Lecture Two:

Observed Properties of Galaxies


Longair, chapter 3
Binney & Merrifield, chapter 4

Wednesday 5th Feb
From pretty picture to science...
Galaxies are Basic Building Blocks of the Universe

A galaxy is a large cluster of stars, gas and dark matter that is held together by the gravitational attraction between its constituents.

Galaxy total masses range from $<10^6 - 10^{13}$ M$_\odot$ and galaxy optical diameters range from $<1$ kpc - $>100$ kpc.

A galaxy can consist of hundreds of millions or billions of stars. It can contain considerable quantities of interstellar gas and dust and can be subject to environmental influences through interactions with other galaxies and intergalactic gas. It may be forming stars with a variety of rates. And it will contain dark matter and the dynamics of galaxies are largely dominated by this invisible dark component, the nature of which is unknown.
The Hertzsprung–Russell magnitude colour diagram

Stars can live a very long time

Ejnar Herzsprung (1873-1967)

Henry Norris Russell (1877-1957)

Hans Bethe (1906-2005)

Physics of stars, 1938 [Noble Prize 1967]
Galaxies are made of stars....
What do colours mean?

The Johnson-Cousins passbands

Transmission

Wavelength (Angstroms)

U  B  V  R_c  I_c
Spectrum of an Elliptical galaxy
What does it mean?

Stellar spectra

>10 Gyr

~8 Gyr

~1.5 Gyr

~5 Myr

Stellar spectra
Star Formation History

Elliptical Galaxy

O'Connell 1986 PASP, 98, 163
Galaxy Morphology

1A. **Descriptive classification** into “natural groups”
- that isolate common structural features seen in photographs;
- that rank galaxies by physical parameters;
- that begin to isolate different physical processes.

1B. **Physical Morphology**: Refine 1A until classification bins segregate galaxies as well as possible by formation mechanism and by present physical structure and content.

2. Study the physics of galaxies by looking for patterns of behavior:
   \[\Rightarrow\] Results of 2 kinds:
   - Definite answers to specialized questions (e.g., galaxy shapes);
   - Specific questions for quantitative work.

Note: Morphology is usually a “soft” science — a preparatory step.

Together, 1 and 2 provide a conceptual framework for studying galaxy physics.

Kormendy
Classical: Hubble Sequence

Fundamental difference between Elliptical galaxies and galaxies with discs

Hubble 1936, *the Realm of Nebulae*

Sa $\rightarrow$ Sb $\rightarrow$ Sc

- bulge decreases
- spiral arm pitch increases
- resolution into young stars and gas increases

The bulge determines the central mass concentration which controls the spiral arm pitch angle from the density wave dispersion relation.

Since this classification scheme does not include transition types it forces galaxies into large morphological bins with heterogeneous properties.

Advantage - when comparing nearby & distant galaxies.

Disadvantage - when studying details of disk dynamics.

For more info, see Sandage 2005, ARAA
The most fundamental distinction is the one between elliptical galaxies (which prove to be ellipsoidal in shape) and galaxies with disks.

“Hubble correctly guessed that the presence or absence of a disk, the openness of the spiral-arm pattern, and the degree of resolution of the arms into stars, would be highly relevant. It was an indefinable genius of Hubble that enabled him to understand in an unknown way ... that this start to galaxy classification had relevance to nature itself.”

Allan Sandage
Carnegie Atlas of Galaxies
Elliptical Galaxies: are almost featureless ellipses. They are predominantly made up of old stars. They are typically a few times more massive than the Milky Way, but there is a wide range: from a few percent to more than 10 times the mass of the Milky Way. They also vary in apparent elongation, from round to 2:1 flattened. This is mostly because of inclination.
Surface Brightness

The apparent surface brightness is the rate at which energy reaches a detector. An isophote is a closed curve connecting points of equal surface brightness. **Surface brightness** profiles are produced by azimuthally averaging around the galaxy along isophotes.

