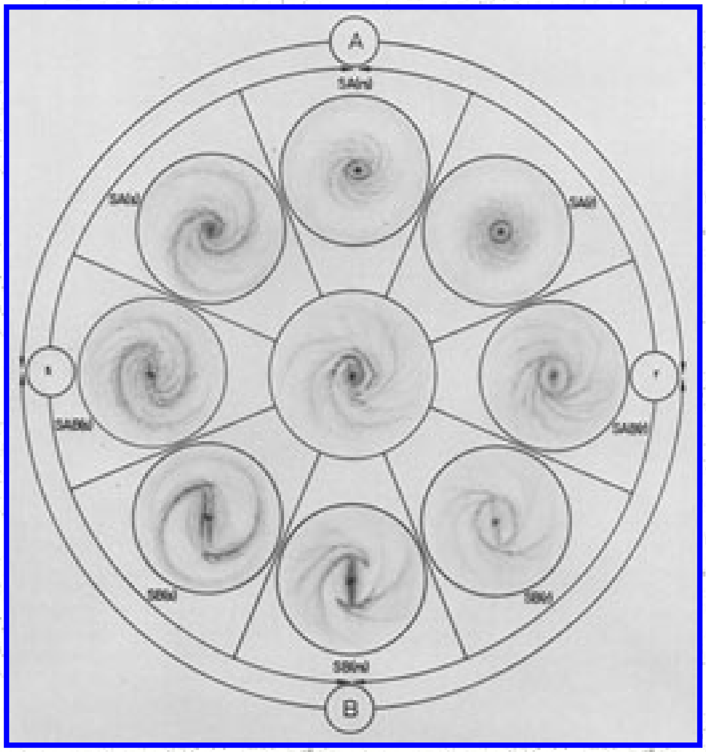

Figure 5. A cross-section of fig. 4 near the region of the Sb and SBb spirals, showing the manner in which the transition cases between ordinary (A) and barred (B) families, and the (r) and (s) strains can be accommodated (from the *Reference Catalogue of Bright Galaxies*, G. and A. de Vaucouleurs 1964).

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[4] Some history can be read from Figure 2. The revision of criteria and the redistribution of the S0, Sa, and SBa types (Section 3.3) had not yet been made by Hubble when this diagram was prepared. This is shown by the nature of the galaxy labeled SBa, which has no spiral arms and would be a modified S0 type in modern notation. Consequently, Hubble isolated the S0 class only after 1936. Back.

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4.5 ADDITIONAL FEATURES OF THE DE VAUCOULEURS REVISION

4.5.1. *Presence of rings*. Galaxies that possess external rings such as NGC 2859 [RSB(r)0^+, *Atlas*, p. 42] are denoted by R preceding the designation of the basic type (SB in this case). The difficulty in designating rings in SB galaxies is that it is often very hard to distinguish a true ring from a form in which two spiral arms are tightly coiled and nearly touch after each has made a turn of 180°. Examples where it is certain that confusion would exist on small-scale plates between this form and true rings include NGC 3185 (*Atlas*, p. 43; note especially the description given), 2217 (*Atlas*, p. 43), and 3081 (*Atlas*, p. 11; note the description). More easily distinguished cases are 3504 (*Atlas*, p. 46), and 4750 (*Atlas*, p. 21). None of these galaxies have true rings. They are classed as $(R)^1$ systems by de Vaucouleurs to denote ``pseudo rings."

True rings do occur in such galaxies as NGC 2859 (*Atlas*, p. 42), but it is not certain that the rings are attached to the main body of the parent galaxy. Examples of definitely attached partial rings outside the regular spiral pattern include the faintest outer structure in NGC 2685 (*Atlas*, p. 7 insert), NGC 4736 (*Atlas*, p. 16), NGC 4457 (*Atlas*, p. 9), NGC 3368 (*Atlas*, p. 12), NGC 1068 (*Atlas*, p. 16), and NGC 5101 (*Atlas*, p. 42). True rings appear to occur predominantly in early-type systems, although cases such as NGC 4736 [(R)SA(r)ab, de Vaucouleurs 1963b; or Sb, Hubble-Sandage: *Atlas* 1961] exist. This case is particularly interesting because partial resolution of the ring into stars ($B \doteq 22$ or $M_B \doteq -8$) is seen on 200-inch plates.

4.5.2. *Increasingly detailed notation*. In his objections to Hubble's simplified system, Reynolds (1927a, b) pointed out that spiral arms differ in *character*. Some systems have ``massive" arms, such as M33 (*Atlas*, p. 36), NGC 4567 (*Atlas*, p. 13), and M51 (*Atlas*, p. 26), while others have thin, delicate, filamentary arms, such as NGC 2841 (*Atlas*, p. 14), NGC 488 (*Atlas*, p. 15), NGC 628 (*Atlas*, p. 29), and NGC 1232 (*Atlas*, p. 32).

This feature is undoubtedly important and, although not recognized in Hubble's notation, does form the basis of a division of galaxies into strains or groups from Sa to Sc, where the characteristics can be traced through the entire sequence. Such groupings are discussed in the *Hubble Atlas* (cf. the section on Sc galaxies where families with similarly shaped arms are isolated).

De Vaucouleurs has proposed to recognize these characteristics explicitly in the notation by adding symbols in (for massive) and f (for filamentary) after the type designation, with an additional symbol to indicate how many arms are present. For example, NGC 1232 (*Atlas*, p. 32), which has filamentary and highly branched segmented structures starting from two main arms of the rs variety, would have a complete notation $\mathrm{SAB(rs)}_{2+C_f}$, where c denotes the arm character, and 2^+ denotes branching from two main arms.

By now the notation has become quite detailed, and is as complete as is likely to be useful. No classification system can describe the infinite variations among galaxies: this was Reynolds's objection. Most classifiers would agree with part of Baade's statement (1963, p. 19) that beyond this stage ``if you want to study the variations on the theme Sc [for example], you simply have to take plates and examine them - only then do you get the full story. No code system can replace this. The code finally becomes so complicated that only direct inspection of plates helps."

But, as de Vaucouleurs points out, the virtue of the extended notation is that symbols can be progressively dropped until the notation becomes as simple as Hubble's original system. The classifier can exclude as much detail as he wishes and still remain within the standard classification at any desired level of complexity.

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5. Selected Illustrations of Galaxy Types

Classification on the Hubble-de Vaucouleurs system depends on subjective criteria; nevertheless, it works in practice, as evidenced by the fact that all classifiers are able to reproduce it well in the mean. Learning the system is best done by comparing photographs (such as those in de Vaucouleurs 1959a; the *Hubble Atlas* [Sandage 1961]; the *Cape photographic Atlas* [Evans 1957]; Morgan 1958; Sersic 1968; and in other more scattered references) with several standard classification catalogs such as Humason, Mayall, and Sandage (1956 [HMS]), Morgan (1958, 1959), van den Bergh (1960c), de Vaucouleurs (1963b), the *Hubble Atlas*, and the *Reference Catalogue* (de Vaucouleurs and de Vaucouleurs 1964) decoded by its tables 1b, 2, 3, 4, and 5.

To reproduce all type-examples here would be an unwarranted duplication of material already in the literature, but a minimal selection is given in plates 1 - 8. The photographs are chosen to show progressive variation of the three classification criteria (and their conflict in some cases), and to illustrate the continuity of arm characteristics for the massive and the filamentary types - a continuity which can be traced throughout the sequence from Sa to Sc^+ for each strain separately.

