1 Galaxy classification

1.1 Introduction

Galaxies are massive systems of stars, gas, dust, and other forms of matter bound together gravitationally as a single physical unit. Based on deep imaging surveys, it can be estimated that the observable Universe includes more than 40 billion galaxies, spread around in complex large-scale structures, such as clusters, superclusters, and the boundaries of large, empty regions called voids. Our Sun is part of what we call the Milky Way Galaxy, which is a highly flattened spiral galaxy containing perhaps as many as 400 billion stars. With large telescopes, we can see galaxies in most directions, populating even the remotest regions of the Universe.

Understanding galaxies is an important part of modern astronomy. Galaxies are fundamental units of matter in space, and determining how they formed and achieved their current state is of critical importance to many issues in astronomy. It is significant that much of what is known about galaxies began with a simple classification of their appearance as seen on direct photographs taken with large observatory telescopes. Galaxies present a wide variety of forms, or morphologies, and can be naturally divided into categories in much the same way as living organisms can be divided into genera and species. Although galaxy morphology presents problems for classification that would not be encountered in biological taxonomy, visual galaxy classification continues to be useful at a time when galaxies have never been better understood. Classification provides order to the "impenetrable thicket of forms" – to quote Stephen Jay Gould (1987), from an essay on biological taxonomy – even if we do not yet fully understand how all the different forms came about. Classification also provides a framework for further studies and suggests a logical approach to studying galaxies.

In 1926, Edwin P. Hubble (1889–1953) published a galaxy classification system that, with revision, has stood the test of time. So useful has this system been to providing physical insight into galaxies that thousands of undergraduates learn about it every year. Hubble recognized a small number of broad classes: the elliptical galaxies E0–E7, the normal spirals Sa, Sb, and Sc, the barred spirals SBa, SBb, and SBc, and the irregulars Irr. These he believed encompassed nearly all the galaxies detected on photographic plates in his day. It was brilliant in the way the different types could be connected together in a tuning-fork-shaped sequence, and also in the way the classification did not depend too strongly on the orientation of a galaxy's principal axis to the plane of the sky. The fact that measured physical properties of galaxies correlated with position on the sequence gave the system a greater significance than other classification schemes available at the time.

Given the power of the original Hubble system, it was inevitable that it would be built upon in later years. Hubble himself worked on a revision to include the mysterious armless disk galaxies, which he labeled S0 systems, and which he placed at the juncture of the tuning fork in his 1936 book, *The Realm of the Nebulae*. He knew these objects had to exist before he actually discovered them, because the transition from E7 to Sa in his original sequence seemed too "catastrophic" to be real. He had made notes on his revisions up until the time of his death in 1953. After that time, Hubble's graduate student assistant, Allan Sandage (who was actually the Ph.D. student of Walter Baade), gathered up the notes and prepared a galaxy atlas in Hubble's honor, called *The Hubble Atlas of Galaxies* (Sandage 1961). The *Hubble Atlas* firmly cemented Hubble's ideas on galaxy morphology into astronomy, and it stands as one of the finest galaxy atlases ever produced. It was followed much later by *The Carnegie Atlas of Galaxies* (Sandage and Bedke 1994), which was based on the entire Carnegie photographic plate collection and which further shored up and improved the accuracy of the classification system.

Not long after Hubble's death, another astronomer was gaining a reputation for extragalactic studies in the southern hemisphere. This was Gérard Henri de Vaucouleurs (1918–1995), a native of Paris who in the 1940s had studied at the Sorbonne Physics Research Laboratory and Institute of Astrophysics of the University of Paris. After receiving his first doctorate (in physics) in 1949 from the University of Paris, de Vaucouleurs began a long-term project at the Institute of Astrophysics to revise the famous 1932 Shapley–Ames catalogue of galaxies brighter than the

13th magnitude. He was eager to collect reliable, homogeneous information on these objects that could be used for basic astrophysical studies of galaxies. The information was initially collected in the form of a card index.

De Vaucouleurs later moved to Australia and received a D.Sc. degree from Australian National University in 1957. It was here where he applied his knowledge of astrophotography to the study of poorly known southern galaxies which were beyond the latitude reach of the large telescopes of Mount Wilson and Palomar observatories. He photographed the galaxies mostly with the 30-inch and 74-inch reflectors atop Mount Stromlo, near Canberra at latitude −35 degrees, and became interested in providing classifications for the galaxies in the Hubble system. He encountered difficulty dealing with galaxies near the juncture of the Hubble tuning fork, and in 1955 he visited Pasadena to discuss the problem with Allan Sandage, who at the time was preparing the *Hubble Atlas*. This visit set the stage for de Vaucouleurs's personal revision of the Hubble–Sandage scheme outlined in the *Hubble Atlas*. In 1958, Sandage invited de Vaucouleurs to return to Pasadena to classify all the galaxies in the Mount Wilson and Palomar plate collections. From his discussions with Sandage and his inspections, de Vaucouleurs developed the classification system that is highlighted in this atlas. Eventually, de Vaucouleurs inspected nearly all existing plate collections available in the late fifties and early sixties to shore up his views on morphology, including plates from Harvard Boyden Station, the Lick Observatory Crossley reflector, and the Isaac Roberts collection stored at the Paris Observatory.