Surface brightness is independent of distance (d) since flux decreases as $1/d^2$, but the area subtended by 1 sq arcsec increases as $d^2$. (until cosmological dimming, $1/(1+z)^4$, becomes important)

NGC4278, a giant elliptical

Note: the largest isophote usually represents the lowest level that can be seen above the instrumental noise (not physical boundary)

See Binney & Merrifield, section 4.2
De-projection of galaxy images

What can we infer about the 3D luminosity density $j(r)$ in a transparent galaxy from its projected surface-brightness distribution $I(R)$?

If $I(R)$ is circularly symmetric, $j(r)$ may be spherically symmetric:

$$I(R) = \int_{-\infty}^{\infty} dz \ j(r) = 2 \int_{R}^{\infty} \frac{j(r)rdr}{\sqrt{r^2 - R^2}}$$

This is an Abel integral equation for $j$ as a function of $I$, and its solution is:

$$j(r) = -\frac{1}{\pi} \int_{r}^{\infty} \frac{dI}{dR} \frac{dR}{\sqrt{R^2 - r^2}}.$$ 

Useful only when $I(R)$ is a smooth function.

Often it is desirable to fit to an observed SB profile a formula that corresponds to a simple analytic form of $j(r)$. Simplest:

$$I(R) = \frac{I_0}{1 + (R/r_0)^2} \quad \leftrightarrow \quad j(r) = \frac{j_0}{[1 + (r/r_0)^2]^{3/2}},$$

where $I_0 = 2r_0j_0$.

this SB profile is known as the modified Hubble Law.
Sources of Error

Sky Background Subtraction—
if the sky is over or under subtracted
this can have a dramatic effect on
the shape of the SB profile.

Sources include: light pollution from nearby
cities, photochemical reactions in the Earth’s
upper atmosphere, the zodiacal light, unresolved
stars in the Milky Way, and unresolved galaxies.

Seeing effects –
unresolved points are spread out due to
effects of our atmosphere, quantified by the
Point Spread Function (PSF) FWHM (σ) on
the images

- makes central part of profile flatter
- makes isophote rounder

See Binney & Merrifield, section 4.2.1
See Binney & Merrifield, section 4.2.2
Surface Brightness of Ellipticals

Characteristic surface brightness profiles for Es of different luminosities

See Binney & Merrifield, section 4.3
de Vaucouleurs Profile

In specifying the radius of a galaxy it is necessary to define the surface brightness of the isophote being used to determine that radius.

**Holmberg radius**, \( r_H \), is defined to be the projected length of the semi-major axis of an ellipsoid having an isophotal surface brightness of \( \mu_H = 26.5 \) B-mag arcsec\(^{-2} \).

**Effective radius**, \( r_e \), is the projected radius within which one-half of the galaxies light is emitted. This means that the surface brightness level at \( r_e \) (\( \mu_e \)) depends on the distribution of surface brightness with radius.

For **large ellipticals**, the surface brightness distribution typically follows an \( r^{1/4} \) law (de Vaucouleurs profile):

\[
\mu(r) = \mu_e + 8.3268 \left[ \left( \frac{r}{r_e} \right)^{1/4} - 1 \right] \quad \text{mag arcsec}^{-2}
\]

Or, in physical units:

\[
\log_{10} \left[ \frac{I(r)}{I_e} \right] = -3.3307 \left[ \left( \frac{r}{r_e} \right)^{1/4} - 1 \right] \quad \text{L}_\odot \text{pc}^{-2}
\]
Sérsic Profile

Generalised version of $r^{1/4}$ law is frequently used in which $1/4$ is replaced by $1/n$. Often called Sérsic (1968) models have been shown (Caon et al 1993) to be an even better fit to E’s, though it increases the number of free parameters:

$$\mu(r) = \mu_e + 8.3268\left[\left(\frac{r}{r_e}\right)^{1/n} - 1\right] \text{mag arcsec}^{-2}$$

Where $\mu_e$, $r_e$ and $n$ are all free parameters used to obtain the best possible fit to the actual surface brightness profile.
Sérsic Profile

This formalism can be used to discriminate between disk-dominated and bulge-dominated galaxies. Especially suited to automated analyses of large samples.

