L16 – Galaxy Properties: I

Prehistory

During the 18th century, Kant suggested that fuzzy "nebulae" were disk-like systems of stars like the Milky Way. Called them "island universes."

Messier catalogued these. Some were nearby, like the Orion Nebula, some were open clusters (Pleiades), + others were the still mysterious "island universes."

Dreyer, in the 19th century, produced the New General Catalog of nebulae – 8000 objects. Again contained cloud, clusters, + "island universes."

1845 – Lord Rosse (Ireland) 1st resolved the spiral structure of some nebulae.

1912 – Slipher detected rotation (V_r) in some of these spiral nebulae.

Shapley – Curtis Debate (1920)

Shapley – Spiral nebulae are within the MW

Curtis – " " are like the MW, but outside of it.

Shapley's arguments –

① Novae observed in Andromeda (M31)

Suppose Andromeda were the same physical size as the MW, which he judged to have a diameter of 100 kpc.

Then, given its apparent size, its distance D would be so great that these novae would be far more luminous than any in the MW.

② Van Maanen had measured a proper rotation rate of M101 of 0.02"/yr.

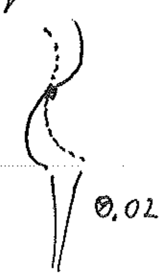
If M101 had 100 kpc diameter, then V_θ at the edge would be huge.

Detail –

The galaxy subtends 0.5° $(0.5 \times 60 \times 60'')$

So rotating half a period would require

$$\frac{0.5 \times 60 \times 60}{0.02} \simeq 10^5 \text{ yr}$$



If the physical diameter of M101 is 100 kpc, then half its circumference is $\frac{\pi D}{2} \doteq \frac{3}{2} 10^5$ kpc $= \frac{3}{2} \cdot \frac{1}{3} 10^5$ ly $= \frac{1}{2} \times 10^5$ lyr

So the outer velocity would be $\frac{\frac{1}{2} \times 10^5 \text{ ly}}{10^5 \text{ yr}} = \frac{1}{2} c$!

(3) Spiral nebula are (almost) absent in the plane of the MW.
Apparently, the MW repels them.
Proof: they are receding from us!

Curtis's reply (in part)

The radial velocities of the nebulae meant they could not possibly be gravitationally bound to the MW. If ~~then~~ their transverse motions were comparable, & they were indeed close by, it would be possible to measure proper motions — but they had none.

Dust lanes are apparent in some edge-on nebulae. A similar dust lane could explain the Zone of Avoidance in the Galactic plane.

Hubble's settling of the debate 1923 —

Detected Cepheid variables in M31. Using the P-L relationship (to be discussed), found D = 300 kpc. So nebulae are extra-galactic. (Today, D = 800 kpc).

Modern Answers to Shapley

(1) Novae in M31 are, in fact, super-novae.

(2) Van Maanen's measurement of proper rotation was wrong. True period is ~ 10^8 yr. So time for M101 to turn through 0.02" is 1000 yr!

(3) As Curtis saw, galaxies close to the MW plane are obscured by dust. They are indeed receding - Hubble's law.

Cosmic Distance Ladder (more later on Cepheids, etc)

$\lesssim 1$ AU	radar ranging	eg, distance to Venus
$\lesssim 100$ pc	stellar parallax	gives main-sequence luminosities
$\lesssim 10$ kpc	spectroscopic parallax	distances to star clusters
$\lesssim 30$ Mpc	Cepheid variables	distances to galaxies.

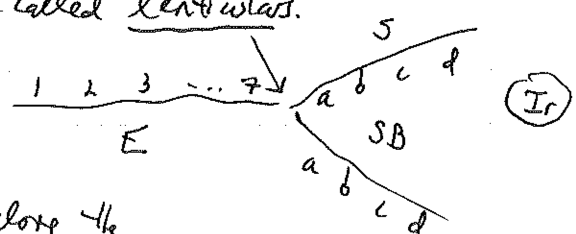
Hubble's Classification Scheme

Handout - Modern tuning fork

Two main divisions:
ellipticals (E) – footballs
spirals (S) – flat disks
Spirals are divided further into normal (S) and barred (SB).

A transitional class, S0 or SB0, are called lenticulars.

At the end is the "closet" of irregulars.



The "Hubble type" gives placement along the sequence. Those to the left (right) are "early" ("late"). Not evolutionary sequence.

