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Galaxies: Classification

Ronald Buta

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Galaxies: Classification

Galaxies are majestically beautiful objects, and anyone who has seen a galaxy through a telescope, or even our own Milky Way Galaxy with the unaided eye, cannot help but wonder at the nature of these remote star systems and what they have to say about our universe and ourselves. 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. However, galaxy morphology presents problems for classification that would not be encountered in biological taxonomy and that make it difficult to classify them with the precision that is normally associated with living species. Still, visual galaxy classification continues to be useful at a time when galaxies have never been better understood. Classification provides order to the daunting variety of forms even if we do not yet know how the different forms came about. Classification also provides a framework for further studies and suggests a logical approach to studying galaxies.

Factors influencing galaxy classification and morphology

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 preferred planes of symmetry, and ideally for classification we would like to view them all from directly above their preferred planes of symmetry. However, these planes are oriented randomly to the line of sight, making the appearance of many galaxies very dependent on viewing geometry. 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.

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, which refers to the distribution of their light with wavelength. 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 (meaning all wavelengths are emitted) 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 in color, while cool stars (surface temperatures of 4000 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 young massive stars, but when viewed in long-wavelength light, such as red or infrared, the appearance of galaxies tends to emphasize cooler and generally older less massive stars. Young 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.

The presence of interstellar material known as dust also has a wavelength-dependent effect on the appearance of a galaxy. Dust consists of fine particles of heavy atoms and light elements that are 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 mid-section; 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 with 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 relativisitic 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 redshift has shifted that part of the spectrum into the red. Thus, galaxies at high redshift can be difficult to classify and compare with those observed at low redshift.

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 with their typical separations, so that interactions may impact 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 catalogs over-represent high-mass galaxies and under-represent 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 (see GALAXY MORPHOLOGY–DENSITY RELATION). Certain types of galaxies are prevalent in high-density environments such as rich galaxy clusters, while others are prevalent in lower-density environments. This correlation is one of the primary observations that any theory of galaxy morphology and evolution would have to explain.

Classification of nearby galaxies at optical wavelengths

For historical reasons, the first classifications for galaxies were made at optical wavelengths and were entirely restricted to relatively nearby galaxies. From 1781 to 1847, Sir William Herschel and his son, John (see HERSCHEL FAMILY), searched the sky for 'white nebulae', objects which were later proved to be external galaxies. Through large telescopes, the Herschels were able to detect different degrees of central concentration, apparent flattening and mottling in these objects. More complex structure could be seen in a few of the brighter cases, but it was William Parsons, Third Earl of ROSSE, who, in 1845, added the attribute 'spiral' to some members of the Herschels' 'white nebulae'. This is when galaxy morphology began to get very interesting. Lord Rosse used a 72 in speculum metal reflector, the largest telescope in the world in his day.

The main classes of galaxies were identified not from visual observations but from photography with large telescopes using plates with emulsions sensitive to the blue region of the spectrum. Photography became important in astronomy towards the end of the 19th century, and by 1920 the main classes of bright galaxies were identified. After establishing the extragalactic nature of the 'white nebulae' in 1924, EDWIN HUBBLE developed a classification system for galaxies that, with some refinements, is still in use today.

The Hubble classification system

A schematic of the HUBBLE CLASSIFICATION system as it is used today is shown in figure 1, and examples of each type are shown in figures 2, 3 and 4. Initially, Hubble distinguished three main classes of galaxies: elliptical galaxies, which were smooth and largely featureless systems having a round or elliptical shape; spiral galaxies, which were highly flattened disk-shaped systems having spiral 'arms' in the disk; irregular galaxies, which showed a chaotic appearance. As with living species, subclasses can be distinguished within these main classes. For ELLIPTICAL GALAXIES, symbolized by the letter E, the only other criterion that Hubble was able to use for classification was the ellipticity of the isophotes. Hubble appended to the letter E a numerical index of ellipticity: $n = 10(1 - b/a)$, where b/a is the ratio of the minor axis dimension to the major axis dimension. E0 galaxies are round while E6 galaxies are highly elongated.

The uppermost panel of figure 2 shows two ellipticals, NGC 221 and Maffei 1. In many elliptical galaxies, the light declines smoothly with increasing distance r from the center as $r^{1/4}$. Some 40% of ellipticals are known to have dust which breaks the characteristic smoothness of the light distribution. The dust may be scattered in patches or collected in planes of symmetry. The intrinsic shapes of ellipticals are nontrivial to deduce, but it is generally believed that many are triaxial, meaning that the semi-axis radii of isophotes (or contours of equal brightness) along three perpendicular symmetry planes are unequal. The projected index n in the classification En does not connect directly to a preferred intrinsic shape, and indeed n may have little intrinsic significance to an actual galaxy. This has led some authors recently to propose replacing the index n with a subclassification based on the deviations of the isophotes of ellipticals from a perfect elliptical shape. The range of shapes, from boxy to pointy or disky, can be tied to more meaningful physics than the index n.

Among the nearest galaxies, the most common type is DWARF ELLIPTICAL or DWARF SPHEROIDAL GALAXIES. These galaxies tend to have much lower masses and surface brightnesses than the giant ellipticals. The nearest normal major elliptical to our Galaxy is Maffei 1, in the far northern sky. Although less than 10 million light-years distant, Maffei 1 is heavily obscured by foreground interstellar dust in our own Galaxy and is difficult to study at optical wavelengths.