What de Vaucouleurs did was develop a revised Hubble–Sandage classification system that he felt provided a better description of what a galaxy looks like without being too unwieldy. His approach gave greater emphasis and more accurate recognition to specific details, such as rings, that have a bearing on the way galaxies evolve. He later published large catalogues summarizing classifications and other basic information for tens of thousands of bright galaxies. These catalogues have made de Vaucouleurs's revision the most used of the Hubble-offshoot galaxy classification schemes today. However, a major disadvantage of his system is that it was published mainly as a research article in a relatively obscure journal. No galaxy atlas has ever been prepared that illustrates his revised *Hubble Atlas* notation and point of view. This means that most astronomers use the de Vaucouleurs system without really understanding how much it actually differs from the Hubble–Sandage revision.

The de Vaucouleurs revision was published in 1959 in the journal *Handbuch der Physik*, which in that year was devoted entirely to astrophysics papers of a review nature. The illustrations in de Vaucouleurs's classification paper are partly based on plates de Vaucouleurs himself took with the large reflectors at Mount Stromlo Observatory, and partly on photographic mockups of Mount Wilson and Palomar photographs from the pre-publication *Hubble Atlas* shared with him by Allan Sandage. However, being printed on a small scale, mostly as negatives, and being relatively few in number, these illustrations are only barely adequate to illustrate the full range of morphologies and notations possible from de Vaucouleurs's point of view.

The present volume is designed to illustrate de Vaucouleurs types for the first time in atlas form, with numerous examples based on modern digital images taken with large reflectors. We will henceforth refer to the system as the *de Vaucouleurs revised Hubble–Sandage*, or VRHS, system, to acknowledge the role that Allan Sandage played in its early development. The atlas is not intended to replace or even supercede the *Hubble Atlas* or the *Carnegie Atlas*, because these excellent atlases illustrate the Hubble–Sandage revision in a consistent and very useful manner. However, galaxy classification is somewhat subjective and different observers may emphasize different features. This is what the VRHS system does compared to the Hubble–Sandage revision: it is a different point of view that places emphasis on details that are more broadly covered by the Hubble–Sandage revision.

We note also that what we present here as the VRHS system is actually a modified version of the 1959 *Handbuch der Physik* system, because we felt that there was no reason why the classification system could not take into account more recent findings and suggestions by other authors. None of these revisions changes the basic system; instead, they simply add to it in useful ways. Also, we use underline notations following de Vaucouleurs (1963a) to emphasize dominant characteristics in pseudorings and mixed bar morphologies.

We have two principal goals with the present atlas. The first is to make the VRHS system more accessible and more understandable to modern astronomy researchers, students, and amateurs, because so many galaxies have types available in the VRHS system, either classified by de Vaucouleurs himself or by other observers in the same system. The first *Reference Catalogue of Bright Galaxies* (RC1, de Vaucouleurs and de Vaucouleurs 1964) included 2599 galaxies and was mainly a revision of the old Shapley–Ames (1932) catalogue of bright galaxies. The *Second Reference Catalogue of Bright Galaxies* (RC2, de Vaucouleurs, de Vaucouleurs, and Corwin 1976) included 4364 galaxies with a considerable increase in basic data on many of the entries. This was followed by the *Third Reference Catalogue of Bright Galaxies* (RC3, de Vaucouleurs *et al*. 1991), which contains more than 23 000 galaxies and is the largest printed galaxy catalogue of its type. Each of these catalogues includes VRHS types for a significant fraction of the entries (17 557 in RC3). Other large catalogues with VRHS types are the *Uppsala General Catalogue* (UGC, Nilson 1973), the *Southern Galaxy Catalogue* (SGC, Corwin, de Vaucouleurs, and de Vaucouleurs 1985) and the *Catalogue of Southern Ringed Galaxies* (CSRG, Buta 1995a).

The second major goal of the present atlas is to describe how much has been learned about the physical underpinnings of galaxy morphology since de Vaucouleurs's 1959 *Handbuch der Physik* article. So much has been learned since that time that galaxy morphology is no longer the purely descriptive subject it used to be. This means that the atlas is not only a picture atlas, but it is also an up-to-date reference on our understanding of the physical processes that underlie galaxy morphology.

The atlas is entitled *The de Vaucouleurs Atlas of Galaxies*, and has been so named to honor de Vaucouleurs's contribution to the field. The three of us who have prepared the atlas are all former students or coworkers of de Vaucouleurs who have extensively studied and used his classification system over many years.

By exclusively using images from electronic detectors, the *de Vaucouleurs Atlas* brings classical galaxy classification into the modern era. The era of the photographic plate ended around 1985, when charge-coupled devices (CCDs) revolutionized astronomical imaging. With CCD images, we can illustrate galaxy morphology in a completely different manner from the *Hubble* and *Carnegie* atlases. Compared to these previous atlases, many of our images reveal much fainter isophotes and have a greater dynamic range than photographic plates. We are also able to calibrate the images with published photoelectric photometry, something that could not be easily done for the previous atlases. This calibration allows us to illustrate the galaxies in a more homogeneous way. Although the *de Vaucouleurs Atlas* emphasizes the blue light (B) waveband for historical reasons, we also include considerable information on galaxy morphology in other wavebands, something that could not be done easily with the other atlases.