5.1 Elliptical Galaxies

E types are not illustrated because nearly all are structureless and have similar appearance, showing smooth intensity distributions with relatively steep gradients. Except for the presence of globular clusters, detected in members of the Local Group (Hubble 1932) and in some of the nearby Virgo cluster ellipticals (Sandage 1961 in the *Hubble Atlas* descriptions; Vorontsov-Velyaminov 1966), no resolved components of the stellar content are usually present brighter than $M_V \simeq -3$ (Baade 1944). (NGC 205 is an exception where dust patches and a few early-type stars begin to resolve at about $M_V = -4$ [Baade 1951].)

E galaxies occur over a wide range of absolute luminosity extending from $M_V = -24$ for the brightest members of clusters of galaxies (based on a Hubble constant of 50 km s^{-1} Mpc^{-1}) to fainter than $M_V = -9$ for dwarf ellipticals (dE) of the Sculptor Fornax type (Shapley 1938a, b; Baade and Hubble 1939). In addition to the Sculptor ($M_V \simeq -13$) and Fornax ($M_V \simeq -12$) galaxies, other low-luminosity ellipticals exist in the Local Group, such as M32 ($M_V \simeq -16.3$), NGC 205 ($M_V \simeq -16.3$), NGC 185 ($M_V \simeq -15.1$), NGC 147 ($M_V \simeq -14.8$), Leo I ($M_V \simeq -11$), Leo II ($M_V \simeq -9.5$), Ursa Minor ($M_V \simeq -9$), and Draco ($M_V \simeq -8.5$). In addition, dwarf ellipticals are found as companions to many giant galaxies of all types. A particularly good example is NGC 4321 (M100) in the Virgo cluster which is surrounded by at least six dE galaxies all fainter than $M_V \simeq -15$. Plate 1 shows the subclustering about the giant Sc as reproduced from a 100-inch plate. Similar dE galaxies have been found in the Virgo cluster (Reaves 1956), in the M81 group (Sandage 1954), and in the Fornax cluster (Hodge 1959, 1960). The dE galaxies together with dwarf spirals and low-luminosity Im are undoubtedly the most frequent type of galaxy per unit volume of space (van den Bergh 1959; Holmberg, chap. 4 of this volume), although they form a totally insignificant fraction of catalogued galaxies to a given apparent magnitude because of their exceedingly low absolute luminosity. Indeed, it has only been since about 1940 (Baade 1944; Wilson 1955) that the dE galaxies have been recognized as a class.

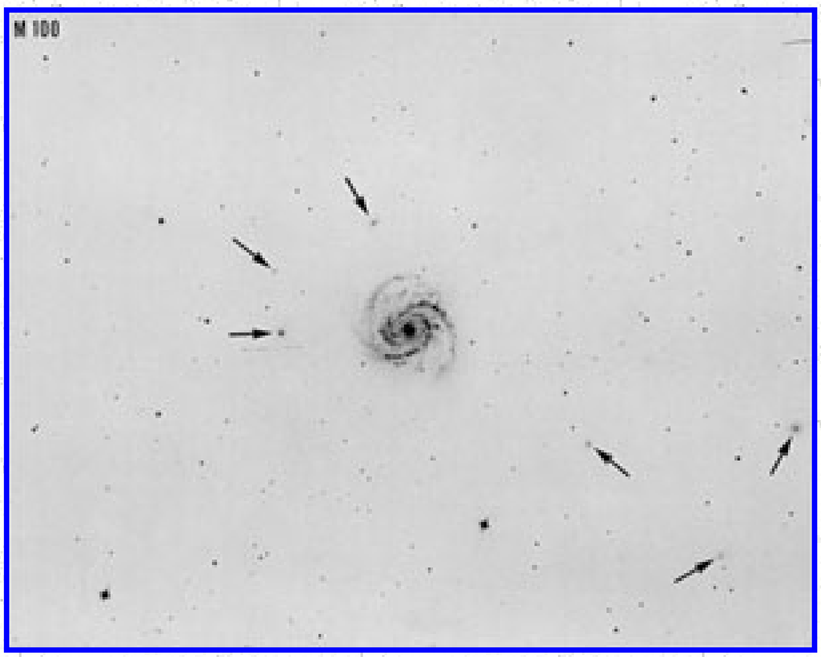

Plate 1. M100 with six of its many dwarf elliptical companions marked. The spiral is of luminosity class I and is one of the brightest galaxies in the Virgo cluster. Many dE galaxies are spread throughout the area (Reaves 1956). From a plate taken with the Mount Wilson 100-inch reflector.

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5.2 Spirals With Thin Filamentary Arms

Such galaxies are shown in Plates 2 and 3, arranged in order of increasingly later forms. The 12 illustrated galaxies form a continuously connected sequence. Along this sequence the size of the amorphous central region relative to the disk-length (see Freeman 1970; Sandage, Freeman, and Stokes 1970) generally decreases (there are exceptions) as the arms become more dominant and as the arms and disk become more highly resolved into knots and stars. For the first three galaxies illustrated (NGC 5273, NGC 1302, and NGC 2811) this spheroidal component, including the unresolved arms, covers a large fraction of the total area. However, by the time NGC 6643 [SA(rs)c] is reached along the sequence (Plate 3) the spheroidal component has shrunk to an exceedingly small region, and by NGC 5204 [SA (s)m] has disappeared entirely. The arms are filamentary, and are generally segmented throughout the sequence. Galaxies in this characteristic subgroup are discussed more thoroughly in the *Hubble Atlas* (cf. section on Sb and the legend to NGC 5055 in *Atlas*, p. 15).

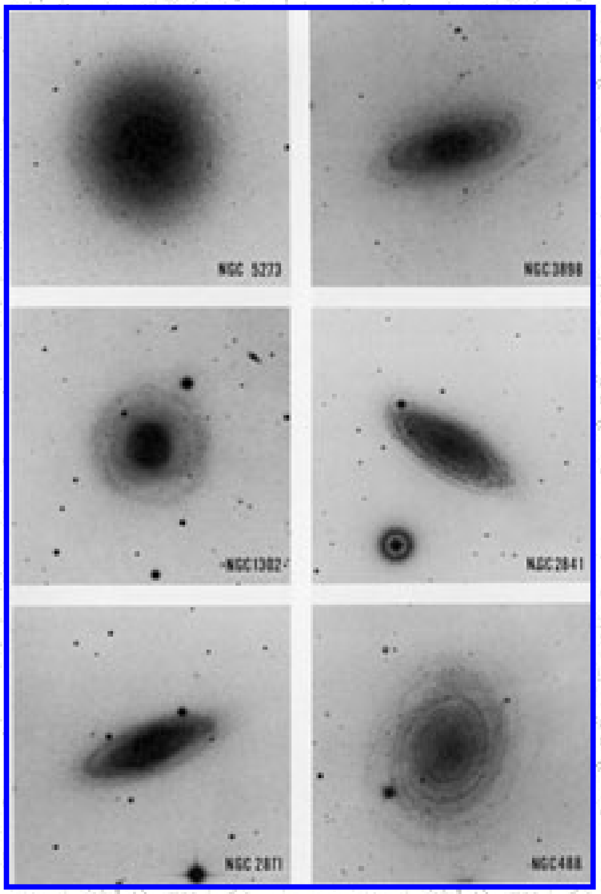

PLATE 2. This and the following plate 3 illustrate the progressive change of appearance along the sequence of classification for thin, multiple-armed ordinary spirals from the earliest type $S0_2$/Sa(s) in the upper left (NGC 5273, *Atlas*, p. 8) to the latest Sm (or Sc/Irr Hubble) at the lower right of plate 3 for NGC 5204. The pictures are arranged in order of increasingly later type by following the left column from top to bottom, and then the right column similarly, in this and the following plate. The types of the galaxies can be found in table 2 of the text. Photographs taken with Mount Wilson or Palomar reflectors as described in the *Hubble Atlas* (Sandage 1961).

