External Galaxies

In the past century anything that looked fuzzy through a telescope was called a nebula. This included gas clouds, star clusters, and galaxies. Even as late as 1930 galaxies were being referred to as external nebulae.

Catalogues of Galaxies (Nebulae)
- Messier Catalogue (M--)
- New General Catalogue (NGC----)
- Index Catalogue (IC----)

Zone of avoidance : A band centered around the plane of the Milky Way where no spiral nebulae could be seen.

Great Debate on the "Island Universe" hypothesis : Held between Curtis and Shapley on 26 April 1920 at the National Academy of Sciences, Washington D.C.

H. D. Curtis's arguments for island universes
- The average apparent brightness of novae in spiral nebulae when compared to novae in our Galaxy indicate distances 150 Kpc or more for spiral nebulae.
- At a distance of 150 Kpc the Andromeda nebula could be comparable in size to Kapetyn's estimate of the size of our Galaxy.
- Radial velocities of spiral nebulae are large; hence not bound to our Galaxy. They show no proper motion; hence must be very distant.
- A spiral when viewed edge-on shows a band of obscuring material in its disk. Can explain the "zone of avoidance" of the Milky Way.

Harlow Shapley's arguments against island universes.
- If spirals are the same size as our Galaxy 100 Kpc (according to Shapley) then a system like Andromeda would be at so large a distance that its novae would be intrinsically brighter than those in our Galaxy.
- Measurements of proper motion by A. van Maanen indicated spirals rotate with an angular velocity of 0.02" per year. If they are separate galaxies the actual velocities implied by van Maanen's proper motions would be ridculously large.

Between 1923-24 Edwin Hubble measured the distance to M31 using Cepheid variables and confirmed that it was an external nebulae.

<u>Hubble's Classification of Galaxies</u>
3 classes : E (ellipticals), S (spirals), and I (irregulars)

Ellipticals : no nucleus, structureless, indefinite boundaries

Shape index : $n = 10\,(1 - b/a)$

E0 , $n = 0 \Rightarrow a = b$

E7, $n = 7 \Rightarrow a = (10/3)\, b$

Spirals : "normal" - S; "barred" - SB.

3 divisions : a, b, c

"early type" a $\rightarrow$ b $\rightarrow$ c "late type"

	early (a)	late (c)
arms	tight	loose
bulge	brightest	faintest
resolution	less	more

Irregulars :

Irr, type I : Magellanic type (faint hint of a bar and spiral arms, e.g. LMC)

Irr, type II : little rotational symmetry, chaotic (M82)

1936 Hubble introduced the type S0 (armles spiral).
1938-41 Shapley introduced a type more chaotic than Sc which he designated Sd. He also introduced a new class of ellipticals called dwarf ellipticals dE.

<u>Revised Hubble's Classification</u>

4 classes : **E** (ellipticals), **L** (lenticulars or S0), **S** (ordinary and barred spirals SA and SB), and **I** (irregulars)

Ellipticals : E^- : compact, dwarf ellipticals
E : ordinary ellipticals
E^+ : supergiant ellipticals (cD)

3 stages for lenticulars : L^-, L^0, L^+

5 main stages for spirals	a	b	c	d	m
Intermediate stages	ab	bc	cd	dm	

Transition between L^+ and Sa is S0/a

2 types of irregular galaxies : Im and I0

Associated with each type is a number

Type	T	Type	T	Type	T
E^-	-6	S0/a	0	Scd	6
E	-5	Sa	1	Sd	7
E^+	-4	Sab	2	Sdm	8
L^-	-3	Sb	3	Sm	9
L^0	-2	Sbc	4	Im	10
L^+	-1	Sc	5		

Luminosity classes (for spirals)
Brightest luminosity (I) : longest, most-highly developed arms
Faintest luminosity (V) : short, filamentary arms
Luminosity Class L : I to V
Intermediate class : I-II, II-III, etc.
Associated with each luminosity class is a number

Luminosity Class	L	Luminosity Class	L
I	1	III-IV	6
I-II	2	IV	7
II	3	IV-V	8
II-III	4	V	9
III	5		

<u>Distance Determination</u>

Working Hypothesis : Principle of the Uniformity of Nature : Laws of Physics that hold good in our local neighborhood hold good throughout the universe. Similar objects have similar properties.

A distance indicator or standard candle is an object that has a small dispersion in its absolute luminosity. If a global property of a galaxy is used as a distance indicator then that property has a small dispersion.

Primary distance indicators : objects measuarable in nearest galaxies but have been calibrated in our Galaxy by fundamental methods. Good to distances less than 1 Mpc.
i) Novae, ii) Cepheids, iii) RR Lyrae, iv) Supergiants type A and B, v) Eclipsing binaries.