Distribution of Sersic-n for 10,095 galaxies selected from the Millennium Galaxy Catalogue (Driver et al. 2006, MNRAS, 368, 414)
Centres of Elliptical Galaxies

- $R^{1/4}$ and Sersic fits tend to fail in the inner regions of Elliptical
- Regions of special interest because they host supermassive black holes
- HST is necessary since largest E’s lie far away and seeing effects degrade profile centers (Lauer et al 1995).

- More luminous E’s ($M_v<-21.7$) tend to have cores – flatten towards center
- Midsize E’s (-21.5$<M_v<-15.5$ with $L<2\times10^{10}L_\odot$) are core-less; steeply rise to center
- Cores could be the result of mergers so central nucleus is more diffuse – caused by binary BHs scouring out centers in “dry mergers” (no gas)
- Core-less also reveal “extra light” which may be result of nuclear starburst resulting from “wet mergers” (with gas) - see Kormendy et al 2009
Kormendy et al. (2009) show that:

- giant E’s (core) have $n>4$
- mid-size E’s (coreless) have $1<n<4$
- Sersic parameter relates to galaxy magnitude and core presence

Figure 33. Correlation between Sersic index $n$ and $M_{VT}$: red, blue, green, and turquoise points show our core Es, extra light Es, Sph galaxies, and S0 bulges. The green triangles show all spheroids from Ferrarese et al. (2006a) that are not in our sample. Crosses show all spheroids from Gavazzi et al. (2005) that are not in our sample or Ferrarese’s. The open squares are for Local Group spheroids (Caldwell 1999; Jerjen et al. 2000). The open symbols refer to galaxies that are not Virgo cluster members.
Coreless

Brighter central surface brightness →

Core

Brighter total galaxy light ←
3-D Shapes of Ellipticals (and Bulges)

See Binney & Merrifield, section 4.3.3

What are the true shapes of surfaces of equal luminosity density (isodensity)?
• 1st order model assumes either prolate (football) or oblate (flattened) spheroids
• But most E’s (at least giant E’s) seem to be triaxial ellipsoids
  * All 3 axes different lengths
  * No axis of rotational symmetry

http://mathworld.wolfram.com/Ellipsoid.html
Evidence for triaxial bodies: **Isophotal twists** and **changing ellipticity** with radius

- A triaxial body viewed from most orientations will have twisted isophotes from all viewing angles except along principal axes (i.e. PA changes with radius)

  a) Surface of constant density. The outer surface is oblate with $x:y:z = 1:1:0.46$. The inner surface is triaxial with $x:y:z = 1:0.5:0.25$.

b) Projected SB
c) Isophotes of SB
d) Isophotes of central region - note isophotal twists

• Triaxial bodies generally show a change in the ellipticity of isophotes as a function of radius
Profile Fitting: cD galaxies

Profile departure caused by remnants of captured galaxies OR the envelope belongs to the cluster of galaxies (not just central galaxy). The ellipticity of the envelope follows curves of constant number density of cluster galaxies.
**S0 galaxies** are conventionally thought to be intermediate between E and S: they have disks, but no spiral structure. In fact, we will see that their properties partly parallel the Sa — Sc sequence; i.e., there are S0s that are structurally more similar to Sbs than to Sas.
Lenticular (S0) Galaxies

NGC 3115: S0-galaxy
$V_{hel} = 663$ km/s
7.2 x 2.5 arcmin
M=9.87

NGC 4371: SB0-galaxy
$V_{hel} = 943$ km/s
4 x 2.2 arcmin
M=11.79
Are Ellipticals really so smooth?