The need for an atlas of this nature follows from the time we live in. Modern technology has provided more and more high quality digital images of galaxies seen from a vast range of distances and times. We need to be able to use these images to study morphology in a manner comparable to what is done for nearby galaxies. The VRHS system was originally defined with photographs of nearby galaxies. This was because nearby galaxies are bright, easily observed, and show the most detail. Nearby galaxies are also being seen at a time, negligibly different from our own, when they are changing very little compared to their formative phases. However, because of modern technology, we can now see very distant galaxies at a similar level of detail as de Vaucouleurs had available for his classifications. Galaxies at extremely large distances (several billion light years) are being seen as they were when the Universe was considerably younger than it is now. It is expected that the morphology of galaxies would undergo significant changes during their formative period, and it is likely that very distant galaxies are showing the structures they had before slow secular evolutionary processes took over. The great value of the present atlas lies in the description it provides of normal galaxies in approximate equilibrium, where gravity has run its course and things have for the most part settled down. Interpreting the morphologies of distant galaxies requires a thorough understanding of the features that characterize nearby galaxies as much as it would require an understanding of galaxy formation.

1.2 Factors influencing galaxy classification and morphology

Galaxy classification, although simple in principle, is in practice difficult because morphology is influenced by factors that have nothing to do with the actual structure of a galaxy. Thus, before discussing the Hubble and de Vaucouleurs classification systems in more detail, it is necessary to highlight the factors that actually influence

Fig. 1.1 Blue light images of four galaxies of similar morphology, viewed with different inclinations and bar/disk orientation angles. *Upper left*: NGC 1433. *Upper right*: NGC 5905. *Lower left*: NGC 2713. *Lower right*: NGC 5792.

classification and morphology. Classifying galaxies is similar in some ways to classifying living organisms. One first identifies basic classes, and then focuses on features that allow you to divide those classes according to finer details. However, galaxy classification involves problems that would not be encountered with living species. Due to various factors, the amount of information available for classification can vary from galaxy to galaxy.

The main problem with classifying galaxies is that no galaxy can be brought into a laboratory so that it can be viewed from any particular direction or distance. Most galaxies have planes of symmetry, and ideally for classification we would like to view them all from directly along at least one of their symmetry axes, preferably the principal axis of rotation. But these axes are oriented randomly to the line of sight, making the appearance of many galaxies dependent on viewing geometry (Figure 1.1). Also, galaxies are spread over a wide range of distances, such that the farther they are away from us, the harder it is to see details of their morphology. We can deal with this by building bigger telescopes, or placing telescopes into orbit, but nearby galaxies will always be better resolved than distant ones.

The appearance of many galaxies also depends on the wavelength of light in which they are viewed. Photography and imaging of galaxies is usually done through filters which transmit a relatively small portion of their spectral energy distribution. With some exceptions, spectral energy distributions of galaxies are dominated by starlight, with a small fraction of their light coming from glowing interstellar gas. Starlight tends to be mostly continuous thermal radiation whose color is determined by the surface temperature of the star. Hot stars (surface temperatures of 20 000 K or more) emit most of their light as ultraviolet radiation and appear bluish-white in color, while cool stars (surface temperatures of 3000 K or less) emit most of their light as infrared radiation, and appear reddish in color. When imaged in short wavelength light, such as blue or ultraviolet, the appearance of galaxies tends to emphasize hot, blue, and relatively massive young stars, but when viewed in long wavelength light, such as red or infrared, the appearance of galaxies tends to emphasize cooler, and generally

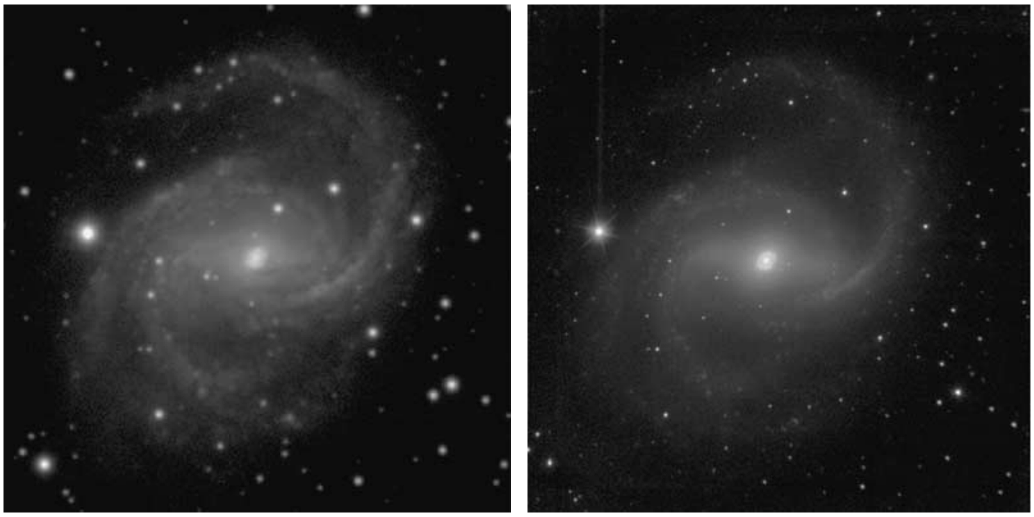

Fig. 1.2 The spiral galaxy NGC 6951, type SAB(rs)bc, in the *B* band (0.44 microns, *left panel*) and the K_s band (2.2 microns, *right panel*). The blue image emphasizes the younger Population I constituents, while the near-IR image emphasizes the older stellar components, including Population II.

older, less massive stars. Young, massive stars tend to be less smoothly distributed and much less frequently present than old stars, so many galaxies appear more patchy and uneven in blue filters than in red filters (Figure 1.2).