The symbol for spiral galaxies in the Hubble classification system was S, but these systems offered four criteria for subclassification. SPIRAL GALAXIES tend to be composite systems consisting of a smooth, relatively spherical bulge of old stars superposed within a highly flattened disk consisting of spiral arms and often young massive stars lining the arms. Spirals differ according to the presence or absence of a bar-shaped feature, the relative prominence of the bulge, the degree to which the arms are open or tightly wrapped and the degree to which the arms are lined by discrete, resolved objects. The last three aspects seem to correlate in that galaxies having large bulges also have smooth, tightly wrapped arms while those having little or no bulge have patchy, open spiral arms. These characteristics led to the Sa–Sb–Sc and SBa–SBb–SBc 'tuning fork' classification of spirals shown in figure 1, where the B stands for bar. In BARRED SPIRAL GALAXIES, the arms break from the ends of the bar, while in nonbarred spirals the arms break directly from the bulge region. Galaxies of types Sa and SBa are frequently referred to as 'early-type' spirals in astronomical literature while those of types Sc and SBc are frequently referred to as 'late-type' spirals, nomenclature which draws from terms used in stellar astronomy to connote an evolutionary sequence. Studies by H Shapley and G de Vaucouleurs led to the extension of the spiral sequence to types considered to be 'later' than Sc. At types Sd and SBd, the bulge is very

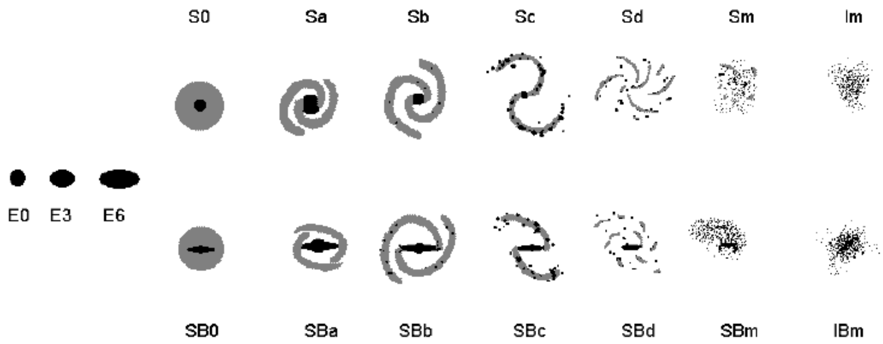

Figure 1. The Hubble sequence of galaxy types modified with additional types.

small or absent and the structure becomes increasingly open and highly resolved. The types Sm and SBm in figure 1 represent Magellanic-Cloud-type spirals. For a long time, the MAGELLANIC CLOUDS, two nearby galaxies seen in the far southern sky that are physical companions of our Galaxy, were regarded as IRREGULAR GALAXIES, but in the 1950s G de Vaucouleurs demonstrated that both have spiral structure with a characteristic asymmetry and no bulge component.

The majority of the galaxies that are listed in galaxy catalogs tend to be spirals of relatively high luminosity. In the Sa galaxy shown in the upper left panel of figure 3, the arms are smooth, tightly wrapped around the center, and the bulge is large compared with the disk. In the SBa galaxy in the upper right panel of figure 3, the bright bulge is crossed by a luminous bar. The bars of galaxies in general are composed of rather old stars compared with spiral arms.

The middle panels of figure 3 show typical examples of Sb and SBb galaxies, defined to be intermediate in bulge-to-disk strength, pitch of arms and resolution of arms compared with Sa,SBa and Sc,SBc galaxies. The Sb example, NGC 5985, shows a multi-armed spiral pattern. The SBb example, NGC 5850, shows a well-resolved spiral pattern of intermediate pitch angle.

The two lowest panels of figure 3 show typical examples of Sc and SBc galaxies. These tend to have the most well-developed and open spiral arms with a high degree of knottiness or resolution of the arms. The bulges tend to be very small compared with the extended disks. The objects that dot the arms tend not to be individual stars but unresolved clusters or loose associations of massive young stars. Such stars have spectral classes of O and B, and hence the clusters are usually referred to as OB ASSOCIATIONS. In the Sc example NGC 5457, these associations are several hundred light years in diameter and include hundreds of such stars.

The galaxies shown in the two upper panels of figure 4 are examples of Sd (NGC 45) and SBd (NGC 2500) types. In NGC 45, the spiral arms are weak and the bulge is very small; the bulge can only contribute a few per cent or less to the total luminosity of the system in this case. This is also true for NGC 2500, which has a clear bar. Note how both NGC 45 and NGC 2500 have many scattered 'knots', most of which are likely to be OB associations. The lower left panel of figure 4 shows a classic Magellanic barred spiral, NGC 4618, of type SBm. Although NGC 4618 has two clear arms, one arm is much brighter than the other and the center of the bar does not coincide with the center of symmetry of the outer disk light. These are characteristics of the SBm class.

Irregulars were originally characterized as 'nondescript' and lacking rotational symmetry. Although some are generally chaotic looking at relatively high surface brightness levels, at low light levels a faint, more symmetric disk can often be seen. It is now known that many irregulars do rotate and have bar-like structures in their disks. The properties of irregulars are so varied, and the range in their total luminosities is so great, that they have been the subject of much recent research. Irregular galaxies resembling the Magellanic Clouds but lacking any clear spiral structure are now referred to as Im or IBm types. The middle right panel of figure 4 shows a Magellanic irregular, NGC 2366, type IBm. This galaxy has numerous bright OB associations but no clear spiral structure. Its highly elongated shape suggests that it might be highly inclined.

In 1936, Hubble revised his classification system to include a fourth major galaxy class: S0 galaxies, which were armless DISK GALAXIES representing the transition from ellipticals to fully developed spirals. Some authors believe that the addition of this class destroyed the simple beauty of Hubble's original system. S0 galaxies are still an enigma because their relationship to spirals and ellipticals is still very unclear. Some authors believe that S0s represent spirals that were stripped of their residual gas by interactions in a cluster environment. Thus, rather than being transition types they form a separate sequence parallel to the spiral sequences. Other S0s may indeed be true transition forms between spirals and ellipticals. Note that elliptical and S0 galaxies are collectively referred to as 'early-type' galaxies, while irregulars are referred to as 'late-type' galaxies. These bracket the 'early-' and 'late-type' spirals. Some S0s have clear bars and are referred to as the SB0 type in figure 1.