Shells - seen at faint levels around most E’s
- Origin could be merger remnants or captured satellites
- prominent shells goes with evidence for some young stars in the galaxy

Shells in Cen A

Dust - visible dust clouds seen in many nearby E’s (maybe 50% of E’s have some - but not much – dust)
Early-Type Galaxies

Hubble’s classification scheme for early-type galaxies, based only on apparent ellipticity, is virtually irrelevant. Most physical characteristics are independent of ellipticity. It has proved more useful to focus on other properties: size, absolute magnitude and surface brightness.

cD: huge (sometimes ~1Mpc across), rare, bright objects

Normal Es: centrally condensed objects with relatively high central surface brightness, giant & compact versions.

dE: lower surface brightness at same $M_B$

compared to Es

dSph: extremely low luminosity and SB mostly detected in vicinity of Milky Way.

BCDs: blue compact dwarf galaxies.

| TABLE 11.3 Characteristic Data for cD, Elliptical, and Lenticular Galaxies. |
|-----------------|---------|---------|---------|
| $M_B$           | cD      | E       | SO/SB0  |
| $M (M_\odot)$   | $10^{11}$ | $10^{13}$ | $10^{10}$ |
| Diameter ($D_{25}$, kpc) | 300-1000 | 1-200 | 10-100 |
| $(M/L_B)$ ($M_\odot/L_\odot$) | > 100 | 10-100 | 10 |
| $(S_N)$         | ~ 15    | ~ 5     | ~ 5     |

| TABLE 11.4 Characteristic Data for Dwarf Elliptical, Dwarf Spheroidal, and Blue Compact Dwarf Galaxies. |
|-----------------|---------|---------|---------|
| $M_B$           | dE      | dSph    | BCD     |
| $M (M_\odot)$   | $10^{7}$ | $10^{7}$ | $\sim 10^9$ |
| Diameter ($D_{25}$, kpc) | 1-10 | 0.1-0.5 | < 3 |
| $(M/L_B)$ ($M_\odot/L_\odot$) | ~ 10 | 5-100 | 0.1-10 |
| $(S_N)$         | $4.8 \pm 1.0$ | --- | --- |
**Spiral galaxies** contain a disk of stars and gas arranged in a spiral pattern. Sa and Sb galaxies also contain a central bulge that is like a small elliptical. The bulge is old (“Population II”). Usually the disk is made partly of young stars (“Population I”). There are two sub-types: barred and ordinary spirals.

Along the sequence Sa → Sc,

- the contribution of the bulge decreases,
- the fractional amount of gas increases,
- the contribution of young stars increases
- the disk looks more patchy, and
- the spiral arms become more open.

**Basic points:**

- disks are flat
- disks have spiral structure
- orbits are almost in a single plane
  - disks rotate
  - random motions are small
  - stars have a large range of ages

Our Milky Way is a typical spiral, intermediate between Sb and Sc. It has a weak bar.
Spiral (Sa) Galaxies:

NGC 3223: Sa-galaxy
$V_{hel} = 2891$ km/s
4.1 x 2.5 arcmin
M=11.9

M 104 (Sombrero), Sa-galaxy
$V_{hel} = 1024$ km/s
8.7 x 3.5 arcmin
M=9
Spiral (Sb) Galaxies:

M 31 (Andromeda): Sb-galaxy
$V_{\text{hel}} = -300 \text{ km/s (750kpc)}$
197 x 92 arcmin
M=4.36

M 81: Sb-galaxy
$V_{\text{hel}} = -34 \text{ km/s (3.6Mpc)}$
8.7 x 3.5 arcmin
M=7.89
Spiral (Sc) Galaxies:

M 51: Sc-galaxy  
$V_{\text{hel}} = 600$ km/s  
9 x 9 arcmin

M 101: Sc-galaxy  
$V_{\text{hel}} = 241$ km/s (6.7Mpc)  
28.8 x 26.9 arcmin  
M=8.3
Barred–Spiral (SBb) Galaxies:

M 91: SBb-galaxy  
$V_{\text{hel}} = 486$ km/s (15.4Mpc)  
5.4 x 4.3 arcmin  
M=10.96

NGC 2523: SBb-galaxy  
$V_{\text{hel}} = 3471$ km/s  
3 x 1.8 arcmin  
M=12.63
Barred–Spiral (SBc) Galaxies:

NGC 1365: SBc-galaxy
$V_{\text{hel}} = 1636$ km/s
11.2 x 6.2 arcmin
M=10.32

NGC 613: SBc-galaxy
$V_{\text{hel}} = 1481$ km/s
5.5 x 4.2 arcmin
M=10.7
Orientation is an important consideration

Hubble Sequence

The effect of star formation, spiral arms, gas, dust
Wavelength/filter is important

Rest-frame wavelength (the wavelength at which the radiation was emitted) is important. Of course it depends what you want to know about a galaxy, which radiation you want to detect.

