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:
   ⇒ 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

Galaxy Morphology

How do you quantify the properties of galaxies? and how do you put them in groups which allow you to study physically meaningful characteristics?
Elliptical Galaxies

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.

Shapes of Elliptical galaxies

It might be thought that the internal dynamics of elliptical galaxies would be relatively simple - the surface brightness distributions appear to be ellipsoidal, with a range of flattenings - due to rotation? or orientation? or something else?

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

Are Ellipticals really so smooth?

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)
Elliptical galaxies

The shapes of the massive clouds of hot gas that produce X-ray light differ from the stellar distribution that produces the optical light. A powerful source of energy must be pushing the hot gas around and stirring it up.

A correlation between the shape of the hot gas clouds and the power produced at radio wavelengths by high-energy electrons suggests this power source can be traced back to a super-massive black hole in the central regions.

Lenticular (S0) Galaxies

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

NGC 4371: S80-galaxy
$V_{hel} = 943$ km/s
4 x 2.2 arcmin
$m=11.79$

Dwarf galaxies

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

NGC205: dE-galaxy
$V_{hel} = -241$ km/s (830 kpc)
21.9 x 11 arcmin
$m=8.9$
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
- dE: lower surface brightness at same $M_B$
- dSph: extremely low luminosity and SB mostly detected in vicinity of Milky Way.

<table>
<thead>
<tr>
<th></th>
<th>cD</th>
<th>E</th>
<th>S0/SB0</th>
<th>dE</th>
<th>dSph</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_b$</td>
<td>-22 to -25</td>
<td>-15 to -23</td>
<td>-17 to -22</td>
<td>-13 to -19</td>
<td>-8 to -15</td>
</tr>
<tr>
<td>$M(M_\odot)$</td>
<td>$10^{13}$ - $10^{14}$</td>
<td>$10^8$ - $10^{13}$</td>
<td>$10^0$ - $10^2$</td>
<td>$10^7$ - $10^9$</td>
<td>$10^7$ - $10^9$</td>
</tr>
<tr>
<td>$D_{25}$ (kpc)</td>
<td>300-1000</td>
<td>1-200</td>
<td>10-100</td>
<td>1-10</td>
<td>0.1-0.5</td>
</tr>
</tbody>
</table>

Spiral Galaxies

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, $V_{hel} = -300$ km/s (750kpc), 197 x 92 arcmin, $m = 4.36$
- M 81: Sb-galaxy, $V_{hel} = -34$ 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)
26.8 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
Bulge-to-Disc Ratios

Bulge-Disc ratio (B/T) varies with Hubble type, but there is also a lot of scatter, and so B/T is NOT an accurate predictor of type.

Irregular (Irr) Galaxies:

LMC: Irr-galaxy
$V_{hel} = 278 \text{ km/s (51 kpc)}$
645 x 550 arcmin
$m=0.9$

SMC: Irr-galaxy
$V_{hel} = 158 \text{ km/s (64 kpc)}$
320 x 185 arcmin
$m=2.7$

Unusual Galaxies....

Sextans A

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.

More Dwarf galaxies

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

Leo A: dIrr-galaxy
$V_{hel} = 24 \text{ km/s (800 kpc)}$
$5.1 \times 3.1 \text{ arcmin}$
$m=12.92$
Late-Type Galaxies

Hubble's classification scheme for late-type galaxies has proved to be very successful in organizing 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>
<thead>
<tr>
<th>Type</th>
<th>Sa</th>
<th>Sb</th>
<th>Sc</th>
<th>Sd/Sm</th>
<th>Im</th>
</tr>
</thead>
<tbody>
<tr>
<td>M_B</td>
<td>-17</td>
<td>-17</td>
<td>-16</td>
<td>-15</td>
<td>-13</td>
</tr>
<tr>
<td>M(M_B)</td>
<td>10^8</td>
<td>10^9</td>
<td>10^9</td>
<td>10^8</td>
<td>10^7</td>
</tr>
<tr>
<td>D25 (kpc)</td>
<td>5-100</td>
<td>5-100</td>
<td>5-100</td>
<td>5-100</td>
<td>5-100</td>
</tr>
<tr>
<td>(L[HI]/L_B)</td>
<td>0.3</td>
<td>0.13</td>
<td>0.05</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>&lt;V_max&gt; km/s</td>
<td>299</td>
<td>222</td>
<td>175</td>
<td>80-120</td>
<td>50-70</td>
</tr>
<tr>
<td>&lt;M_HI/M_B&gt;</td>
<td>0.04</td>
<td>0.08</td>
<td>0.16</td>
<td>0.25</td>
<td>0.5-0.9</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, have a higher peak in its rotation curve (V_max) have a smaller mass fraction of gas and dust and contain a higher proportion of older, red stars.

Physical Parameters along Hubble Sequence

- The fractional mass of HI (neutral hydrogen) relative to the total galaxy mass increases as B/D decreases.
- This means the fuel for star formation increases as B/D decreases, so SFR increases as B/D decreases.
- can be seen (roughly) from colors as function of type:
  - early-types are red (~no SF)
  - late-types are blue (lots of SF)

Density-wave theory for spiral structure predicts that number of arms increases when disk mass decreases.

- Bulges are dense and concentrated, so they have rapidly rising rotation curves and significant differential rotation, so as B/D increases, arms get tightly wound
  - B/D increases, lots of tightly-wound arms
  - B/D decreases, few loosely-wound arms
Most Massive Galaxies: Early Types

- mass increases, B/D increases
- most massive galaxies, largest B/D: EARLY TYPES
  - bulges
  - rising rotation curves -> differential rotation
    - tightly-wound arms
  - low disk mass
  - large number of arms
  - low HI content
  - low SFR today

Least Massive Galaxies: Late Types

- least massive galaxies (still on Hubble Sequence): LATE TYPES
  - disks
  - linear rotation curves -> solid-body motion
    - loosely-wrapped arms
  - high disk mass
  - small number of arms
  - high HI content
  - high SFR today

Why?

Main question about Hubble Sequence:
- why does B/D increase with mass?
  - We will see later that mergers help to explain this:
    - mergers make bulges by destroying disks, and make galaxies bigger
    - therefore, mergers tend to have mass increase as B/D increases
  - but how did big spirals settle down to have big gas disks without forming stars along the way?

Active Galaxies

SAb
$V_{max} = 1663$ km/s
1.7 x 1.7 arcmin
$m = 12.35$
NGC 7742, a Seyfert galaxy
Radio Galaxies, Jets

NGC 383 (= 3C31), a radio galaxy, blue: optical, red: radio (A. Bridle)

Cen A

S0-pec

\[ V_{\text{rel}} = 547 \text{ km/s} \]

25.7 x 20 arcmin

m=7.84

Interacting and merging galaxies

Galaxies NGC 2207 and IC 2163

Collisions: Antennae

Colliding Galaxies NGC 4038 and NGC 4039

HST • WFPC2

Note that spiral disks are not optically thick!
Peculiar galaxies are important too

"Peculiar" galaxies can have:
- distortions of bulges and disks by gravitational processes
- gas and dust in systems where unexpected, often unrelaxed
- starbursts
- Nearly all due to mergers or interactions with other galaxies
- Toomre & Toomre (1972): first models of tidal encounters

Galaxies move between Hubble classes through the "peculiar" stage:
- "peculiar" galaxies are actively forming
- Hubble Sequence only fits passively evolving galaxies!

Don't Forget:
Bandpass "bias": Hubble Sequence is defined in the blue part of the optical window!