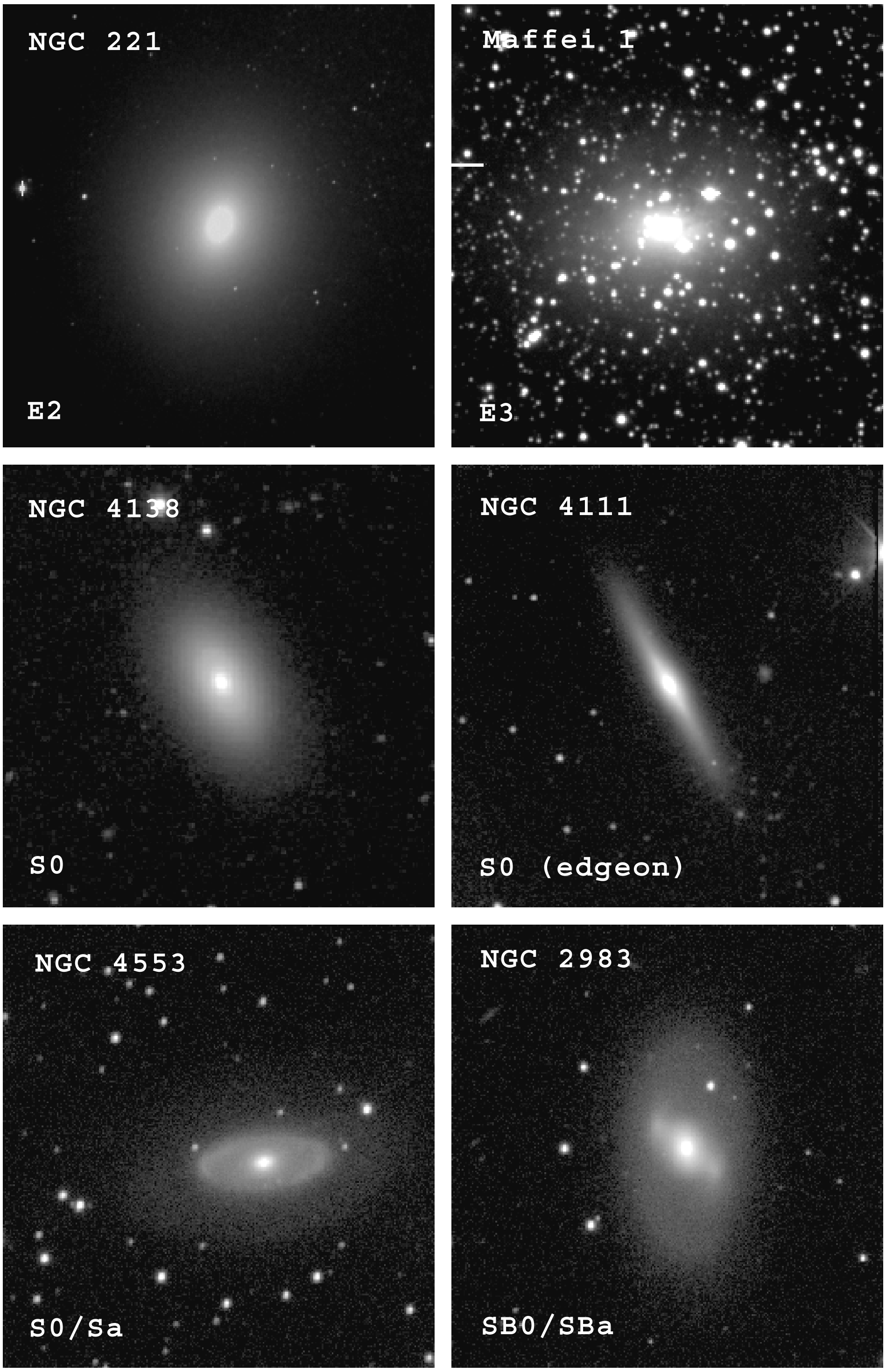

Figure 2. Examples of elliptical, early S0 and late S0 galaxies.

The morphology of S0 galaxies is best revealed by edge-on examples. When edge on, an S0 galaxy clearly shows its highly flattened, disk shape (see NGC 4111 in the middle right panel of figure 2). However, while edge-on spirals reveal dark lanes of dust in their midplanes, the best S0 galaxies show no such midplane of dust, implying