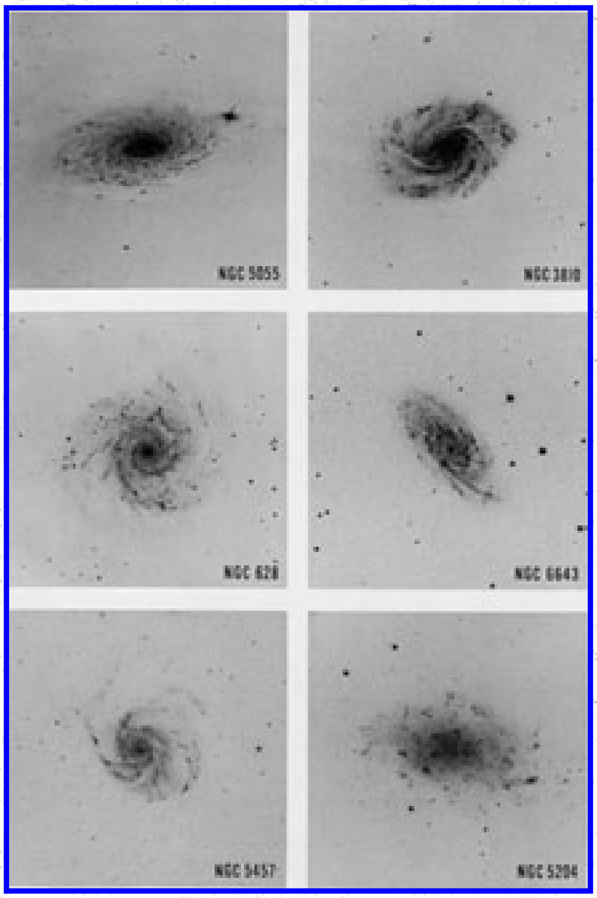

Plate 3. Continues the sequence of thin, multiple-armed ordinary spirals from plate 2 into the middle Sb to late Sd-Sm sections. The gradual and progressive changes of arm structure from Sa to late Sc form the continuous pattern visible in this sequence. The continuity is described in the *Hubble Atlas* in the text of the Sb section (*Atlas*, p. 16), and in the commentary to pictures on pp. 14 and 15 of the Atlas section (see in particular the description of NGC 5055). Mount Wilson-Palomar photographs.

5.3 Spirals With Massive Arms

Massive-armed spirals form a second strain through the spiral sequence and are shown in Plate 4. No dominant spheroidal component is present for the galaxies illustrated here, even among the earliest types such as NGC 4293 [Sa or RSB (s)0/a] and 3623 [Sa or SAB (rs)a] in Plate 4. The reproductions emphasize that Hubble's three criteria do not always agree. The most obvious examples are 4293 and 4569 [Sb or SAB (rs)ab]. In such conflicting cases Hubble, Sandage, and de Vaucouleurs place most emphasis on the arm structure, and therefore classify such systems as Sa or early Sb despite the small spheroidal component. Besides the examples just mentioned, other such galaxies are NGC 4866 (*Atlas*, p. 11) and especially 4941 (*Atlas*, p. 10).

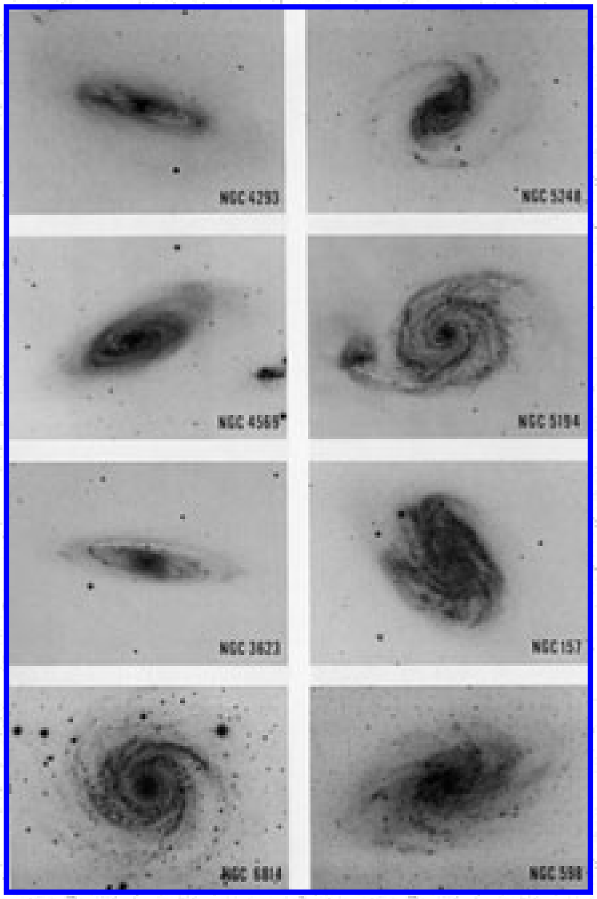

Plate 4. Progressive change of form of the massive-armed spirals from the earliest (NGC 4293, Sa) in the upper left, to the latest (M33, Scd) in the lower right. The nature of the arms changes continuously in the left column from top to bottom, and similarly in the right-hand column. Although all galaxies in this and the preceding two plates are of the same family (ordinary spirals), the difference in the arm structure pointed out by Reynolds (thin and filamentary in plates 2 - 3, and massive here) is evident. The division continues along the full length of the sequence from Sa to Sm. The plates were taken with the Mount Wilson or Palomar reflector.

On the other hand, Morgan (cf. Section 7) emphasizes the relative size of the spheroidal component as his primary criterion. Morgan's system has advantages for certain problems because Morgan and Mayall (1957) show that the degree of dominance of the spheroidal component correlates well with integrated spectral type.

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5.4 Transitions Between SA and SB

Transition galaxies are shown in Plate 5. Those illustrated are among only the most obviously mixed cases previously called S/SB by Hubble and Sandage. De Vaucouleurs emphasizes the transitions more strongly than Hubble by using the SAB notation for galaxies where the bar is quite subtle. For example, five of the eight galaxies in Plate 4 are called SAB by de Vaucouleurs, whereas none of these were called transition cases in the *Hubble Atlas*. De Vaucouleurs's procedure recognizes the fact that most galaxies possess an incipient bar, as discussed most explicitly by Lindblad and Langebartel (1953). The effect of the finer division in the revised system is that among the 1500 bright galaxies reclassified by de Vaucouleurs (1963b, table 5) there are about equal numbers of SA, SAB, and SB systems, whereas very few transition cases were isolated in the Hubble system (see, e.g., the types listed in HMS 1956).