This fact that galaxies change how they look with wavelength is especially important if you want to compare galaxies with a significant REDSHIFT, e.g.,

The R- filter image of a galaxy at redshift, $z=1$ should be compared to the U-filter image of a nearby galaxy.
K-correction

Correcting for red-shifting of light out of wavelength region

This is most important for high-redshift galaxies. If it is not taken into account conclusions can easily be in error.
M31 - different wavelengths

Spitzer IR

Optical

Galex NUV+FUV
Spirals in ultraviolet (dominated by massive stars) and visual (average population), Ultraviolet Imaging Telescope, Astro mission. 
Note: Redshifted spirals observed in the optical will show rest-frame UV morphology!
What is a Spiral Galaxy?

- bulge
- thick disk
- thin disk
M31

Sensitive image of M31 and environment

100+ sq deg
What is a Spiral Galaxy?

- stellar halo
- bulge
- thin disk
- thick disk
Looking at the gas
Neutral gas
Rotation Curves of Galaxies

![Graph showing rotation curves of various galaxies, including M31 Sb, M81 Sab, M101 Sc, and IC 342 Sc. The graph illustrates the rotational speed in km s⁻¹ as a function of radial distance from the center in kpc. The inset figure highlights the velocity and distance relationship, indicating dark matter.](image_url)
What is a Spiral Galaxy?

- bulge
- stellar halo
- dark matter halo
- thick disk
- thin disk
- + interstellar medium
Deconstructing Galaxies

Classical versus Physical Morphology

Kormendy 1979, in Photometry, Kinematics and Dynamics of Galaxies, ed. D. S. Evans (Austin: Dept. of Astronomy, Univ. of Texas at Austin), 341
Kormendy 1982, in Morphology and Dynamics of Galaxies, 12th Saas-Fee Course, ed. M. Martinet & M. Mayor (Sauverny: Geneva Observatory), 113

"We aim to identify as distinct components groups of stars or gas whose structure, dynamics, and origin can profitably be thought of as distinct from the dynamics and origin of the rest of the galaxy. Some components, such as ellipticals, bulges, and disks, form separately and are largely independent of the rest of the system. Others, such as lenses and rings, seem to form from the primary components by interactions. All components can have secondary behavior, such as spiral structure in disks.

The large number of cells in classical morphology is now thought of as the many ways that components and their secondary behavior can be combined to make a galaxy.

The strength of this approach is twofold. It breaks up the complicated problem of galaxy structure into smaller and more manageable pieces to which it is easier to attach dynamical interpretations. Secondly, investigations of correlations and interactions between components are very efficient at suggesting the presence of previously unrecognized dynamical processes.

The component approach provides an efficient framework for studies of galaxy dynamics. The ultimate goal is a classification scheme which describes not only the observed forms but also dynamical states and evolution processes."

Kormendy
Galaxy Components

Kormendy 1982, in Morphology and Dynamics of Galaxies, 12th Saas-Fee Course, ed. M. Martinet & M. Mayor (Sauverny: Geneva Observatory), 113