The presence of interstellar dust also has a wavelength-dependent effect on the appearance of a galaxy. Dust consists of fine grains of complex compounds such as silicates, carbonaceous material, ices, and polycyclic aromatic hydrocarbons (Greenberg and Shen 1999), and is thought to be produced by processes connected with the evolution of stars. In highly flattened galaxies, dust collects within a thin plane at the galaxy's midsection; in other, less flattened galaxies dust may be distributed more randomly. Since interstellar dust scatters short wavelength light more effectively than long wavelength light (by virtue of the small size of the particles compared to the wavelength of visible light), the effects of dust on galaxy morphology and classification are more serious on blue light images than on red light images. Dust also impacts the appearance of galaxies at far-infrared wavelengths, where thermal emission from dust can actually dominate over the contribution of starlight. At longer (radio) wavelengths, starlight from galaxies can be very weak, and the appearance of a galaxy can be determined mainly by synchrotron radiation (nonthermal electromagnetic radiation produced by relativistic electrons spiraling in strong magnetic fields) or by emission from cold neutral atomic hydrogen at 21 cm wavelength.

The expanding universe can affect the appearance of galaxies. The cosmological redshift both shifts and stretches the spectral energy distribution of galaxies, which would impact their appearance in any set of fixed standard filters. For example, the blue light appearance of a galaxy may be seen only in a red filter because the cosmological expansion has shifted that part of the spectrum into the red. Thus, galaxies at high redshift can be difficult to classify and fairly compare with those observed at low redshift unless filters are matched to their rest-frame wavelengths.

The appearance of a galaxy is not expected to be perfectly fixed with time. Galaxies tend to rotate, new stars may be born and older stars may die, and interstellar gas may be consumed or replenished at rates dependent on both internal and external factors. Galaxies tend to be large compared to their typical separations, so that interactions may affect their structure over a long period of time. Because of the finite speed of light, very distant galaxies are seen as they were when the Universe was much younger than it is now, and their appearance may have been influenced by the different conditions that existed at those times.

Finally, the morphology of a galaxy is also seriously influenced by its total mass and its environment. Massive galaxies tend to be much more structured and well ordered, more luminous, and of higher average surface brightness than low mass galaxies, such that catalogues overrepresent high mass galaxies and underrepresent low mass galaxies. Because of this selection effect, the galaxy classification systems in use today apply mainly to massive galaxies. There do not necessarily exist low mass counterparts of all of the known types of high mass galaxies. For this reason, statistics of galaxy types must take into account the luminosity dependence of morphology in order to get an accurate picture of the entire population of galaxies. There is also a well-established correlation between a given galaxy's morphology and the density of surrounding galaxies. Ellipticals and S0 galaxies are prevalent in high density environments such as rich galaxy clusters, while spirals are prevalent in lower density environments. This "morphology–density relation" was first discussed by

Hubble and Humason (1931; see also Dressler 1980) and is one of the primary observations that any theory of galaxy morphology and evolution would have to explain.

1.3 Galaxy morphology: an historical overview

Galaxies were first discovered in great numbers in the late eighteenth century, when telescopes improved in both size and quality. At this time, galaxies were mainly seen as "white nebulae,"[1] faint nebulous patches of light located mostly away from the Milky Way. Charles Messier (1730–1817) visually discovered many bright examples for his catalogue of nonstellar objects, and produced the famous "Messier Catalogue" which includes 40 galaxies with "M" numbers. William Herschel (1738–1822) used a larger (18.7 inch) reflector to sweep the sky and catalogued 2500 nonstellar objects, most of which were galaxies. Herschel's son, John, continued his father's work in the southern sky and in 1864 prepared a large catalogue, the *General Catalogue of Nebulae and Clusters of Stars*, which included 5079 objects discovered not only by the Herschels but by other observers as well. By the 1880s, a large number of observers using a variety of telescope sizes had discovered more than 7800 nonstellar objects. This led J. L. E. Dreyer (1852–1926) to publish the *New General Catalogue of Nebulae and Clusters of Stars*, which is the principal source of names (NGC numbers) used today for many of the brighter galaxies in the sky. The NGC was followed by two supplements, the first and second *Index Catalogue of Nebulae and Clusters of Stars*, in 1895 and 1908. These lists provide the familiar IC numbers for some bright galaxies.[2]

All of these observations were made at a time when the true nature of galaxies was not known, mostly because galactic distances were unknown. At first, even with the relatively large Herschel telescopes, most galaxies revealed little detail. Descriptions of the faint nebulous objects in the GC and NGC/IC boil down mainly to issues of size, shape, central concentration, brightness, and degree of mottling. Thus, visual galaxy morphology in the nineteenth century, for most observers, involved a rudimentary classification based on gross form and brightness, but on few of the details we use for classification today.