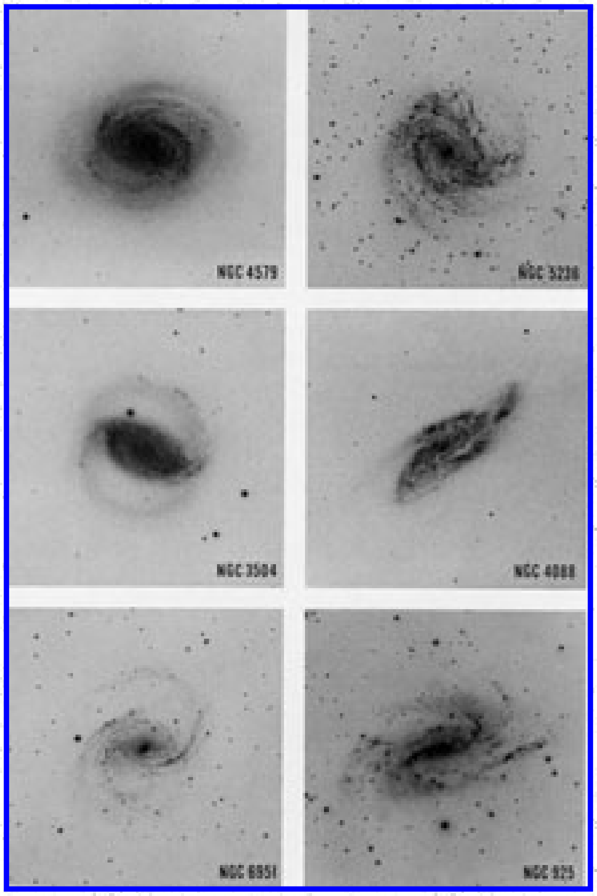

Plate 5. Transition types between ordinary and barred spirals. The types assigned by various classifiers are listed in table 2.

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5.5 Pure Barred Galaxies

Pure cases of the r and s varieties are shown in Plate 6, s on the left, r on the right. As previously mentioned, NGC 3185 (*Atlas*, p. 43; and Plate 6 here) is especially interesting because of the very tightly wound arms, which on casual inspection appear (incorrectly) to form a complete ring. The first galaxy in the upper left [NGC 7743; SBa(s) Hubble, or (R?)SB(s)0^+ de Vaucouleurs, which must be a misclassification because of the presence of distinct arms] has a similar pattern, but the arms are more clearly separated, perhaps due to a more favorable orientation of this galaxy to the line of sight. The separation of the end of the bar and the arm that begins at the opposite end of the bar increases progressively along the classification sequence, being clearly separated at the SB (s)b stage, such as NGC 1300 (*Atlas*, p. 45; and Plate 6). This separation can be used as a secondary classification criterion for SBa and SBb types (cf. the discussion on p. 23 of the *Hubble Atlas* text).

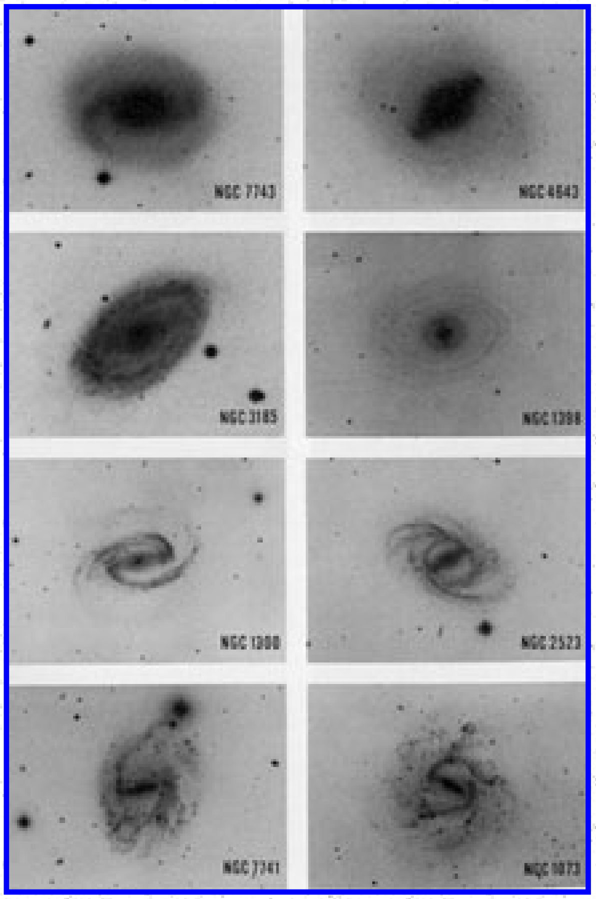

Plate 6. Barred spirals, showing the division into r and s types. Galaxies where the arms start from the end of the bar (s types) are shown on the left. Galaxies in which they begin tangent to an internal ring (r) are on the right. Within each column, the galaxies are arranged in the order from early to late. The one mixed type that is illustrated is NGC 1073 [SBc(rs)] at the lower right. NGC 3185 in the left column is of (s) variety, although it may appear to have a complete ring on small-scale plates. The arms do not touch to form a ring, but are very tightly wound after starting from the end of a bar.

As with the ordinary spirals, the resolution into stars increases, and the arms become more prominent relative to the amorphous central regions (the spheroidal component) as one progresses from the a to d subclasses. These monotonic changes are particularly evident in Plate 6.

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5.6 Sdm, Sm, and Im

These late-type galaxies form an important extension. Most such systems were called Irr by Hubble and Irr I by Holmberg, but they clearly follow naturally beyond the SAd and SBd forms. For example, Hodge and Hitchcock (1966) showed that galaxies of this type are highly flattened as a class (as in the earlier spirals), extending earlier work by de Vaucouleurs (1955a, b) for the Magellanic Clouds themselves. Furthermore, many studies show that the LMC is in a state of regular rotation (cf. Feast, Thackeray, and Wesselink 1961; Feast 1964, 1968 with extensive references therein), again similar to the earlier-type more regular spirals. And finally, ill-defined, subtle, but definite spiral structure has been detected (Section 4.1) by de Vaucouleurs (1954, 1955a).

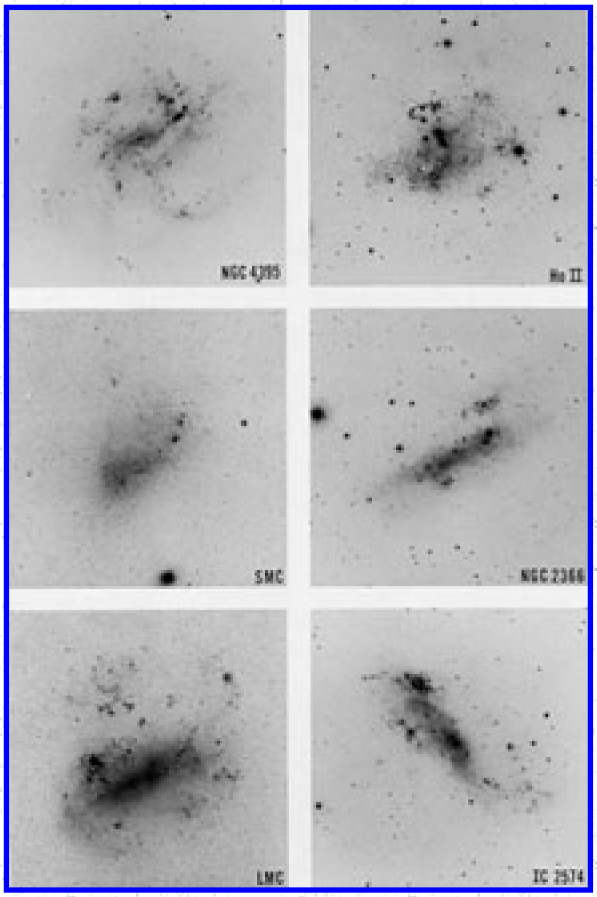

Plate 7. The late end of the sequence of classification showing the varieties of Magellanic Cloud-type systems, classified either as Sm or Im galaxies depending on the presence or absence of vague spiral arms. The plates of the SMC and LMC are by Henize using the Mount Wilson 10-inch refractor in South Africa. The other photographs are from Mount Wilson or Palomar reflector plates.