TABLE 1
LIST OF COMPONENTS

<table>
<thead>
<tr>
<th>Code</th>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hal</td>
<td>Dissipationless collapse of ? during early phase of galaxy formation</td>
</tr>
<tr>
<td>Elliptical</td>
<td>Dissipationless collapse + mergers</td>
</tr>
<tr>
<td>Bulge</td>
<td>(star formation mostly precedes collapse)</td>
</tr>
<tr>
<td>Thick Disk</td>
<td>Smooth progression</td>
</tr>
<tr>
<td>Thin Disk</td>
<td>Dissipational collapse (stars form after collapse)</td>
</tr>
<tr>
<td>Bar</td>
<td>Dynamical instability during collapse phase + later secular growth</td>
</tr>
<tr>
<td>Lens</td>
<td>Made from bar by destruction of resonance?</td>
</tr>
<tr>
<td>Inner Ring</td>
<td>Disk material rearranged by bar</td>
</tr>
<tr>
<td>Outer Ring</td>
<td>Disk material rearranged by bar</td>
</tr>
</tbody>
</table>

NGC 2523
NGC 1291

Kormendy
Surface Brightness Profiles
of galaxy components as a function of (R,z)

See Binney & Merrifield, section 4.4
bulges of spiral galaxies are treated similarly to ellipticals, as the surface brightness distribution typically follows an $r^{1/4}$ law (de Vaucouleurs):

$$\mu(r) = \mu_e + 8.3268 \left[ (r/r_e)^{1/4} - 1 \right]$$

mag arcsec$^{-2}$

$$I = I_e 10^{-3.33((r/r_e)^{0.25} - 1)}$$

disks of spiral galaxies are frequently modelled with an exponential decay:

$$\mu(r) = \mu_0 + 1.09 \left( \frac{r}{h_r} \right)$$

mag arcsec$^{-2}$

$$I = I_0 e^{-r/r_0}$$

$h_r$ is the characteristic scale length of a disk along its mid-plane
Sb Spiral, NGC7331

From Sparke & Gallagher
Photometric properties of NGC 7331

If a disk is circular & very thin, it will appear as an ellipse with axis ratio $\cos i$ when we view it at an angle $i$ from face-on.
In this case the diameter along the minor axis of the disk isophotes is only 0.35 that measured along the major axis, and so we can infer that the galaxy is inclined at about $75^\circ$ from face-on.
This means that the surface brightness is larger by a factor $1/\cos i$ than if we saw the disk face on. Using this we can correct to what we would observe to find the correct average surface brightness at distance $R$ from the centre.
Photometric properties of NGC 7331

Bulges
• Luminosity profiles fit $r^{1/4}$ or $r^{1/n}$ laws
• Structure appears similar to E’s, except bulges are more “flattened” (and bulges can be quite different from E’s dynamically)

Disks
• Many are well-represented by an exponential profile
  $$I(R) = I_o e^{-R/R_d}$$ (Freeman 1970)

Central surface brightness
Disk scale length

![NGC 7331](image)

R. Peletier
At the centre of NGC7331 the I band surface brightness is $I_I(0) = 15\ \text{mag arcsec}^{-2}$. Each square arcsec at the centre of the galaxy emits about 10000 times as much light as the same area at $R = 300''$; the centre is 100 times brighter than the sky, while the outer regions fade to about 1% of the sky brightness.

For historical and technical reasons usually measure the outer edge of the galaxy as the radius of the isophote $I_B = 25\ \text{mag arcsec}^{-2}$. For NGC7331, $R_{25} = 315''$. Integrating the surface brightness over the whole image and extrapolating for the parts of the galaxy too faint to measure give the **TOTAL APPARENT MAGNITUDE**.
Profile fitting: Spirals & S0s

Surface Brightness profile of Spirals and S0s galaxies can be fitted by a (de Vaucouleurs + Exponential) profile.

\[ \mu(r) = \mu_e + 8.3268 \left( \frac{r}{r_e} \right)^{1/4} - 1 \]

\[ \mu(r) = \mu_0 + 1.09 \left( \frac{r}{h_r} \right) \]

Diamonds, Triangles = observed B-band surface brightness profiles of 2 spirals
Dotted curve = Exponential fits to disk
Dashed curve = De Vaucouleurs fit to bulge
Solid curve = Exp + de Vauc fit

2-component
Surface Brightness of Disks


- almost all spirals have disk surface brightness around \( I_o \) (B-band) = 21.5 ± 0.5