This does not mean that relevant details were not seen in the objects that were later discovered to be galaxies. The Birr Castle 72-inch speculum metal reflector (the "Leviathan") of William Parsons, the Third Earl of Rosse (1800–1867), went into operation in the mid 1840s and soon revealed the beautiful spiral structure in M51 (NGC 5194), with many other spirals following (Figure 1.3). This is when galaxy morphology began to get very interesting. Lord Rosse employed six assistants to observe Herschel objects with the telescope, including some of the best-known scientists of the day, such as W. H. Rambaut, G. Johnstone Stoney, Bindon Stoney, R. J. Mitchell, S. Hunter, and R. S. Ball. Laurence Parsons, one of Lord Rosse's sons, also observed frequently with the big telescope, and had C. E. Burton, R. Copeland, and J. L. E. Dreyer as assistants. The intriguing notes compiled by these observers, collected in 1880 in a single volume of the *Scientific Transactions of the Royal Dublin Society*, reveal that they had seen many basic details of galaxy morphology without understanding what the details meant. Spirals, bars surrounded by rings, and s-shaped patterns breaking from bars, were first seen at Birr Castle. Dust lanes in highly inclined galaxies were also seen better than in any previous observations. No systematic classification of the nebulae came out of these observations, but spiral structure in itself was a discovery of great importance that fueled speculation at the time on the true nature of the white nebulae.

The main classes of galaxies were identified not from visual observations but from photography with large telescopes. Isaac Roberts (1829–1904) published an atlas of photographs of many nebulae, some of the finest of his day. His photos were obtained with a 20-inch reflector, showing that one could *photograph* well features that needed a much larger telescope to be *seen* well. His photography revealed the spiral structure in M31 more clearly than could previous visual observations. By the early twentieth century, systematic photographic surveys of nebulae were carried out at major observatories. James E. Keeler (1857–1900), Edward E. Barnard (1857–1923) and Heber D. Curtis (1872–1942) carried out the most extensive of such surveys with the 36-inch Crossley reflector of the Lick

[1] This term is due to William Huggins (1824–1910), who used it to describe nebulae showing a continuous spectrum.

[2] The NGC and IC I and II include numerous errors and mistakes in identifications that up until recently were left largely unexamined. This has changed with the NGC/IC Project organized by one of us (HGC) as a way of clearing up as many of the errors as possible. This project is described at the website www.ngcic.org.

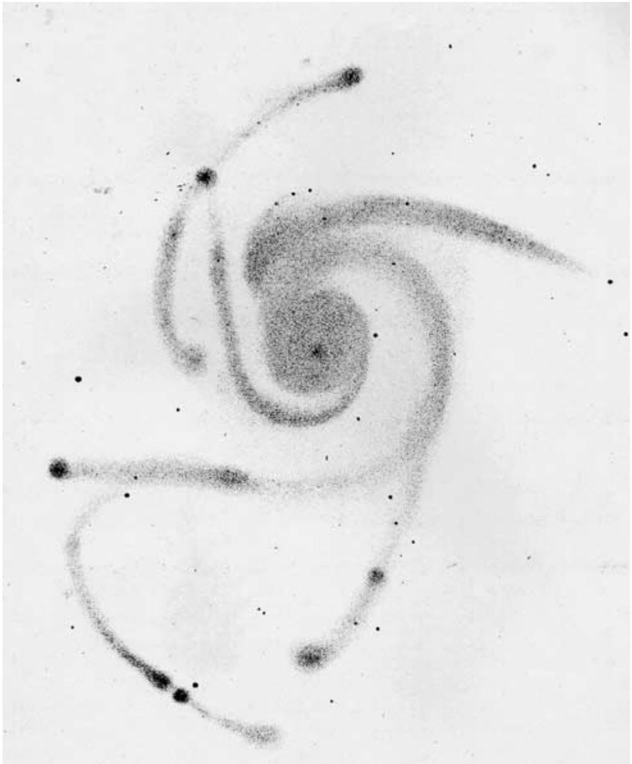

Fig. 1.3 Nineteenth-century pre-photographic-era galaxy morphology. A visual drawing of NGC 5457 (M101) as seen by Birr Castle observer S. Hunter in 1861 (Parsons 1880).

Observatory, beginning in 1898. Curtis (1918) collected all of the information from the survey and described 762 nebulae and clusters, most of which were galaxies. This paper makes the noteworthy recognition of barred spirals, which Curtis called "ϕ-type spirals" because often one saw "straight extensions" across the inner parts of the spiral, which sometimes was ring-like. Curtis recognized 23 examples of this class of object in the Crossley photographic database.

So many new galaxies were being found with photography that in a 1917 paper, Hubble commented that "New nebulae are but rarely seen in the sky, although an hour's exposure made at random with a large reflector has more than an even chance of adding several small faint objects to the rapidly growing list of those already known." By 1917, 17 000 objects had been catalogued, and Hubble estimated that 150 000 were within reach of existing instruments. Huge lists of new nebulae were later published in places like *Harvard Annals*, Vol. 88, 1932.

Sandage (1975) summarizes the Wolf (1908) descriptive system used to classify many of these small, faint objects as well as the brighter nebulae. Although completely obsolete now, the Wolf scheme was the system of choice for over 30 years. Seventeen categories were included in the system, each designated by a lower case letter, ranging from highly inclined to face-on systems. (Unlike the Hubble system, Wolf gave edge-on galaxies a different letter from face-on galaxies.) The categories so identified clearly reflect what the limited plate material at the time had revealed. Hubble (1917), Reinmuth (1926), Lundmark (1927), Holmberg (1937), Reiz (1941), and Danver (1942) used Wolf's notation to classify small to very large samples. Sandage notes that Wolf was the first to arrange galaxies in a sequence ranging from smooth, amorphous types to well-developed spirals. Hubble considered the Wolf system to be "an excellent scheme for temporary filing until a significant system shall be constructed."