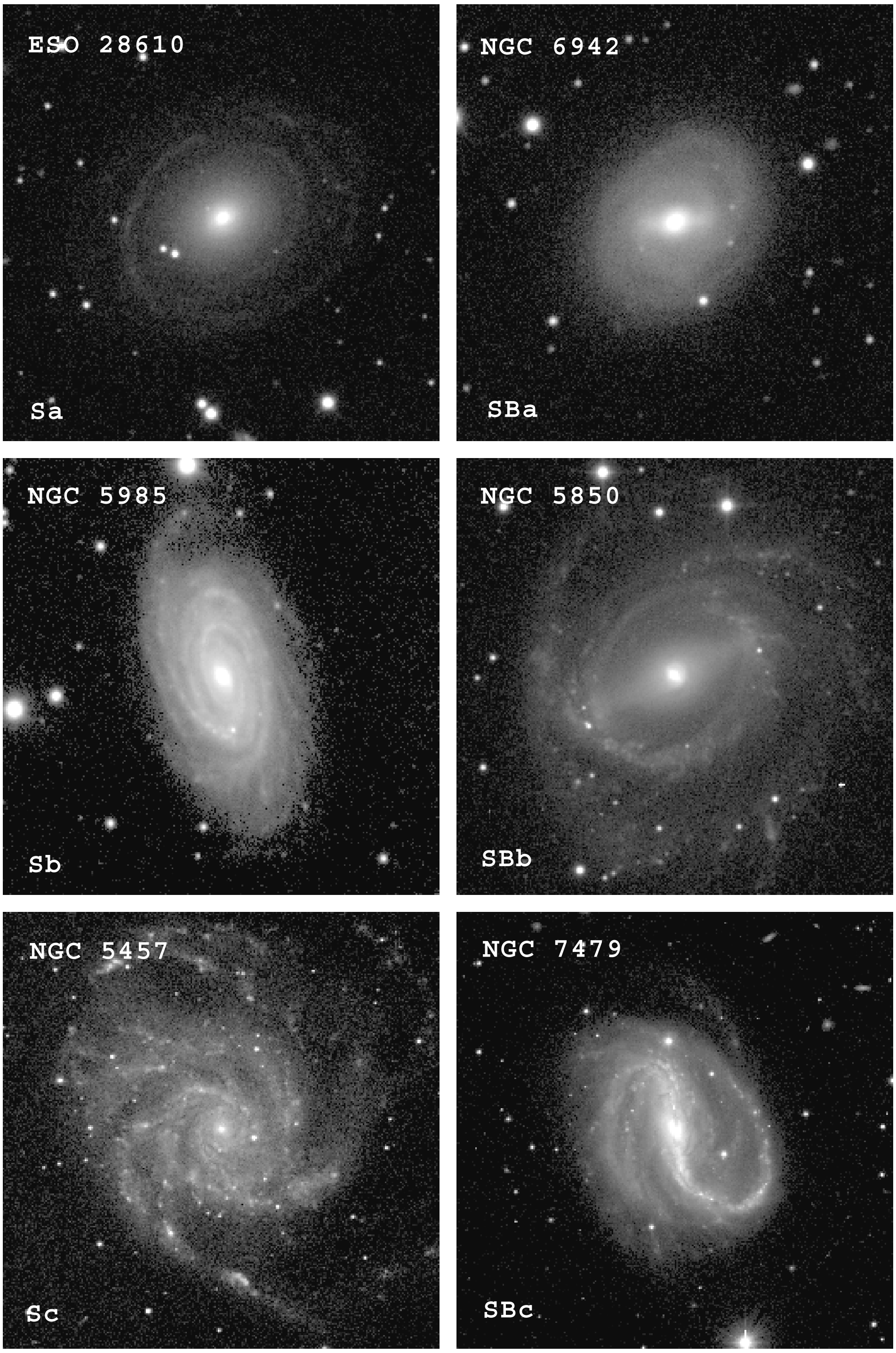

Figure 3. Examples of early- and late-type spiral galaxies.

the absence of much interstellar gas. This accounts for their smooth appearance and relatively red colors compared with spirals. Some 'late' edge-on S0s do show a midplane of dust.

At minimum, a true S0 galaxy should have no spiral arms, a clear bulge, and a clear disk or outer envelope of light. NGC 4138, shown in the middle left panel of figure 2, is a good example seen in an inclined but not

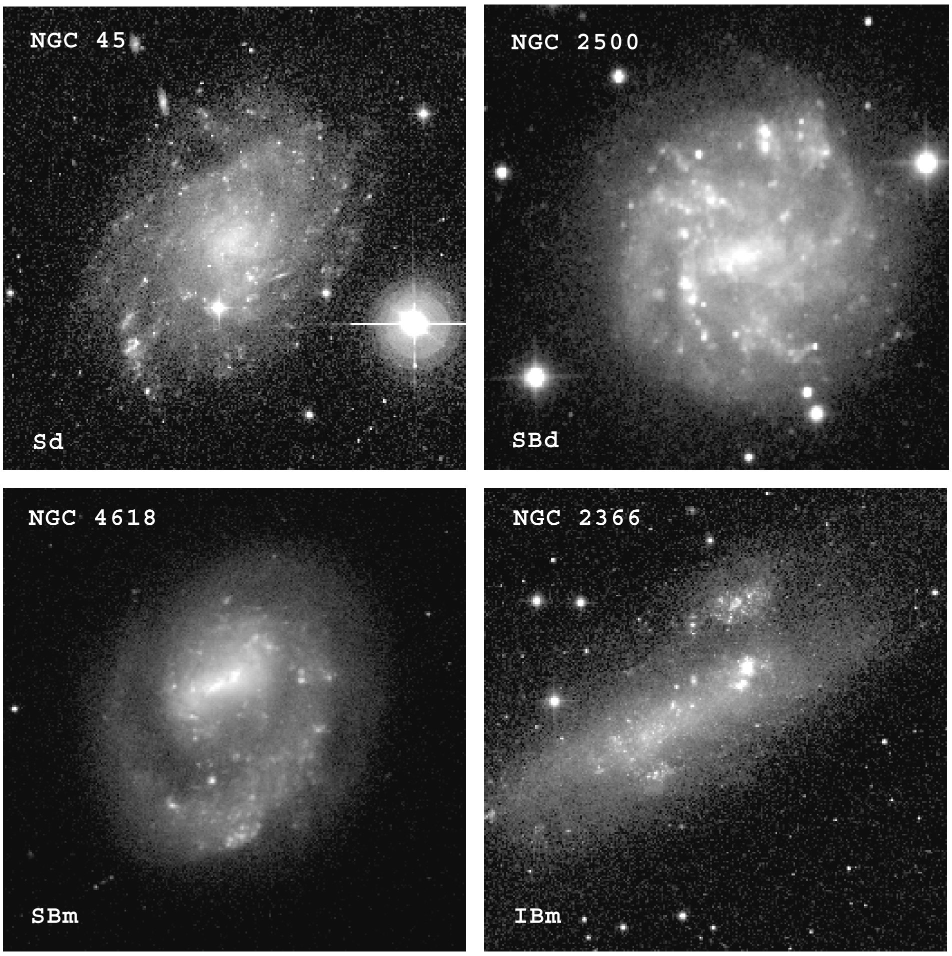

Figure 4. Examples of very-late-type and Magellanic spiral and irregular galaxies.

an edge-on view. This galaxy includes a weak ring of light just outside the bulge, which has led some authors to consider the galaxy to be a late S0. Seen face-on, the earliest S0s can be misclassified as ellipticals on inadequate image material. Late S0s have clearer differentiation of structure. Two examples are shown in the bottom panels of figure 2. NGC 4553 is a late S0 with a clear ring around the center. NGC 2983 is an SB0 with a well-differentiated bar and extended disk component. Both galaxies have also been classified as early-type spirals, although any spiral structure is very weak in both cases.

The relative luminosities of the bulges of S0 galaxies to their disks is a question connected to how we should interpret them. If they tend to have large bulge-to-disk luminosity ratios, then their placement in the Hubble sequence between ellipticals and spirals is likely to be correct. However, if some S0s have a relatively small bulge-to-disk ratio, then they could be 'stripped' spirals and should be placed on a sequence parallel to spirals.

