2 Galaxy morphology and classification

Galaxy classification is an important first step towards a physical understanding of the nature of these objects. For a detailed description of classification systems and their implications, a good reference is the book *Galaxy Morphology and Classification* by Sidney van den Bergh (Cambridge University Press, 1998).

One can divide galaxies into four general categories:

- **normal** galaxies – no gross peculiarities
- **active** galaxies – strong nuclear activity
- **starburst** galaxies – intense star-formation activity
- **interacting** galaxies – disturbed by recent or current gravitational encounter

We begin by considering the morphology of normal galaxies.

The first classification schemes predate an understanding of the nature of spiral nebulae. An early example Wolf’s system, described by Sandage in Stars and Stellar Systems, Volume 9.

![Figure 2.1: Wolf’s classification scheme (from Stars and Stellar Systems, Volume 9).](image)
2.1 The Hubble sequence

The basic classification scheme still employed today is based on tuning-fork diagram devised by Hubble (1936). Comprehensive discussions of the system and its application have been given by Sandage (1961, 1975).

Hubble (mistakenly) thought galaxies might evolve from left to right in the diagram, hence the designation early and late type galaxies.

2.2 Elliptical galaxies

Elliptical galaxies are characterized by a smooth, symmetric distribution of stars. There is little or no, evidence of dust, gas, or star formation. The stars in these galaxies are old, typically $\sim 10 - 13$ Gyr.

The isophotes (lines of constant intensity) are elliptical, generally to within a few percent accuracy. However, most show significant variation in ellipticity and position angle with radius.
Ellipticity $\varepsilon$ is defined by

$$\varepsilon = 1 - \frac{b}{a},$$

(2.1)

where $a$ and $b$ are the semi-major and semi-minor axes of the ellipse.

No elliptical galaxies are observed to have $\varepsilon > 0.7$.

Elliptical galaxies are classified according to apparent flattening. The designation is $E_n$ where $n = 10\varepsilon$.

2.3 S0 galaxies

Also called lenticular galaxies (due to their lens-like appearance when see edge-on), S0 galaxies are more flattened than elliptical galaxies, and have a noticeable disk. However, they show no evidence of gas, spiral arms, star formation or young stellar populations.

Many S0 galaxies have visible dust. The subclasses S01, S02, S03 designate increasing amounts of dust.
Figure 2.4: (a) NGC1316, an S0 galaxy showing dust lanes. This galaxy, also know as Fornax A, is a powerful source of radio emission (NASA/ESA Hubble Heritage Project). (b) NGC 3115, an S0 galaxies seen edge on (J. Kormendy, CFHT).

2.4 Spiral galaxies

Spiral galaxies are characterized by the presence of a distinct disk with abundant gas, dust and ongoing star formation. Spiral arms, traced by young luminous stars, highlight regions of active star formation triggered by density waves propagating in the disk.

As the sequence progresses from Sa through Sc, (from early- to late-type spirals) the spiral arms increase in prominence and become less tightly wound and more irregular. The diffuse central bulge becomes less prominent.

A bar (a radial density enhancement) may be present. The bar may terminate in a ring. Spiral arms often attach to the bar or ring.

2.5 Irregular galaxies

Hubble defined two classes of irregular galaxies:

- **Irr-I** are normal low-luminosity star-forming galaxies.
- **Irr-II** are peculiar systems, such as M82 (Figure 2.9).

The amorphous appearance of M82 is due to a dust-enshrouded burst of star formation thought to have been triggered by a close encounter with M81.
Figure 2.5: Messier 104, the Sombrero Galaxy, is an Sa seen nearly edge on. Note the prominent stellar bulge and the thin symmetric disk (NASA/ESA Hubble Heritage project).

Figure 2.6: NGC 3949 displays the typical characteristics of an Sc galaxy – prominent patchy open spiral arms and a small bulge (NASA Hubble Heritage project).
Figure 2.7: (a) Barred spirals M83, an SBc galaxy (W. Keel, U. Alabama, KPNO 4m telescope), and (b) NGC 613, an SBc galaxy (M. Neeser (Univ.-Sternwarte München), P. Barthel (Kapteyn Astron. Institute), H. Heyer, H. Boffin (ESO), ESO).

Figure 2.8: The Large Magellanic Cloud, classified as SBm by de Vaucouleurs, exhibits irregular, patchy star formation with little evidence of spiral structure (AAO).
2.6 de Vaucouleurs extensions

de Vaucouleurs (1959, 1963) defined extensions to the Hubble system. He introduced intermediate types (eg. Sab) and additional types: Sd, Sm, Im which have increasingly-irregular light distributions.

de Vaucouleurs introduced a more detailed classification of features: (r) means a ring, (s) means S-shaped, SA denotes a normal spiral and SB a barred spiral. He also recognized intermediate types, SAB. de Vaucouleurs’ Im is equivalent to Hubble’s Irr-I.

2.7 Yerkes system

Morgan (1970) introduced a galaxy classification system based primarily on the degree of central concentration of the light. He found that the integrated spectrum of the galaxy correlates strongly with central concentration (Elliptical galaxies have an integrated spectrum resembling those of K giant stars, whereas Sc galaxies, which have small bulges, have integrated spectra resembling those of A stars). This is the first classification scheme based on physical properties rather than merely on appearance.