Most galaxies of this type are of low surface brightness, and have much lower luminosity than earlier-type spirals (HMS 1956; van den Bergh 1959, 1960a; de Vaucouleurs 1963b). Van den Bergh (1960b) has discussed the Sm and Im, types and has produced a catalog (1959), including the dE group, from the Palomar Sky Survey prints. Representatives are illustrated in Plate 7 and in the *Hubble Atlas* (pp. 38-40).

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5.7 Irr II Galaxies

Systems such as M82, NGC 520, and the companion to M51 (*Atlas*, p. 26; and plate 4 here) were often classified as peculiar by Hubble. This group represents a more restricted definition than that given by Arp (1966). As defined here, Irr II galaxies have an amorphous texture of the luminous form (M82: *Atlas*, p. 41; NGC 3077: *Atlas*, p. 41) and fall outside the standard system. Although peculiar, they should be distinguished from those galaxies whose peculiarities are caused by tidal interactions.

5.8 Interacting Galaxies

Galaxies that show the effects of mutual interaction need not be extensively discussed here. They clearly represent tidal perturbations (Toomre and Toomre 1972), and the classification system need not be changed to accommodate them. But the forms are so interesting in themselves that a few illustrations (Plate 8) are useful.

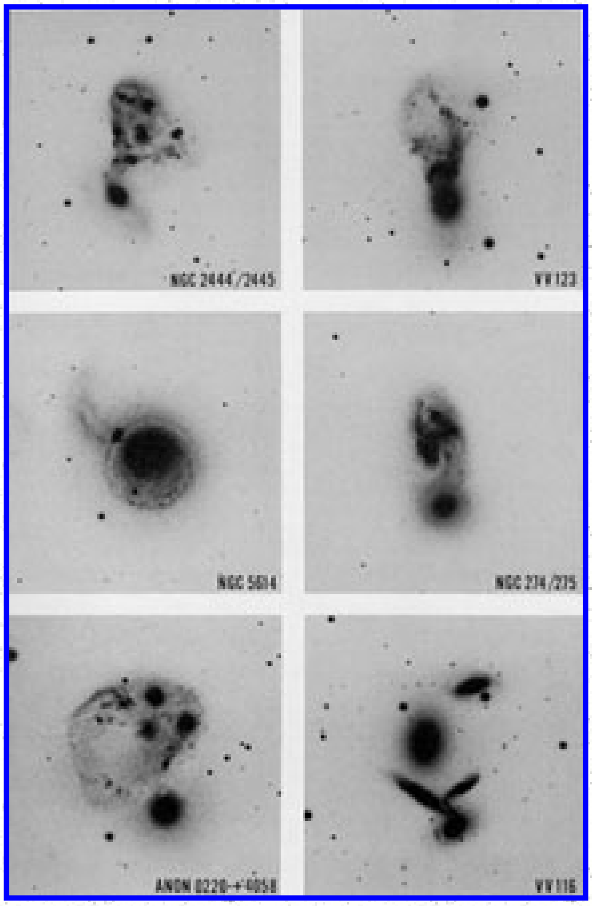

Plate 8. Various interacting galaxies showing the effects of tidal distortion. This is not a representative sample such as the compilations of Vorontsov-Velyaminov (1959) or of Arp (1966).

An extensive compilation with photographs has been made by Vorontsov-Velyaminov (1959). Some such galaxies are illustrated in the series of photographs taken with large reflectors published in an atlas by Arp (1963). Studies of particular individual galaxies include papers by Zwicky (1956, 1959), Burbidge and Burbidge (1959), Sandage (1963), Sersic (1966), and others.

A general theory of interacting systems is discussed by Toomre and Toomre (1972), and for several particular systems by Limber (1965).

6. VAN DEN BERGH'S CLASSIFICATION

By inspecting *Palomar Sky Survey* prints, van den Bergh (1960a, b) made the important discovery that the appearance of the spiral arms was a steep function of the absolute luminosity of galaxies. He showed that galaxies of the highest luminosity have the longest and most highly developed arms, whereas fainter systems such as NGC 5204 (Plate 3) have poorly developed arms.

The result is equivalent to stating that the appearance of galaxies varies systematically as one proceeds from left to right within the scatter of redshift-apparent-magnitude diagrams for field galaxies (see, for example, Figures 6, 7, and 9 of HMS).

By inspecting the character of the spiral arms alone, van den Bergh was able to divide Sb types into five luminosity classes (I, I-II, II, II-III, and III), which subsequent calibration showed were ~ 0.5 mag apart in $\langle M_{pg} \rangle$. The Sc-Irr systems could be divided into eight half-classes (I to V with intermediates).

van den Bergh's system is two-dimensional. It retains the Hubble types a, b, and c as a division along a linear sequence, and adds the luminosity class as the second parameter.

Additional symbols are used such as + and - (following Holmberg) to divide the Hubble classes more finely, n for nebulous arms such as NGC 3623 (plate 4) and NGC 4569 (Plate 4), an asterisk (*) for patchy arms such as NGC 157 (plate 4) and 4088 (plate 5), and t for indications of ``tidal" distortion. Extreme characteristics are noted by double symbols; incipient features, by (n), (*), and (t).

van den Bergh notes that most of the Hubble-type examples usually illustrated in textbooks, in the *Hubble Atlas*, and in plates 1-8 are supergiant galaxies, and that the early Hubble classification system defined by such bright galaxies cannot generally be applied to dwarf galaxies without modification. He emphasizes that all dwarf and sub-giant galaxies classified in HMS (1956) are of type Sc, which shows that few if any dwarf Sa and Sb systems exist. This fact is recognized in van den Bergh's system for Sb systems where only class I, II, and III galaxies are present, whereas class V (dwarf) galaxies exist in the Sc to Irr classes.

The validity of the luminosity classes is shown by the clear separation of the classes in the redshift-magnitude relation (van den Bergh 1960a, fig. 4; 1960b, fig. 4). Van den Bergh's preliminary calibration of $\langle M_{pg} \rangle$ for each class was based on this separation, adopting H = 100 km s^{-1} Mpc^{-1}. The calibration is reproduced in table 1. The dispersions of $\langle M_{pg} \rangle$ were found to be σ 0.3-0.4 mag for the well-defined cases (van den Bergh 1960a, table 4), as obtained by comparing differences between the M_{pg} predicted from the luminosity classification and known values for particular galaxies in groups and clusters.