The arrangement of ellipticals, S0s, spirals and irregulars along a sequence as shown in figure 1 is known as the Hubble sequence. The Hubble sequence is considered among the most important aspects of galaxies because certain properties of galaxies vary smoothly along the sequence. Interpreting what the sequence actually means is difficult because the mean luminosity of the galaxies is not the same at each type. The greatest spread in luminosity is found near the ends of the sequence, among the ellipticals and the late-type spirals and irregulars. An extremely important observation is how elliptical and S0 galaxies dominate the populations of rich and dense CLUSTERS OF GALAXIES, while spirals dominate looser clusters and the general field. This is the 'morphology–density' relation alluded to in the previous sections.

Other approaches to galaxy classification

Hubble's classification system is easy to use because it focuses on gross characteristics of galaxies. All of the original Hubble classes are rather broad in the galaxies they cover, but greater attention to detail is possible and other authors have proposed somewhat different points of view for classification, building on Hubble's idea.

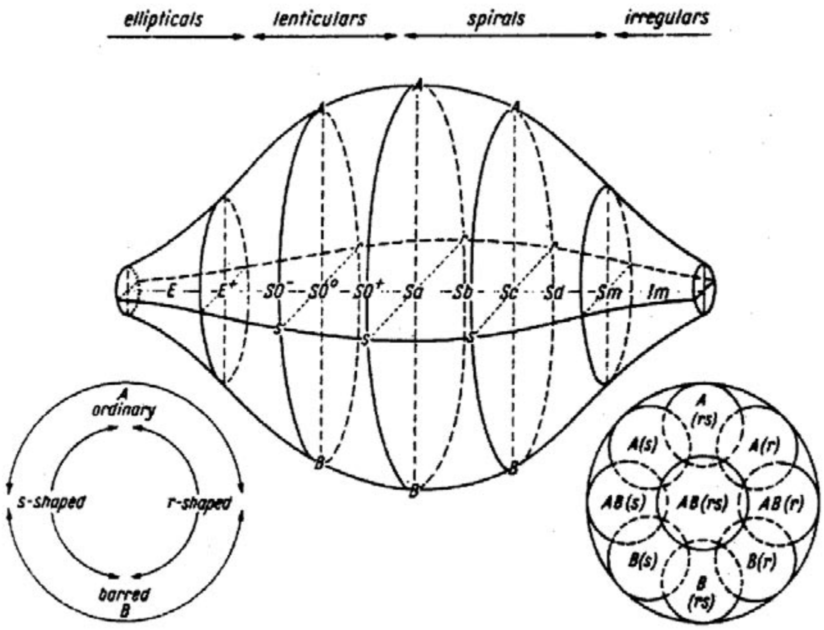

Figure 5. Illustration of the de Vaucouleurs revised Hubble classification system. In this system, S0 galaxies are referred to as 'lenticulars'. The lower left and right circles illustrate the arrangement of families and varieties within a cross-section through the system.

For example, rather than a two-pronged 'tuning fork' classification, G de Vaucouleurs proposed a classification volume whose main dimension is the basic Hubble type (i.e. E, S0, Sa, Sb, Sc, etc) and whose secondary dimensions are the family (presence or absence of a bar) and variety (presence or absence of a feature known as an inner ring; see figure 5). de Vaucouleurs' classifications provide a better description of what a galaxy looks like without being too complicated. Still, there are more than 100 'cells' in the de Vaucouleurs system compared with about 10 in Hubble's original system. The de Vaucouleurs system is recognized mainly for the addition of spiral types later than Sc, called Sd and Sm, and for the notation SA, SAB and SB to denote continuity of the bar characteristic. SA galaxies are true nonbarred (ordinary) galaxies, SB galaxies are true barred galaxies, while SAB galaxies are intermediate in apparent bar strength. Galaxies having a ring-shaped pattern in the inner regions are denoted as being of the (r) variety while those having no ring are said to be pure spirals, or the (s) variety. Galaxies having weak or partial, broken rings are assigned a variety of (rs), meaning a pseudoring is present. Examples of all nine possible combinations of families and varieties are illustrated in figure 6. The galaxies shown all have types of Sa or Sb. Inner rings are fairly common among these types, but are very much rarer among Sc types and later and nonexistent among ellipticals and early S0s.

In 1960, S van den Bergh demonstrated that galaxy morphology is influenced by the total luminosity or energy output of a galaxy. He assigned not only modified Hubble types to spiral and irregular galaxies, but also luminosity classes symbolized in a manner similar to stellar luminosity classes. The most luminous spirals or irregulars are luminosity class I while the least luminous are luminous class V. Categories II, III and IV have intermediate luminosities between these extremes. Most galaxies of luminosity classes IV and V are irregulars or very late-type spirals (Sd or Sm types). Of the spiral galaxies illustrated in this article, NGC 210, NGC 1300, NGC 1433, NGC 5457, NGC 5985 and NGC 7479 are luminosity class I or I–II, NGC 45 and NGC 2500 are luminosity class III, while NGC 2366 is luminosity class IV–V, as judged by A Sandage and G Tammann. Note how much more contrasted the spiral structure of the high luminosity class galaxies is compared with the intermediate or lower luminosity classes.