Morgan’s classification system uses a letter (see Table), followed by one or two letters (a, af, f, fg, g, gk, k) indicating the approximate spectral type of the integrated spectrum and finally a number in the range 1 – 7 representing elongation or inclination. For example, Egk3.
Table 2.1: Morgan’s classification codes

<table>
<thead>
<tr>
<th>Shape code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>barred spiral</td>
</tr>
<tr>
<td>D</td>
<td>rotational symmetry but not a normal spiral or elliptical galaxy</td>
</tr>
<tr>
<td>cD</td>
<td>large D galaxy in a cluster</td>
</tr>
<tr>
<td>E</td>
<td>elliptical</td>
</tr>
<tr>
<td>Ep</td>
<td>elliptical with dust</td>
</tr>
<tr>
<td>I</td>
<td>irregular</td>
</tr>
<tr>
<td>L</td>
<td>low surface brightness</td>
</tr>
<tr>
<td>N</td>
<td>small bright nucleus</td>
</tr>
<tr>
<td>S</td>
<td>spiral</td>
</tr>
</tbody>
</table>

2.8 DDO system

van den Bergh (1960a,b, 1976), working at the David Dunlap Observatory, noticed that S0 galaxies have a range of central concentrations, as do spirals. He proposed a trident classification in which S0s are placed in a sequence parallel to that of spirals. S0a, S0b, S0c refer to disk galaxies that resemble Sa, Sb, Sc in shape but lack gas.

He also introduced a sequence Aa, Ab, Ac, of anemic galaxies that are intermediate between spirals and S0s. The presence of bars is indicated by a B, as in ABc for instance.

van den Bergh noted that luminous spiral galaxies have more distinct and regular spiral arms that do low-luminosity spirals and introduced a luminosity classification system (I to V) based on the appearance of the arms:

*Class I* (eg M101 – type Sc I), with well developed structure, are the most luminous spiral galaxies

*Class V* are the least luminous, with little spiral structure.

2.9 Giant elliptical galaxies

Morgan (1958, 1959) defined new categories of luminous elliptical galaxies.

* D – a giant elliptical

* cD – a supergiant elliptical.

Both have extended luminous envelopes, and are found in clusters.

cD galaxies are the most massive and luminous galaxies known. It is believed that their unusual properties are a result of their location at the centre of rich clusters, where they have accreted debris stripped from other cluster galaxies by gravitational interactions.
2.10 Dwarf elliptical galaxies

For a review see Ferguson & Binggeli (1994). There are two distinct categories:

* **Dwarf ellipticals** (dE) - Small galaxies, typically $\sim 10^{-3}$ of the mass of a normal elliptical. Having a smooth distribution of stars and little or no gas.

* **Dwarf spheroidal** (dSph) - Low-luminosity very diffuse spheroidal systems of stars

The Andromeda galaxy (M31) has three dE companions (NGC 147, 185 and 205 see Figure 2.11).

Dwarf spheroidal galaxies have masses of order $10^7 M_\odot$. They are very common – nine are known to orbit the Milky Way. They show no signs of recent star formation or gas, but their stellar populations exhibit a range of ages indicating an extended period of star formation.

2.11 Structural components

It is useful to consider galaxies as being made up of one or more distinct structural components. The morphological type of a galaxy is then a statement of a more fundamental property – the types of components that comprise the galaxy.
Figure 2.11: NGC 205 (lower left), a dE companion to the Andromeda Galaxy (Messier 31 upper right) (J-C Cuillandre, CFHT).

Figure 2.12: The dwarf spheroidal galaxy Leo I is believed to be a distant satellite of the Milky Way (David Malin, AAO).
The **spheroid** is the smooth elliptical distribution of stars found in elliptical galaxies. It is composed primarily of an old, metal-poor, population of stars typically having ages $\sim 12$ Gyr or more. The spheroid is thought to be among the first stellar components to form.

The **stellar halo** is a diffuse, roughly spherical, system of stars and globular clusters that surrounds most large galaxies. It is comprised mostly of old, metal-poor, stars. The halo has little or no net angular momentum. It is thought to have formed, at least in part, by the accretion of small satellite galaxies.

The **dark halo** is the dark matter component that envelopes all galaxies. It extends well beyond the visible extents of the galaxy. The mass density decreases with radius roughly as $\rho \propto r^{-3/2}$. The nature of the particles that comprise this component is not known, but there is strong evidence that the particles are non-relativistic (and therefore have mass).

The **gaseous halo** refers to the hot gas that envelopes some galaxies. It can be detected by the soft X-rays that are emitted from thermal bremsstrahlung. The typical gas temperature is found to be $\sim 10^6$ K. This component includes cosmic rays and the galactic magnetic field.

![Figure 2.13: X-ray image of the elliptical galaxy M87. A diffuse envelope, due to thermal emission from hot gas, is punctuated by filaments emanating from the nucleus.](image)

The **bulge** is a smooth distribution of old stars that surrounds the nucleus of many spiral galaxies. Large bulges are similar in appearance to the spheroids of elliptical galaxies. Many galaxies have small bulges or none at all. Small bulges have light distributions that more resemble the disk, and may be rotating.
The **thin disk** is a flat distribution of stars, gas and dust, having a typical vertical scale height of about 300 pc. In spiral galaxies, it contains stars with a wide range of ages. The thin disk is the home of spiral arms, molecular clouds, star formation, etc. It is thought to have formed by dissipation during the collapse of the protogalactic gas cloud.

The **thick disk** is a fainter component seen in some galaxies (see Figure 2.13). It has a typical scale height of \( \sim 1 \text{ kpc} \), and is comprised of a population of old, metal-poor, stars. The thick disk is thought to arise soon after the formation of the thin disk as a result of heating by accretion of satellite galaxies.

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Figure 2.14: NGC 4762 (lower left). This edge-on galaxy shows a prominent thick-disk component (NASA/ESA HST).