TABLE 1
VAN DEN BERGH's CALIBRATION BASED ON
H_0= 100 km $s^{-1}Mpc^{-1}$

Type	M_{pg}	Type	Mpg
SbI	-20.4	ScI	-20.0
SbI-II	-19.9	Sc I-II	-19.7
SbII	-19.4	Sc and Irr II	-19.4
SbII-III	-18.6	Sc and Irr II-III	-18.9
SbIII	-18.0	Sc and Irr III	-18.3
		Sc and Irr III-IV	-18.0:
		Sc and Irr IV	-17.3:
		Sc and Irr IV-V	-16.1:

From *Pub. David Dunlap Obs.*, Vol. **2**, No. 6, 1960.

The importance of the luminosity classification, regardless of its calibration, is that relative distances can be obtained to large numbers of field spirals within an accuracy of $\delta r / r = 0.461\, \delta M$. This error is small when $\sigma(\delta M)$ is, say, 0.4 mag that arises from classification errors and from true cosmic spread. The distances can be changed to absolute values once H_0 is accurately known. (Table 1, based on an assumed value of H_0, is subject to modification. A calibration in 1972 by Sandage and Tammann gave $H_0 \simeq 55$, which would require the values in table 1 to be about 1 mag brighter). On a distance scale with H_0 = 100 km s^{-1} Mpc^{-1}, van den Bergh has given absolute moduli for many Shapley-Ames galaxies in his reclassification catalog (van den Bergh 1960).

The van den Bergh classification is defined by the many type-examples given in his catalog, as classified from the Palomar prints. Because of the burned-out nature of many galaxies on these prints, he could usually make no distinction between S0 and E systems, and many flattened systems were classed E with flattenings ranging to 8. Such large flattenings do not, of course, exist in the standard system because E galaxies are never flatter than E7, and very few of these exist (cf. Sandage, Freeman, and Stokes 1970). Many of the flattened E8 so classified in the catalog are actually edge-on spirals and S0 galaxies, which, for this reason, are not represented in the *DDO Catalogue*. Comparison of the DDO types with other classification lists is made by de Vaucouleurs (1963b, table 10 and fig. 5).

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7. MORGAN'S CLASSIFICATION BASED ON THE LUMINOSITY CONCENTRATION OF THE SPHEROIDAL COMPONENT

A most important feature of galaxies is the great difference in stellar content between their spiral arms and the spheroidal component. The difference is evident from direct photographs: it was shown explicitly by Baade's resolution studies in 1944, and is apparent from the change of integrated colors along the classification sequence as the relative importance of the old (spheroidal) and young arm populations exchange dominance in going from S0 to Sm systems.

Because the difference is pronounced, it must be expected that the integrated spectral type should correlate with the light ratio of the spheroidal to young-disk populations, and therefore roughly with Hubble type, since this ratio is one of the classification parameters.

The earliest indication of such population differences was noted by Seares (1916a, b), who discovered that the central parts of galaxies are redder than the arm regions. After the start of the Mount Wilson and Lick systematic redshift programs, both Humason and Mayall noted gross spectroscopic differences among galaxies, and summarized their results in the discussion of their redshift catalog (HMS 1956). Starting in 1932, Humason regularly classified the dominant spectral class and showed that it correlated with Hubble type in the expected sense.

Morgan and Mayall (1957) reviewed these early results and advanced the work by showing that the composite spectral class correlates well with the degree of dominance of the spheroidal component alone, i.e., with the concentration of the luminosity toward the center. [5] Morgan (1958, 1959) developed this spectral-type concentration correlation into a classification system whose color-class notation explicitly isolates the spectral type that is expected on the basis of the correlations.

The Morgan system contains information on the *state of stellar evolution* in the central regions of galaxies. The classification complements information in the Hubble-de Vaucouleurs system which, in cases of conflicting criteria, emphasizes more strongly the strength of the spiral-arm population [see, e.g., NGC 4941, Sab: Hubble; SABab: de Vaucouleurs; *Atlas*, p. 10].

In the introduction to his 1958 paper, Morgan states: ``The correspondence between form and spectral appearance is especially close for two categories of galaxies: (1) irregular systems of the Magellanic Cloud-type and spirals having an insignificant central concentration of luminosity [Sd, Sm], and (2) giant ellipticals such as those found in the Virgo cloud and spiral systems such as M31, in which the major share of the luminosity of the main body is due to a bright amorphous central region. In the first category, early-type stars and emission nebulosities have a profound effect on the spectrum in the blue and violet regions [producing strong hydrogen absorption lines and bright emission lines such as found in galactic HII regions); in the second, the luminosity of the brighter parts is due principally to yellow giant stars."

``Systems possessing an intermediate degree of central concentration of light (M51 [Plate 4 here on NGC 5194]) give spectroscopic evidence of an intermediate kind of stellar population: the degree of compositeness is very high, and it appears likely that most of the luminosity is due to a mixture of F to G main-sequence stars and K giants."

Morgan's notation contains a *concentration* class ranging from a through af, f, fg, g, gk, and k, in the direction of increasing domination of the nuclear light (and consequently later composite spectral type according to the Morgan-Mayall correlation), and a *form* notation similar to Hubble's with E for ellipticals; S, spirals; B, barred spirals; and I for irregulars. Three new form classes are added: D for dustless systems dominated by the amorphous light; L for galaxies of low surface brightness (such as NGC 45 (*Atlas*, p. 37]); and N for systems having small, brilliant nuclei superposed on a considerably fainter background.

The addition of an inclination index ranging from 1 (circular) to 7 (spindle with a/b $\simeq$ 10) and the symbol p denoting ``peculiar" completes the notation. Examples of well-known galaxies classified on the Morgan system, many of which are shown in plates 2 - 7, are NGC 5273 (gkD2 Morgan; S0/Sa Hubble), NGC 488 (kS2 Morgan; Sb Hubble), NGC 628 (fgS1 Morgan; Sc Hubble), NGC 5204 (fI-fS4 Morgan; Sc/Ir Hubble; SAm de Vaucouleurs); M33 (fS3 Morgan; Sc Hubble) and NGC 4449 (aI Morgan; Ir Hubble; IBm de Vaucouleurs).

There is a general correlation of the Morgan class with the Hubble-de Vaucouleurs types. A comparison has been made by de Vaucouleurs (1963b, Table 13). The major difference is in the definition of the D systems. The closest Hubble type is S0, although there is a rather large extension into the E's on one side of the scatter and the early SA and SB types on the other. The difference is of some importance because Morgan classifies the brightest galaxies in rich clusters as cD (c for supergiant), whereas the Mount Wilson observers do not.

Following Matthews, Morgan, and Schmidt (1964), the cD notation has been generally adopted by radio astronomers for the radio ellipticals, but these galaxies are still classified as giant E galaxies on the Mount Wilson system. The Mount Wilson procedure follows naturally from the discovery of Hubble and Humason in the 1930s that rich clusters of galaxies are composed *almost entirely of E and S0 galaxies*. The brightest member galaxies are of the same general type as the fainter very numerous E systems (restricting to the top 4-mag range), differing only slightly if at all in the occasional presence of a extended envelope (it is not yet known if these outer regions follow a power intensity law as in true E galaxies, or if there is a small exponential component as in the disks of true S0's).

The introduction of a separate D class in an otherwise continuous sequence of E forms among the brighter cluster members is then the chief difference between the Mount Wilson and the Yerkes classification of galaxies in rich clusters.

A summary of the Morgan system and its significance for studies of stellar content is given by Morgan and Osterbrock (1969).