Photographic surveys continued at various observatories but, by 1920, the main classes of bright galaxies had already been identified. After establishing the extragalactic nature of the "white nebulae" in 1924, Hubble developed the classification system for which he is famous. We first discuss the original system, then Hubble's own revision, extended and published by Sandage (1961), and finally de Vaucouleurs's personal revision.

1.4 The Hubble classification system

The Hubble (1926) classification system began with a simple description of the basic types of galaxies and the notation to be used for those types. Hubble stated that only 3% of the "nebulae" he could see on photographic plates were irregular in shape, and that the remainder "fall into a sequence of type forms characterized by rotational symmetry about dominating nuclei. The sequence is composed of two sections, the elliptical nebulae and the spirals, which merge into each other." The merging followed because Hubble noticed that the most flattened elliptical galaxies resembled the first group of spirals, the Sa galaxies, suggesting a natural blend. Also in this paper, Hubble describes barred spirals as comprising only about 20% of all spirals and that these spirals "also form a sequence, which parallels that of the normal spirals, the arms apparently unwind, the nuclei dwindle, the condensations form and work inward."[3] This is the famous "Hubble Sequence" of galaxy types which Hubble himself first schematicized in his book, *The Realm of the Nebulae* (Hubble 1936), as a "tuning fork" (Figure 1.4). Believing that the transition from E7 to Sa was "catastrophic," Hubble hypothesized a

[3] We now know that barred galaxies are much more frequent than Hubble had recognized at the time; see Section 2.11.

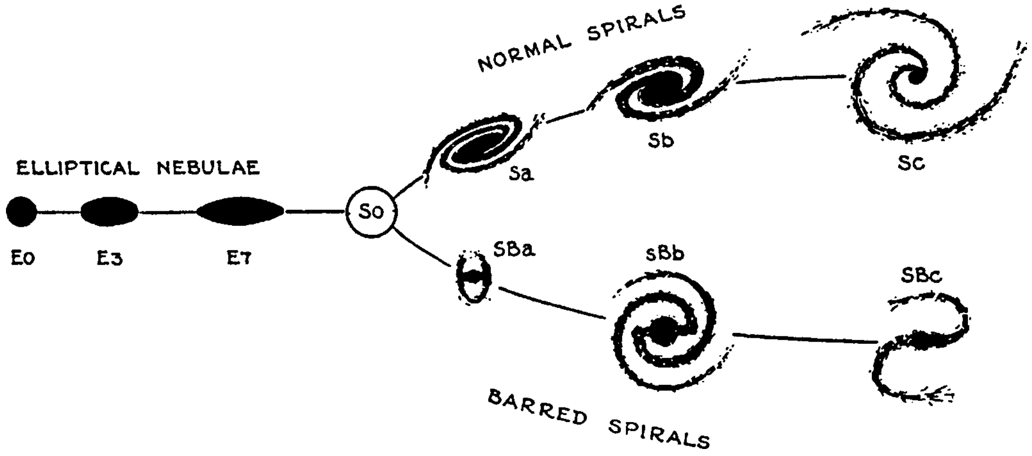

Fig. 1.4 The original Hubble sequence of galaxy types, from Hubble (1936).

class of disk galaxies lacking spiral arms but flatter than the flattest E galaxy. He called these hypothetical systems S0 galaxies and placed them at the juncture of the arms of the tuning fork.[4]

The Hubble (1936) description of galaxy morphology contains much of the terminology still used to describe galaxies. For example, since he could connect all galaxies into a single sequence, he used the notation "early" and "late" to describe the position of a galaxy in the sequence. Ellipticals and S0 galaxies are "early-type galaxies," Sa and SBa galaxies are "early-type spirals," Sb and SBb galaxies are "intermediate-type spirals," and Sc and SBc galaxies are "late-type" spirals. No temporal order was implied.

In his description of elliptical nebulae, Hubble noted a range of ellipticities from E0 to E7, with the latter having a "lenticular" shape (i.e., like the end-on view of a double convex lens). He considered the lenticular shape to be a limiting form, beyond whose flattening one would only encounter spirals. The lenticular term is still widely used to describe edge-on S0 galaxies, and de Vaucouleurs later regarded all S0 galaxies, whether edge-on or face-on, to be "lenticulars."

For the spirals, Hubble used the term "normal" to describe nonbarred spirals and "barred" to describe the spirals with a bar crossing the center. The barred term has survived but the "normal" spiral term is less used because it turns out that having a bar is more "normal" than not having one. De Vaucouleurs preferred the term "ordinary" for nonbarred spirals. Particularly interesting is that Hubble already noted the existence of "mixed forms" between the barred and nonbarred spirals. He considered them to be rare. Two of the mixed spirals that he notes, M83 and M61, were later adopted by de Vaucouleurs as prototypes of the mixed "SAB" family.

On the issue of position along the spiral sequence, Hubble noted that the classification of borderline objects within his a, b, c spiral divisions could be difficult, and suggested that combined notation such as ab or bc could be used.