Spiral galaxies may also be classified strictly according to the appearance of their arms. Some spiral galaxies show a 'grand-design' spiral structure, consisting of two well-defined symmetric and long spiral arms. The first attempts to understand the nature of spiral structure in galaxies focused on grand-design spirals because they showed the best-defined spiral patterns. In other galaxies, however, the spiral arms are only chaotic or fragmentary and do not appear to be global in nature; such spiral patterns are often called 'flocculent'. The Hubble classification system and its revisions do not distinguish between these extremes in spiral arm morphology. D and B Elmegreen brought greater attention to these differences and proposed recognizing them with arm classes (ACs) ranging from 1 for the purely flocculent types to 12 for the best grand-design types. Intermediate-looking spirals

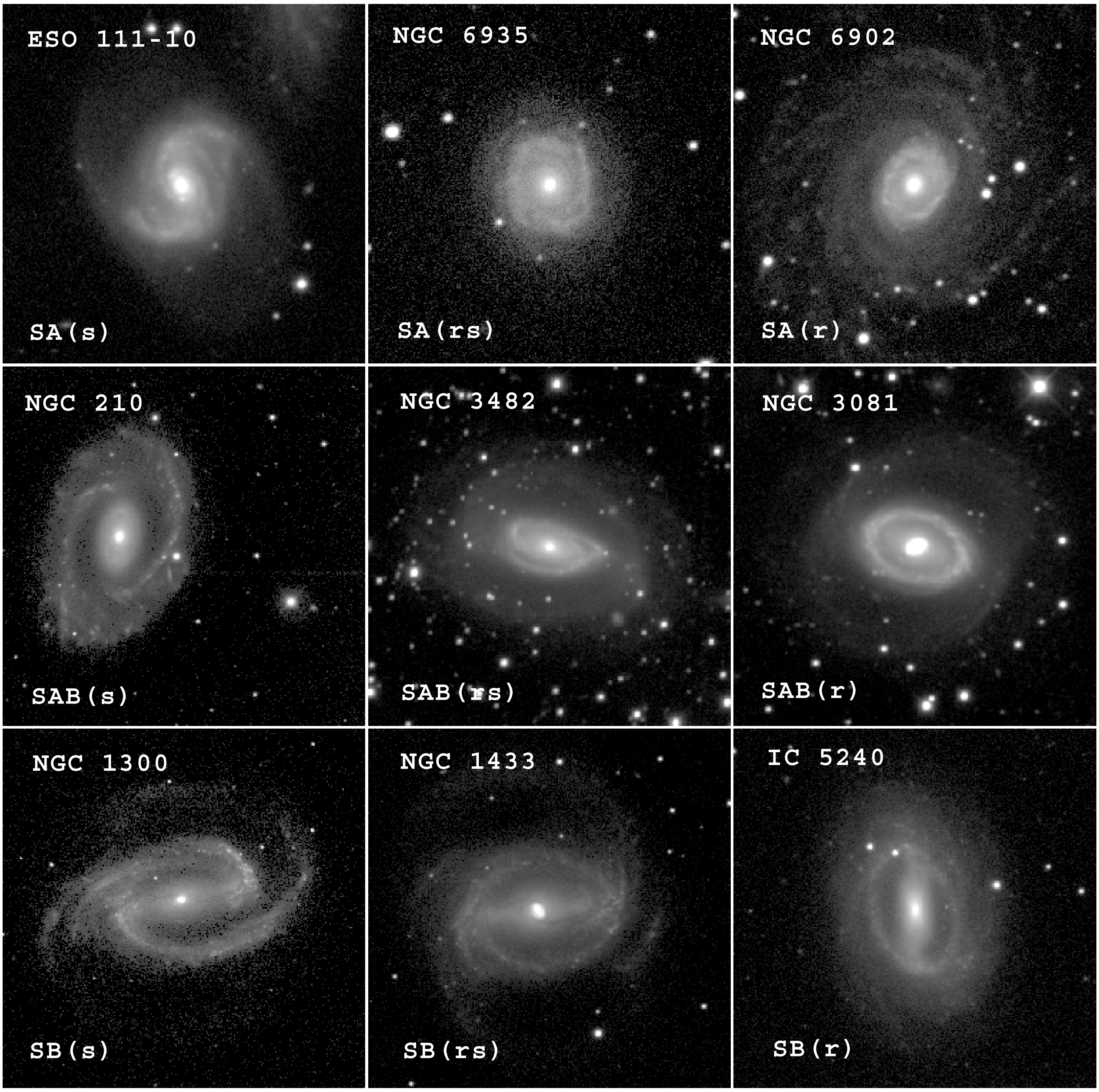

Figure 6. Examples of galaxies having different families and varieties in the de Vaucouleurs revised Hubble classification system.

have intermediate arm classes. In this article, NGC 1300 is an example of an AC 12 spiral while NGC 45 and NGC 2500 are examples of AC 1 systems. The distinction is worth recognizing because the origin of spiral patterns may differ among the different arm classes. Recognizing them allows one to do statistics to identify environmental factors that may be relevant.

W W Morgan proposed another classification system for galaxies in 1958 that tied galaxy morphology to the then-current ideas of stellar populations in galaxies. The degree of central concentration of a galaxy was used to define a spectral classification system (population group) based on form alone. Galaxies with strong central concentration were known to be dominated by spectral class K giants (population group k) in their central areas, while those with little central concentration were dominated by spectral class A stars (population group a). The elliptical, S0 and early-type spirals illustrated in this article are all population group k systems, while the late-type spirals (Sd, Sm) and irregulars (Im) tend to be population group a. Morgan also identified an extremely important rare type of galaxy known as a cD galaxy. These