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[5] The difference in scatter between the Morgan-Mayall and the Humason spectral-type, galaxy-class correlation shows clearly that the size of the nuclear region does not vary uniquely and monotonically with Hubble type, although there is a general trend. The point has previously been made by Vorontsov-Velyaminov in his comments on the Hubble system (cf. Introduction, Vol. **2**, *Morphological Catalog of Galaxies*, p. 4) and by Freeman (1970) in his plot of the spheroidal-to-disk length ratio as a function of Hubble type. Back.

8. SYSTEM OF VORONTSOV-VELYAMINOV

The *Morphological Catalog of Galaxies* (MCG) in four volumes by Vorontsov-Velyaminov, Arhysova, and Krasnogorskaja contains positions, sizes, magnitudes, and descriptions of 29,000 galaxies on prints of the *Palomar Sky Survey* from the pole to δ = -30°. The catalog is essentially complete to m_{pg} = 15 mag.

A new system of description was devised, using the symbols that are illustrated and discussed in the Introduction to Volume 1 of the MCG. In philosophy, the system is similar to Wolf's scheme, but more particularly to Reynolds's hope for a less simple system than Hubble's (Section 3.2), where the great diversity of pattern would be recognized in the notation. This hope is realized, because the combined symbols in the MCG are sufficient to describe a large variety of detailed structural features. But as yet the system does not constitute a classification of the second kind (Section 1), where continuously varying parameters are used to provide connective relations. This, however, was not the purpose of the Vorontsov-Velyaminov descriptions, and the system cannot be criticized on such grounds because the authors state in the Introduction to Volume 2: ``Our descriptions do not [constitute a] classification. They are merely a step forced by the diversity of galaxies revealed by the Palomar Atlas and by the peculiarity of this *Atlas*. [It] may be [that] our descriptions will help to elaborate a new [more] appropriate classification." Undoubtedly features such as the γ forms, the rings, pseudo-rings, and peculiar arm structures to which Vorontsov-Velyaminov has often called attention will prove to be important when the detailed dynamics of galaxies become better understood. At the moment, the other classification systems in general use emphasize the more gross aspects of galaxy systematics.

9. COMPARISON OF THE CLASSIFICATION SYSTEMS

To aid in learning the classifications, the types assigned by Hubble, Sandage, Holmberg, de Vaucouleurs, van den Bergh, and Morgan to galaxies illustrated in this chapter are listed in table 2. The illustrated examples are insufficient to show all complications, and reference should be made to various classification catalogs, supplemented by published photographs. Some of the more extensive classification lists are: (1) Pettit (1954) and the *Hubble Atlas* for the modified Hubble system, (2) Holmberg (1958), (3) de Vaucouleurs (1963b), (4) van den Bergh (1959, 1960a, b, c), and (5) Morgan (1958, 1959). [(6)]

TABLE 2
CLASSIFICATION OF THE GALAXIES ILLUSTRATED IN PLATES II-VII

Name NGC	Hubble	Holmberg	de Vaucouleurs	van den Bergh	Morgan
			Thin Multiple-Armed Spirals (Plate II)		
5273	$S0_2$/Sa(s)	-	SA(s)0^0	E 1(p?)	gKD2
1302	Sa	-	(R)SB(r)o/a	S(B)a	kB1
2811	Sa	-	SB(rs)a	Sb^+ II-III	-
3898	Sa	-	SA(s)ab	Sb^- II	kD5-KS5
2841	Sb	Sb^-	SA(r:)b	Sb^- I	kS5
488	Sb	Sb^-	SA(r)b	Sb^- I	kS2
			Thin Multiple-Armed Spirals (Plate III)		
5055	Sb	Sb^+	SA(rs)bc	Sb^+II	gS4
628	Sc	Sc^-	SA(s)c	Sc I	fgS1
5457	Sc	Sc^-	SAB(rs)cd	Sc I	fS1
3810	Sc	Sc^-	SA(rs)c	Sc I	fS3
6643	Sc	Sc^-	SA(rs)c	Sc I-II	-
5204	Sc/Irr	Sc^+	SA(s)m	Ir^+ IV	fI-fS4

Massive-Armed Spirals Plate IV

4293	Sa	-	RSB(s)o/a	Pec	fg:S6
4569	Sb	Sb^{+}	SAB(rs)ab	$Sb^{+}n$	fS4p
3623	Sa	Sa	SAB(rs)a	Sbn II:	gS5
6814	Sb	-	SAB(rs)bc	Sb^{+} I	-
5248	Sc	Sc^{-}	SAB(rs)bc	Sc I	fS4
5194	Sc	Sc^{-}	SA(s)bcp	Sc(t) I	fS1
157	Sc	Sc^{-}	SA(rs)bc	Sc(*)I	afS3
598	Sc	Sc^{+}	SA(s)cd	Sc II-III	fS3

Ordinary-Barred Transitions Plate V

4579	Sb/SBb	Sb^{-}	SAB(rs)b	Sbn	gk S3-gKB
3504	SBb(s)/Sb	-	SAB(s)ab	Sb(t?)	fg B1?
6951	SBb(s)Sb	Sb^{+}	SAB(rs)bc	Sbp I-II	f:S1p-f:BpN
5236	Sc/SBb	-	SAB(s)c	-	fgS1
4088	SBc/Sc	Sc^{-}	SAB(s)bc	Sc* I-II	a:B:4
925	Sc/SBc	Sc^{+}	SAB(s)d	S(B)c II-III	afB

Barred Spirals r and s Types Plate VI

7743	SBa(s)	-	(R?)SB(s)0^{+}	Sa?	gkB1
3185	SBa(s)	Sa	(R)SB(r)a	S(B)b^{+} III	fB
1300	SBb(s)	Sb^{+}	SB(rs)bc	SBb I	fB2
7741	SBc(s)	Sc^{+}	SB(s)cd	SBc II	afB
4643	$SB0_3$/SBa(r)	-	SB(rs)o/a	SBa	kB
1398	SBb(r)	-	(R')SB(r)ab	S(B)b^{-} I	kB2
2523	SBb(r)	-	SB(r)bc	SBb- I	fgB
1073	SBc(sr)	Sc^{+}	SB(rs)c	S(B)c II	afB1

Magellanic Cloud and Irregular Types Plate VII

4395	Sc/Irr	Sc^+	Sa(s:)m	S^+ IV-V	aS1
SMC	Irr	-	IB(s)mp	III-IV	-
LMC	Irr	-	SB(s)m	Ir IV-V	-
Hol II	Irr	Ir I	Im	Ir IV-V	-
2366	Irr	Ir I	dIB(s)m	Ir IV-V	aL?
IC 2574	Irr	Ir I	SAB(s)m	Ir IV-V	-

[6] Recall that Holmberg does not separate the ordinary and barred spirals and thqat van den Bergh does not distinguish E, S0, and edge-on spirals (spindles) because of the burned-out nature of the Sky Survey prints. Back.

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10. SEYFERT GALAXIES, N GALAXIES, AND QUASARS

A group of galaxies that, to varying degrees, stand apart from the standard classification are those whose parts (Seyfert nuclei), or nearly the whole of their optical image (QSOs) are in a more highly condensed state than normal systems. As far as classification of their optical properties is concerned, they form a continuum which can be conveniently divided into three sections called Seyferts, N galaxies, and quasars. Although their radio properties were emphasized most strongly in the decade of the 1960s, radio emission appears to be superficial as regards the optical forms. Both radio-intense and radio-quiet examples exist in all three sections of the compact regime, and the radio-quiet (or radio-weak) objects form the majority of the sample per volume of space.