Hubble also brought attention to objects whose positioning in the sequence was uncertain because of peculiarities. He suggested adding the letter p (for peculiar) to whatever symbol of classification was needed.

Figures 1.5 and 1.6 provide reconstructions using *Atlas* images of Plates I and II of Hubble (1936), showing all but one galaxy that originally defined the indicated types. Of these, all but three are still classified as Hubble classified them. The exceptions are NGC 3115, NGC 2859, and NGC 3034. NGC 3115 was the prototype of E7, and in Hubble's original photograph displayed a lenticular shape. In our image, displayed in logarithmic *Atlas* Units (see Section 3.1), the lenticular shape is lost and a clear thin disk is seen. Thus, NGC 3115 is now recognized as an early S0 system. NGC 2859 was originally classified as type SBa by Hubble even though it lacks spiral structure. It was later reclassified as an SB0 once Hubble established the existence of the S0 class.

The irregulars in Figure 1.5 were not considered part of the sequence of spiral forms in the original Hubble system. The reason for this was that Hubble believed they lacked "rotational symmetry." He divided the irregulars into two groups, one resembling the Magellanic Clouds, of

[4] The genesis of this diagram has been recently investigated by David Block, and discussed at a meeting in South Africa. He found a diagram in the book *Astronomy and Cosmogony*, by Jeans (1929), showing a Y-shaped version of the same diagram, which could be Jeans's own schematicization of what Hubble described. Sandage (2004) comments on these issues and agrees that the Jeans's Y-shaped diagram could have inspired Hubble to schematicize his sequence. However, the basic tuning fork, not a Y, is described in Hubble's 1926 paper. The Jeans Y was also noted by Berendzen, Hart, and Seeley (1976).

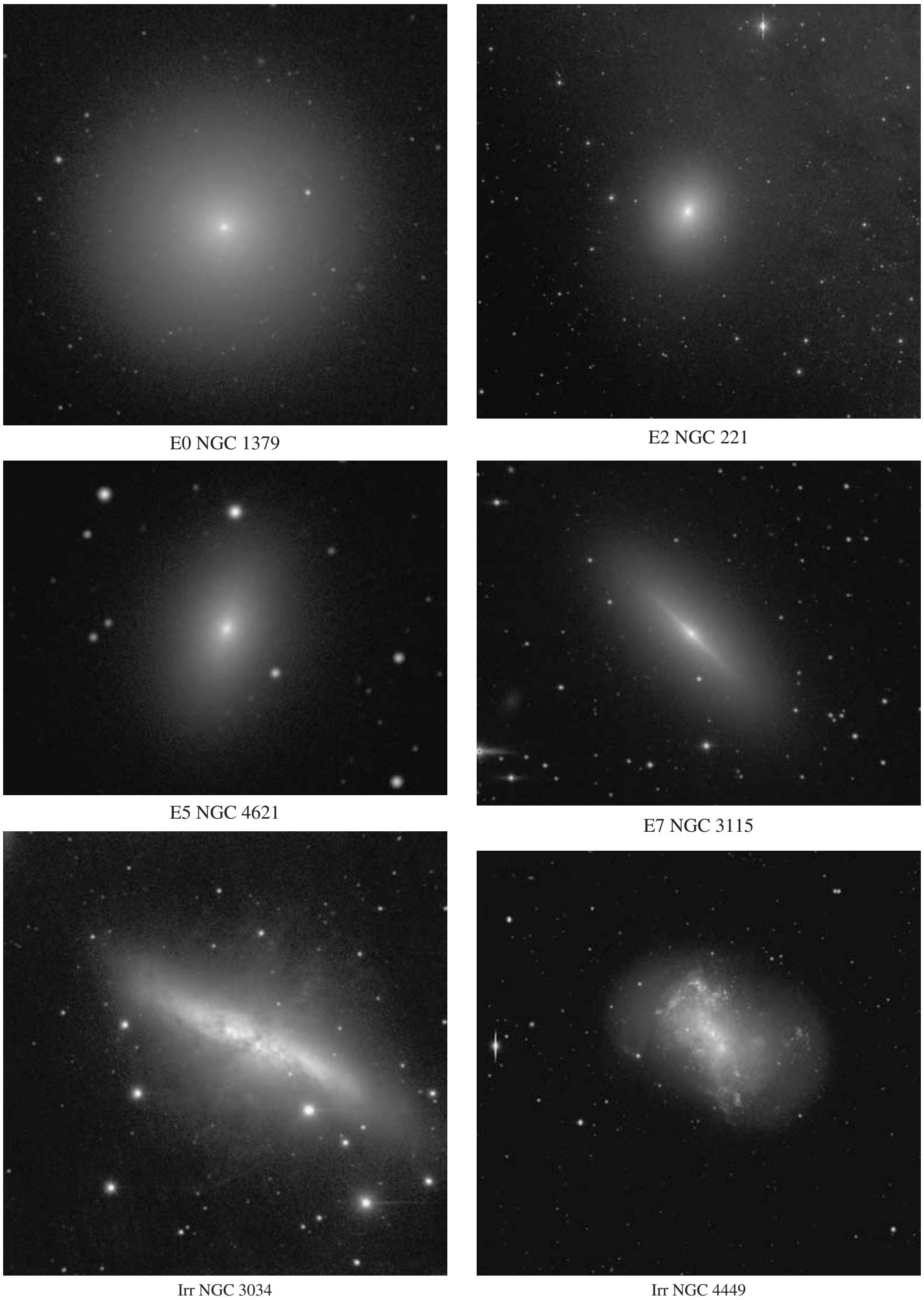

Fig. 1.5 Reconstruction of Plate I of Hubble (1936), showing ellipticals and irregulars.

which NGC 4449 is the illustrated example, and a second group including everything else, of which NGC 3034 is the illustrated example. The non-Magellanic group was characterized as "nondescript."