- partly a selection effect since low-surface brightness (LSB) galaxies are harder to identify

- Many LSB disks identified since e.g., extreme case - Malin 1 (\( I_o = 25.5 \) and \( R_d = 55 \) kpc!)
SYSTEMATICS OF BULGE-TO-DISK RATIOS

F. SIMIEN
Observatoire de Lyon

AND

G. DE VAUCOULEURS
Department of Astronomy and McDonald Observatory, University of Texas

ASTROPHYSICAL JOURNAL, 302: 564–578, 1986 March 15

ABSTRACT

Decompositions of the blue-band luminosity profiles of 98 galaxies into spheroidal ($r^{1/4}$) and disk (exponential) components on a homogeneous system are used to study the systematics of bulge-to-disk ratios and related parameters. The mean dependences on morphological type of the fractional luminosity of the spheroid, of the effective radii and specific intensities, and of the mean absolute magnitudes of each component are established.

![Graph showing the relationship between bulge luminosity and total luminosity for different morphological types of galaxies.](image)

Fig. 2.—Fractional luminosity of spheroidal component expressed as magnitude difference ($\Delta m$) between spheroid and galaxy as a whole. Individual values vs. morphological type $T$ (stage along revised Hubble sequence). Most of the scatter ($\sigma = 0.7$ mag) is due to photometric and decomposition errors, with little contributions from classification errors or cosmic scatter.
The Milky Way
The Milky Way (optical)
The effect of dust....
Sbc-galaxy (MW) in different wavebands
Milky Way’s Components

Figure 1.1. A sketch of the structure of the Milky Way: the stellar halo, bulge, thick and thin disk are indicated together with the mean metallicity of the stars in each galactic component. The galactocentric distance of the Sun together with the dimension of the optical disk are shown on the bottom. Reproduced here by kind permission of E. Zoccali and S. Ortolani.
More Types of Galaxies from Hubble Sequence

Irregular galaxies are asymmetric & messy. They contain no bulge. They are made mostly of “Population I” (i.e., young) stars, and they contain large amounts of cool gas.

Sextans A

Kormendy
Irregular (Irr) Galaxies:

**LMC: Irr-galaxy**

- $V_{\text{hel}} = 278$ km/s (51 kpc)
- 645 x 550 arcmin
- $M=0.9$

**SMC: Irr-galaxy**

- $V_{\text{hel}} = 158$ km/s (64 kpc)
- 320 x 185 arcmin
- $M=2.7$
Dwarf galaxies

Leo I: dSph galaxy
$V_{\text{hel}} = 285$ km/s (260 kpc)
9.8 x 7.4 arcmin
$M=11.2$

NGC205: dE-galaxy
$V_{\text{hel}} = -241$ km/s (830 kpc)
21.9 x 11 arcmin
$M=8.9$
More Dwarf galaxies

I Zw 18: BCD galaxy
$V_{\text{hel}} = 751 \text{ km/s}$
$0.3 \times 0.3 \text{ arcmin}$

Leo A: dIrr-galaxy
$V_{\text{hel}} = 24 \text{ km/s (800 kpc)}$
$5.1 \times 3.1 \text{ arcmin}$
$M=12.92$
Large HI halos

Dwarf irregular NGC 2915  yellow: optical  blue: HI
Late-Type Galaxies

Hubble’s classification scheme for late-type galaxies has proved to be very successful in organising our study of these objects: bulge-to-disk ratio; tightness of spiral arms; ability to resolve arms into stars and HII regions all correlate well with Hubble type. But so do a host of other physical parameters.