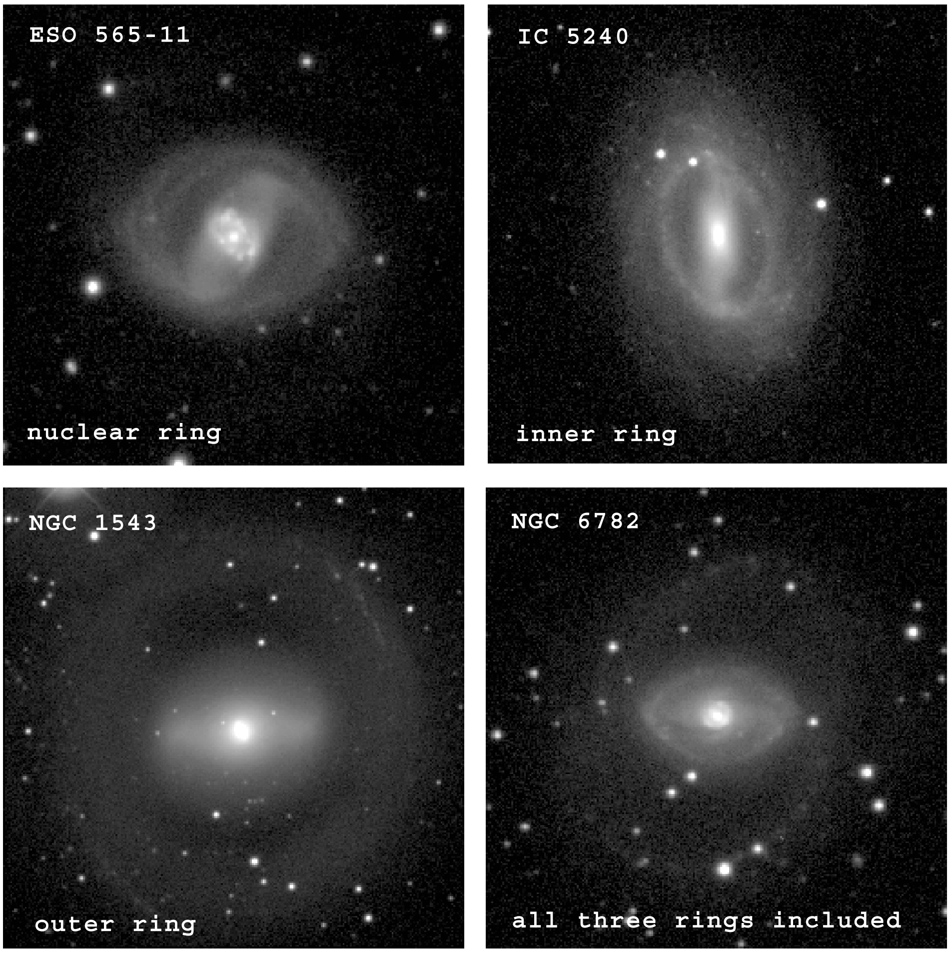

Figure 7. Examples of ringed galaxies.

are extremely large elliptical-like systems often found at the centers of rich galaxy clusters. They are characterized by a shallow light profile, low central concentration, and an extended envelope of light. The origin of such systems has been a topic of much research, and mergers of other galaxies is one possible interpretation.

Other classes or aspects of galaxy morphology

Ringed galaxies

A ringed galaxy is a normal spiral or S0 galaxy having a ring or ring-like pattern as part of the light distribution. In the jargon of normal galaxy morphology, there are three different types of rings: nuclear rings, which are small rings of active star formation often found in the centers of early-type barred galaxies, inner rings, which usually envelop the bars of barred spirals, and outer rings, which are large and faint structures having a diameter about twice that of the bar in barred galaxies. Of the three different types of rings, only inner rings are included as a major part of galaxy classification in the Hubble system, as noted in the previous section. The four panels of figure 7 show examples of all three ring types, one of which (IC 5240) is also included in figure 6. The classification symbols (nr), (r) and (R) are used for nuclear, inner and outer rings, respectively, and all three ring types may coexist in the same galaxy (see NGC 6782 in the lower right panel of figure 7). Inner rings and pseudorings can be identified in more than 50% of normal giant galaxies, and all three ring types are most frequent among early-type barred spirals.

Of the many morphological features of galaxies we have so far discussed, rings are among the best understood. They are features that seem to be generated by the way a bar can redistribute residual gas in a galactic disk, collecting the gas into ringed-shaped patterns that eventually condense into stars. The patterns are tied to locations known as orbital resonances, places where gas clouds move in step with the rotation rate of a bar pattern. Thus, rings and bars are features which are intimately connected.

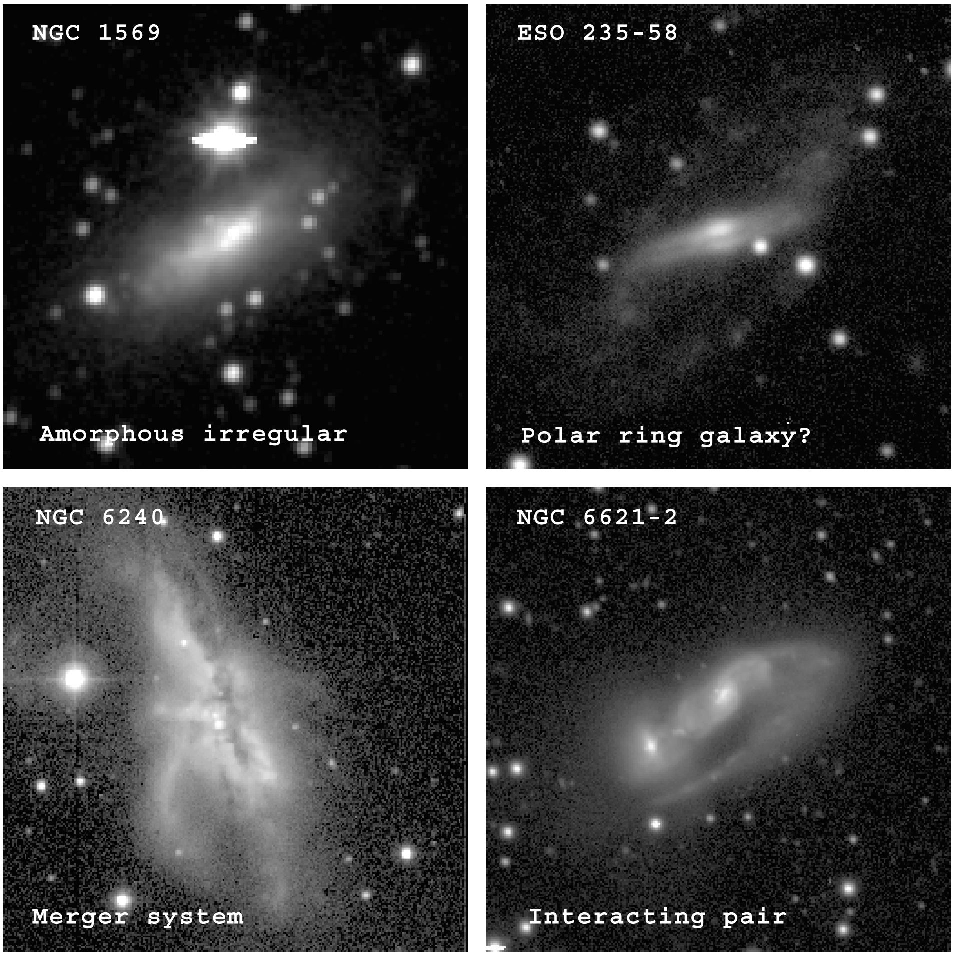

Figure 8. Examples of interacting galaxies and an amorphous irregular galaxy.