The degree of compactness varies along the sequence in the order Seyfert, N, QSO. Seyfert galaxies are almost normal in the Hubble sense, except for an intensely bright nucleus. Those Seyferts that are spirals (e.g., NGC 1068, NGC 4051, NGC 4151) have slightly abnormal outer arms that form nearly complete faint exterior ``rings'' beyond the inner spiral pattern (cf. Hodge 1968), but otherwise (and aside from their nuclei) they are easily placed within the Hubble sequence. N galaxies are dominated to a larger extent by their compact, nonthermal, central region, whereas most quasi-stellar objects (QSOs or quasars) are completely stellar (*by definition*) on photographs with a scale of 10" mm^{-1}.

The continuity between Seyferts, N galaxies, and QSOs in their classification has been discussed by many authors, and will not again be reviewed here (cf. Sandage 1971, 1973). Early classical papers on the Seyferts alone include the original discussion by Seyfert (1943), and the renaissance of the subject by Woltjer (1959). The N systems of Morgan (1958, 1959) were reemphasized by Matthews, Morgan, and Schmidt (1964) via the route of radio sources, and the connections between Seyferts and QSOs were summarized by Burbidge, Burbidge, and Sandage (1963).

Discussions of the classification system as it existed in mid-1971 were given by Morgan (1971) in the Pontifical Academy volume devoted to this subject (O'Connell 1971). A useful summary of the Seyfert problem, of the group characteristics of these compact systems taken as a whole, and of the effect of different spatial resolutions on the classification of a given object can be found in the *Proceedings of the Conference on Seyfert Galaxies and Related Objects* edited by Pacholczyk and Weymann (1968).

11. STELLAR CONTENT RELATED TO TYPE: FORMATION AND EVOLUTION

One of the most remarkable features of the standard classification system is that the stellar content of galaxies varies systematically along the linear sequence from E to Sm. In the order Sa to Sd, the progressive changes are (1) increasing absolute luminosity of the brightest stars in regions of the spiral arms, (2) increasing percentage of mass in the form of gas and dust, (3) increasing sizes and numbers of H II regions in the spiral arms, and (4) progressively bluer integrated (B - V) and (U - B) colors, indicating progressively earlier type stars that contribute most of the light.

The correlations represent a physical result because the classification is made principally not on the resolution of the galaxy into stars, but rather on the character of the nuclear bulge, and on the presence, the shape, and the regularity of the arm structure.

Some of the questions raised by the correlation of *content* and *form* have been discussed by Sandage, Freeman, and Stokes (1970) in a review of Hubble's (1926) problem to find the true flattening of elliptical galaxies from the observed distribution of apparent flattenings. In that study, flattenings were compared for ellipticals and spirals, and we concluded with Hubble, Holmberg (1946), and de Vaucouleurs (1959a) that all spiral and S0 galaxies are flatter than the flattest elliptical.

Because flattening is a dynamical property that, in an equilibrium configuration, cannot change in times less than the relaxation time (~ 10^{12}-10^{14} years), the difference in intrinsic flattening between E and S galaxies shows that one type cannot evolve into the other. A basic difference must then have existed between E and S systems *at the time of their formation to cause* such different forms now. An identification and an understanding of this difference is necessary at the outset of even the most elementary discussion of galaxy evolution.

Flattening can occur on a *short* time scale only if (1) the relaxation time itself is short under conditions that prevailed before the system formed into stars, (2) the gravitational potential energy of a stellar system is rapidly changing (cf. Lynden-Bell 1967), or (3) both. The difference in formation history of E and S galaxies must then be due to some difference, such as the angular-momentum distribution of the contracting protogalaxies, or any other agent that would *control the initial rate of star formation during the collapse time of the protogalaxy toward the fundamental plane*. Elliptical galaxies obviously *did not* collapse completely (they are not now highly flattened), and this shows that nearly *all star formation took place in times short compared to the free-fall time* (~ 10^9 years), leaving no gas to interact by gas-gas collisions to damp into a fundamental plane that is characteristic of spirals. On the other hand, the existence of such a plane in all spirals seems to betray a *slower* initial conversion of gas to stars. Furthermore, much of the gas has remained in the plane over the lifetime of the system.

The required rapid star formation in E systems and in the spheroidal components of spirals and S0 galaxies finds considerable direct support from observations. Baade's resolution of parts of the Local Group galaxies M31, M32, NGC 205, NGC 185, and NGC 147 into stars at $M_V \simeq -3$, $B - V \simeq + 1.5$ at the same intensity level as the globular clusters embedded in their galactic halos shows the antiquity of these resolved subsystems (Baade 1944). The argument is made stronger by the lack of bright young blue supergiants in the spheroidal regions of S0, Sa, and Sb galaxies, and in E systems. Constraints on the age are stringent (Sandage 1969, 1971) from these data.

Considering the flattening and the stellar content data, and arguing from the relaxation problem of Lynden-Bell (1967), Sandage, Freeman, and Stokes reached the following conclusions.

1. Stars in the spheroidal component of all galaxies were formed very rapidly on a time scale comparable to the collapse time of the protogalaxy ($\lesssim 10^9$ years). The argument is independent of that used by Eggen, Lynden-Bell, and Sandage (1962) which was based on the orbital eccentricities of galactic stars. It depends here only (*a*) on the absence of a fundamental plane both in E galaxies and in the spheroidal subsystems of spirals, and (*b*) on the observation that the stellar distribution itself appears to be relaxed, presumably by Lynden-Bell's (1967) mechanism.

2. The *halo* stars were formed from matter having low angular momentum per unit mass, i.e., the spheroidal component, during the collapse time. Other matter with higher angular momentum collapsed to a disk.

3. The galaxy type was determined by the amount of free gas left over in the disk after collapse. No appreciable evolution along the Hubble sequence has occurred since the galaxies were formed.

4. The dominance of the disk in spiral and S0 systems betrays their mean angular momentum per unit mass, higher than that which exists in less-flattened E galaxies. Does the higher angular momentum slow the rate of star formation, keeping uncondensed matter (gas and dust) in reserve for new generations to form continuously in the dusty disks?

5. All stars in the spheroidal component of galaxies should show an age distribution δT which is *small* compared to the total age T, such that $\delta T / T \lesssim 0.1$. This expectation agrees with observational data for halo globular clusters in our own Galaxy, and with the uniformity of observed energy distributions $I(\lambda)$ for E galaxies and the centers of S0, Sa, and Sb systems.

Without collapse of matter from a wider configuration it is difficult to understand the presence of a dominant plane in spirals. But in ellipticals it is difficult to understand *its absence* without rapid and complete star formation on a time scale *short* compared with the free-fall time from the edges of a protogalaxy.

The comments in this last section may be more speculative than substantive, but they are discussed here because they follow naturally from certain characteristics of the Hubble classification. Because of this, it seems possible that the classification is fundamental in the sense discussed in Section 1 i.e., the connective parameters of the system appear to contain part of the physics of galaxies. That the Hubble system has this property would follow if ideas of this section could be substantiated. And likewise, that the Morgan nuclear sequence might also be a classification of the second kind would follow if the stellar component of the spheroidal bulge is understood in terms of stellar evolution of the composite H-R diagram (Chap. 2), as we now believe.

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