**TABLE 11.1** Characteristics of Early Spiral Galaxies.

<table>
<thead>
<tr>
<th></th>
<th>Sa</th>
<th>Sb</th>
<th>Sc</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_B$</td>
<td>$-17$ to $-23$</td>
<td>$-17$ to $-23$</td>
<td>$-16$ to $-22$</td>
</tr>
<tr>
<td>$M$ ($M_\odot$)</td>
<td>$10^9$–$10^{12}$</td>
<td>$10^9$–$10^{12}$</td>
<td>$10^9$–$10^{12}$</td>
</tr>
<tr>
<td>$\langle L_{\text{bulge}}/L_{\text{total}} \rangle_B$</td>
<td>0.3</td>
<td>0.13</td>
<td>0.05</td>
</tr>
<tr>
<td>Diameter ($D_{25}$, kpc)</td>
<td>5–100</td>
<td>5–100</td>
<td>5–100</td>
</tr>
<tr>
<td>$\langle M/L_B \rangle$ ($M_\odot/L_\odot$)</td>
<td>$6.2 \pm 0.6$</td>
<td>$4.5 \pm 0.4$</td>
<td>$2.6 \pm 0.2$</td>
</tr>
<tr>
<td>$\langle V_{\text{max}} \rangle$ (km s$^{-1}$)</td>
<td>299</td>
<td>222</td>
<td>175</td>
</tr>
<tr>
<td>$V_{\text{max}}$ range (km s$^{-1}$)</td>
<td>163–367</td>
<td>144–330</td>
<td>99–304</td>
</tr>
<tr>
<td>pitch angle</td>
<td>$\sim 6^\circ$</td>
<td>$\sim 12^\circ$</td>
<td>$\sim 18^\circ$</td>
</tr>
<tr>
<td>$\langle B - V \rangle$</td>
<td>0.75</td>
<td>0.64</td>
<td>0.52</td>
</tr>
<tr>
<td>$\langle M_{\text{rot}}/M_{\text{total}} \rangle$</td>
<td>0.04</td>
<td>0.08</td>
<td>0.16</td>
</tr>
<tr>
<td>$\langle M_{\text{H} I}/M_{\text{H} I} \rangle$</td>
<td>2.2 ± 0.6 (Sab)</td>
<td>1.8 ± 0.3</td>
<td>0.73 ± 0.13</td>
</tr>
<tr>
<td>$\langle S_N \rangle$</td>
<td>1.2 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>0.5 ± 0.2</td>
</tr>
</tbody>
</table>

**e.g.**, if we compare an Sa galaxy with an Sc galaxy of comparable luminosity, the Sa will be more massive (large $M/L_B$), have a higher peak in its rotation curve ($V_{\text{max}}$) have a smaller mass fraction of gas and dust and contain a higher proportion of older, red stars.

**TABLE 11.2** Characteristics of Late Spiral and Irregular Galaxies.

<table>
<thead>
<tr>
<th></th>
<th>Sd/Sm</th>
<th>Im/Ir</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_B$</td>
<td>$-15$ to $-20$</td>
<td>$-13$ to $-18$</td>
</tr>
<tr>
<td>$M$ ($M_\odot$)</td>
<td>$10^8$–$10^{10}$</td>
<td>$10^8$–$10^{10}$</td>
</tr>
<tr>
<td>Diameter ($D_{25}$, kpc)</td>
<td>0.5–50</td>
<td>0.5–50</td>
</tr>
<tr>
<td>$\langle M/L_B \rangle$ ($M_\odot/L_\odot$)</td>
<td>$\sim 1$</td>
<td>$\sim 1$</td>
</tr>
<tr>
<td>$V_{\text{max}}$ range (km s$^{-1}$)</td>
<td>80–120</td>
<td>50–70</td>
</tr>
<tr>
<td>$\langle B - V \rangle$</td>
<td>0.47</td>
<td>0.37</td>
</tr>
<tr>
<td>$\langle M_{\text{gas}}/M_{\text{total}} \rangle$</td>
<td>0.25 (Sed)</td>
<td>0.5–0.9</td>
</tr>
<tr>
<td>$\langle M_{\text{HI}}/M_{\text{H} I} \rangle$</td>
<td>0.03–0.3</td>
<td>$\sim 0$</td>
</tr>
<tr>
<td>$\langle S_N \rangle$</td>
<td>0.5 ± 0.2</td>
<td>0.5 ± 0.2</td>
</tr>
</tbody>
</table>
fin