Amorphous irregular galaxies

Although classical irregular galaxies tend to be late-type systems with a considerable degree of patchiness and irregularity, another class of irregular galaxies has such amorphous characteristics that some astronomers considered them to belong near the transition between S0 and spiral galaxies. An example, NGC 1569, is shown in the upper left panel of figure 8. These objects tend to have much smoother distributions of luminosity than classical Magellanic irregulars. The distinction has been recognized since 1950, when E Holmberg suggested the term 'Irr I' be applied to normal late-type irregulars and 'Irr II' to these amorphous irregulars. de Vaucouleurs applied the term 'I0' to some of these objects, while Sandage prefers the general term 'amorphous' galaxies. The hallmark of the class is that the spectral character of the unresolved light is consistent with the presence of many young stars, unlike most other galaxies in the transition region between spirals and S0s. Interactions may play a role in the creation of these objects.

Interacting galaxies

Some of the most complex morphologies seen in the galactic population form directly as a result of gravitational interactions with neighboring galaxies (see GALAXIES: INTERACTIONS AND MERGERS). Interactions can be mild and may do no serious damage to the symmetry of a galaxy; however, such interactions may help to generate the formation of bars or even grand design spiral structure. Stronger interactions can lead to asymmetry and peculiar structure, and possibly even features known as 'tidal tails'. The strongest interactions can be so disruptive that the galaxies involved lose their individual identities and merge into a single, different type of object. It is currently thought that many giant elliptical galaxies formed as a result of the mergers of two spiral galaxies rather than naturally. Figure 8 shows a few cases of interacting systems. NGC 6240 in the lower left panel has been shown by numerous authors to be a remnant of a merger between two once separate galaxies; the system has not settled completely into a stable configuration and shows much peculiar structure. In the lower right panel, NGC 6621-2 is a pair of clearly interacting galaxies. Interactions of this nature are not rare and many galaxies may go through a phase of interaction throughout their evolution. Gravity has drawn out material into the form of an apparent bridge between the two systems.

Certain types of interactions can lead to very special and very rare galactic morphologies. For example, if a small galaxy plunges directly through the center of a larger disk-shaped galaxy, a collisional ring galaxy can result. These unusual systems can look like smoke rings in lacking a central nucleus. The ring in this case represents a shock wave moving outward, much like a water wave that results when a pebble is dropped in a pond. Another type of morphology can result when a small companion galaxy, usually a gas-rich irregular, passes close over the pole of a gas-poor S0 disk galaxy. In this circumstance, the interaction can disrupt the companion and capture it into a polar orbit. Eventually, the material that made up the companion spreads along the whole orbit, producing a POLAR RING GALAXY. The upper right panel of Figure 8 shows a likely example of a polar ring galaxy in formation. Known as ESO 235-58, this object actually shows a midplane dust lane dividing the central disk. Although the central section looks like a bar, bars do not normally have dividing dust lanes crossing them from end to end. The central section of ESO 235-58 must be an edge-on disk galaxy, and the other material is orbiting out of the plane of that disk.

Galaxy classification and morphology in the next decade

The era of the orbiting HUBBLE SPACE TELESCOPE (HST) has added a new dimension to galaxy morphology and classification that could not be tapped from previous ground-based observations. HST can provide images of galaxies at large cosmological redshifts of the same quality and resolution used to define the main morphological classes on ground-based images. GALAXIES AT HIGH REDSHIFT are being seen as they were when the universe was much younger than it is now. As noted at the beginning of this article, we do not expect that galaxy morphology is fixed and unchanging, but that change must have occurred. Thus, by studying high-quality images of galaxies at high redshift, we can see what typical changes must have occurred. Current results suggest that interactions between galaxies were more frequent in the past and that some galaxies had not yet settled into well-organized shapes. Thus, morphology contains clues as to how galaxies evolve, and galaxy classification will continue to be refined and adjusted to account for new findings.

The sheer numbers of galaxies available for classification will also have an impact on how astronomers will be classifying galaxies. A large survey can provide high-quality images of more than a million galaxies, and it is impractical to classify so many galaxies visually by one or more experts. Instead, the coming decade will see more and more the use of computers to objectively classify large numbers of galaxies for cosmological and other research.

Galaxies can also be classified in wavelength bands other than the blue-light band used to develop the Hubble classification system. The tendency for blue filters to emphasize hot, young, massive and relatively rare stars means that the classification system tends to overestimate the significance of these objects. In the next decade, galaxy classification will be revised in order to group galaxies according to their appearance in infrared light, which tends to emphasize the stars that dominate the mass distribution. This will be especially important for intermediate to late-type spirals.

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Image credits
NGC 221, NGC 4618, NGC 5985, and NGC 7479 were obtained by S Odewahn and R Gal with a green filter and the Palomar 1.5 m telescope. NGC 45, NGC 2366, NGC 2500, and NGC 5457 are blue light images obtained by D Elmegreen and coworkers with telescopes at the Kitt Peak National Observatory. NGC 4111 and NGC 4138 are near-infrared images from the Ohio State University bright galaxy survey, supported by a grant from the National Science Foundation. For these early-type galaxies, there is little difference between the appearance in the near-infrared and the appearance in a standard blue light filter. W C Keel provided the images of NGC 6240 and NGC 6621-2. The image of NGC 6240 was obtained in blue light at the European Southern Observatory while that of NGC 6621-2 was obtained in red light at the Kitt Peak National Observatory. The remaining images were obtained by the author and coworkers with telescopes at the Kitt Peak National Observatory and the Cerro Tololo Inter-American Observatory, and are in blue light only. All images are based on electronic detectors and are in logarithmic units.

Ronald Buta