Elliptical Properties and Classification

Define ellipticity $\epsilon \equiv 1 - \beta/\alpha$ $\quad$ α, β } apparent major/minor axes, projected

The Hubble type of the elliptical is then $\boxed{10\epsilon}$

In practice, ellipticals range from E0 to E7. [That is, highest observed ellipticity is $\epsilon = 0.7 \rightarrow \beta/\alpha = 0.3$].

None of this pertains to intrinsic structure. In fact, ellipticals are neither oblate nor prolate, but triaxial.

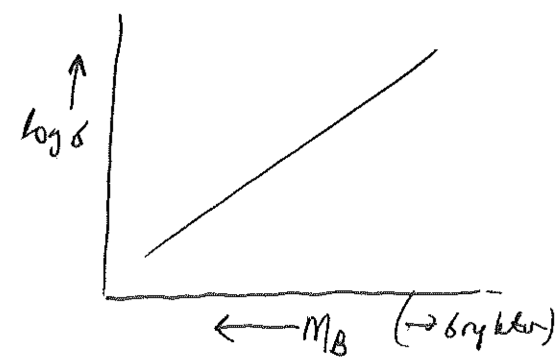
In general, ellipticals are red in color & have no or little emission lines (HII regions). They tend to be found in clusters. Have more globular clusters than spirals.

Classified more physically as:

- cD galaxies – Rare & luminous, found at the centers of rich clusters. Can have diameters of 1 Mpc! $M = 10^{13} - 10^{14}\ M_\odot$! (including DM). Bright central region and very extended envelope.
- normal ellipticals – $M = 10^{8} - 10^{13}\ M_\odot$, diameters: 1 – 100 kpc
- dwarf ellipticals – (dE) – $10^{7} - 10^{9}\ M_\odot$ " 1 – 10 kpc
- dwarf spheroidals – (dSph) – $10^{7} - 10^{8}\ M_\odot$ " 0.1 – 0.5 kpc
  Are not strongly centrally peaked in L like dE's
  Are the main type of galaxy in the Local Group.

Faber-Jackson Relation

Normal ellipticals, dE's, and dSph's all exhibit a correlation between their central radial-velocity dispersion σ_0 and M_B. The bigger the σ_0, the brighter the galaxy.
[Bulges of spirals also fall in this plot.]



A rough "proof": From virial theorem,

$$M \sim \frac{R\sigma_0^2}{G}$$

Suppose $\langle L/M \rangle$ is always the same. Then

$L \propto R\sigma_0^2$. Suppose, as is empirically true, that all galaxies have the same avg surface brightness. $L \propto R^2 \longrightarrow R \propto L^{1/2}$ Then
$L \propto L^{1/2}\sigma_0^2 \longrightarrow L^{1/2} \propto \sigma_0^2 \longrightarrow \boxed{L \propto \sigma_0^4}$, about right.

A better fit to the data comes from re-introducing the "effective radius" r_e*

$$\boxed{L \propto \sigma_0^{2.65} r_e^{0.65}}$$ fundamental plane — applies to all ellipticals

* Projected radius in which 1/2 the galaxy's light is emitted.

Spiral Properties & Classification

- All have central bulge, disk – with spiral arms, and halo (w/ g. clusters)
- All have emission lines – from HII regions
- All are blue in color, especially the arms.

Earlier ones have: biggest $\frac{L_{bulge}}{L_{disk}}$ (~0.3 for Sa or SBa)
tightest-wound spiral arms
smoothest flux distribution along arms

Later ones have: smallest $\frac{L_{bulge}}{L_{disk}}$ (~0.05 for Sc, SBc)
most open arms (pitch angle ~ 20°)
clumpy arms (from HII regions)

MW is an SBbc

Masses of spirals range from $10^9\, M_\odot$ to $10^{12}\, M_\odot$ (including DM)
Diameters 5 kpc to 100 kpc

Irregular Properties & Classification

Handout: pictures of LMC and SMC

- Some have disks, but little or no arms
- All are small
- All have emission lines (HII regions)
- All are blue in color

Ones with some spiral structure have been tacked onto the spiral sequence as Sm & Im (here, m = "Magellanic")

LMC = SBm
SMC = Im

Truly irregular remainder classed as "Ir"

Modern sequence:

E0 ... E7, S0, Sa, Sab, ... Sd, Sm, Im, Ir

(S0 through Sm: can be BARRED)