NGC 3034 was already recognized as a different kind of irregular galaxy when Holmberg (1950) distinguished it as an Irr II system as opposed to an Irr I system like NGC 4449. He considered the distinction as one of stellar populations, with Irr I galaxies dominated by Population I stars and Irr II galaxies dominated by Population II stars. Sandage (1961) states that the normal spirals blend smoothly into the Irr I galaxies.

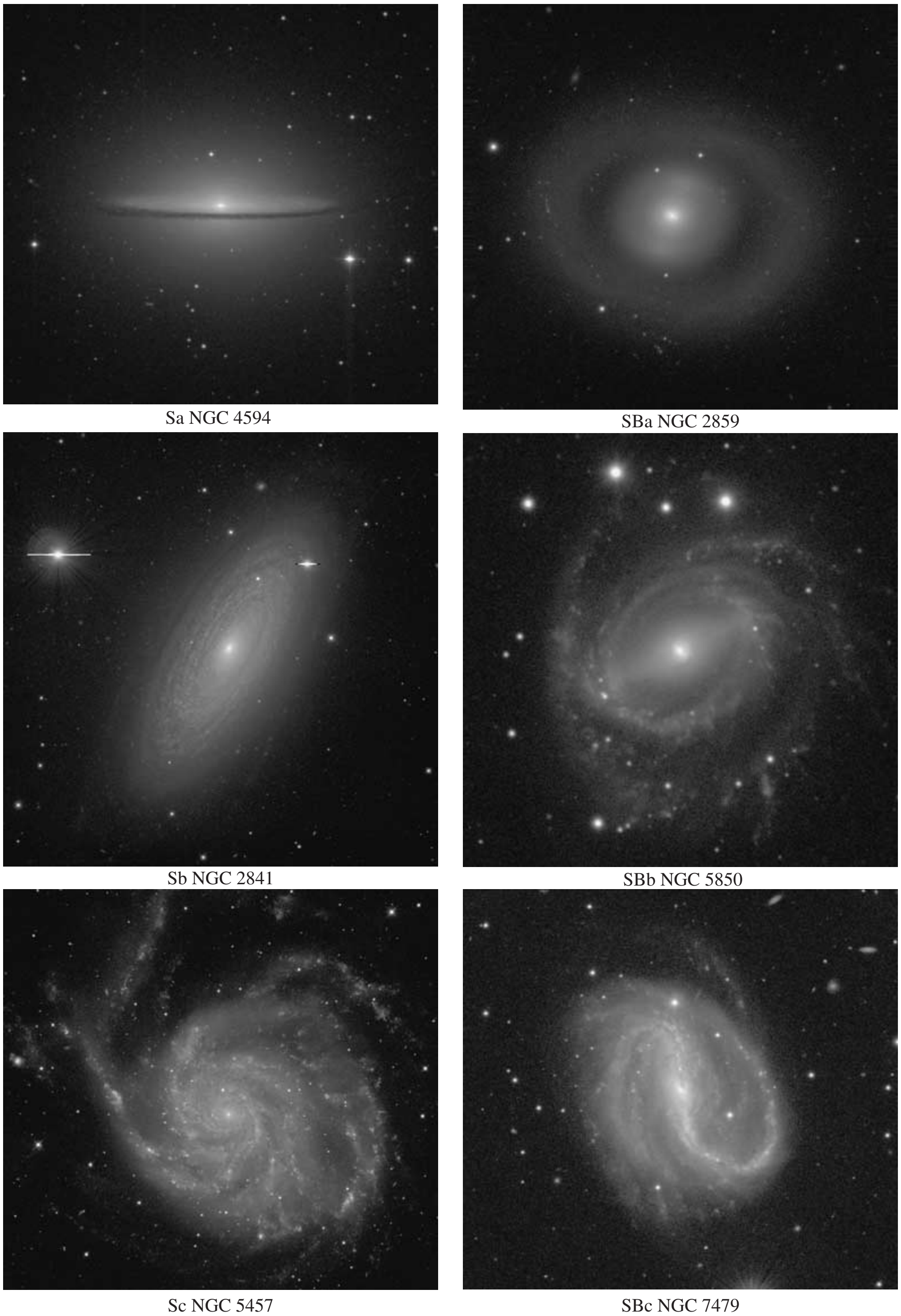

Fig. 1.6 Reconstruction of Plate II of Hubble (1936), showing normal and barred spirals.

A schematic of the Hubble tuning fork classification system as it was defined in the *Hubble Atlas* is shown in Figure 1.7. This contains Hubble's full accounting of the classification of S0 galaxies as well as the introduction of the (r) and (s) varieties by Sandage. The varieties are distinguished by whether an s-shaped spiral directly emerges from a central bulge or the ends of a bar, or if the arms break instead from a ring-shaped pattern known as an