Secondary distance indicators : objects that can be distinguished in galaxies beyond 1 Mpc. They have been calibrated in nearby galaxies whose distances have been measured from primary distance indicators. Good upto 10 Mpc.
i) Globular clusters, ii) Brightest blue supergiants, iii) Brightest red variables, iv) Brightest blue variables, v) Diameters of HII regions.

Tertiary distance indicators : are the global properties of galaxies. These distance indicators are calibrated in galaxies whose distances have been obtained by primary and/or secondary indicators. Good upto 100 Mpc.
i) Luminosity index $\Lambda = (T + L) / 10$, used with the total brightness of the galaxy B_T.
ii) Log V_m where V_m is the maximum rotation velocity obtained from the width of HI lines. Used with the total brightness B_T to obtain distance (Tully-Fisher relation).
iii) Brightest superassociations

For distances beyond 100 Mpc use - i) Supernovae, ii) Redshift

Mass Determination

- Find stars very distant from center. Obtain rotational velocity v_r. Obtain distance from center, R. The mass m is

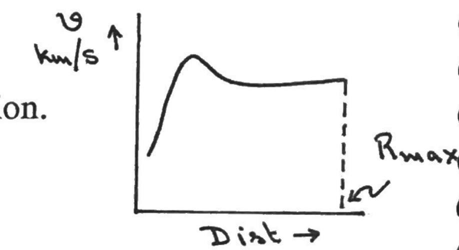
$$m = (v_r^2 \times R) / G$$

where G is the universal gravitation constant

Problems : i) Hard to isolate individual stars
ii) Need to know distance and orientation

- Mass of spiral galaxies (that have lots of H gas)
Determine the rotation curve using 21-cm HI line emission.

$$m_{tot} \propto (v_{max}^2 \times r_{max}) / G$$



- Mass of elliptical galaxies
Use velocity dispersion (σ) → greater the mass → greater the motion of stars and gas → greater the velocity dispersion

$$m \propto (\sigma^2 \times R) / G$$

Comparison of Elliptical and Spiral Galaxies

Ellipticals	**Spirals**
1)Large range in size (dE to cD)	1) Smaller range in size (10 to 100 Kpc)
2) Large range in mass and luminosity (10^6 to 10^{12} $M_\odot$)	2) Smaller range in mass and luminosity (10^{10} to 10^{12} $L_\odot$)
3) Higher mass-to-light ratio (M/L)	3) Lower mass-to-light ratio (M/L)
4) Less gas and dust	4) More gas and dust
5) Redder (more PopII)	5) Bluer (More PopI)

- Difference in structure not due to age but due to differences in the initial star formation rate and rotation.
Elliptical galaxies - high initial star formation + low rotation
Spiral galaxies - low initial star formation + high rotation

Local Group

This is a loose group with no central condensation. It is roughly disk like : $2 \times 1.9 \times 1$ Mpc^3. It contains :
2 Giant Spirals : M31, Galaxy (MW)
1 Average Spiral : M33
1 Average Im : LMC
> 8 Dwarf Im : SMC, NGC6822, IC10, IC1613, WLM
> 12 Dwarf E : NGC147, NGC185, NGC205, NGC221(M32)
Additional members maybe hidden in the zone of avoidance by the interstellar extinction.

- LMC and SMC satellite galaxies of MW. Distances of 52 and 63 Kpc respectively. Irregular galaxies with incipient bar, lots of gas and dust - active star formation.
Enormous HII region in LMC- 30 Doradus or Tarantula Nebula
Magellanic Stream - a bridge of H connecting LMC, SMC, and MW.

- Andromeda Galaxy (M31) - spiral galaxy at a distance of 670 Kpc. Diameter at least 40 Kpc.
Stellar populations first discovered in M31 : PopI in the disk and PopII in the bulge.
Mass at least 3×10^{11} $M_\odot$
Nucleus elliptical in shape 3.2 x 5 pc containing 3×10^6 stars total mass in nucleus is $10^8 M_\odot$

Groups of Galaxies

Most galaxies are members of groups rather than isolated or "field" galaxies.

Average diameters of groups or clusters ~ 2 Mpc

Average separation between cluster centers ~ 7 Mpc

Nomenclature

Group : < 100 galaxies, no marked concentration

Cluster : 100 to 1000 galaxies, marked concentration

Close encounters between galaxies more frequent than encounters between stars. Such encounters produce a smooth distribution of galaxies with the heaviest galaxies near the center - cD or S0's.

In galaxy collisions

- stars remain unaffected
- gas clouds collide
  - produce intense radio emission
  - tidally affect their shapes
  - induce "starbursts" or star formation
- galactic cannibalism - merging of two galaxies to form a giant elliptical galaxy (cD).

Superclusters : Second order clustering - cluster of clusters of galaxies

e.g. Local Supercluster : Virgo cluster, Local Group, etc.

Size ~ 30 Mpc; Shape ~ Disk-like; Mass ~ 10^{15} $M_\odot$.

Origin of Clusters : Which came first galaxies or superclusters?

- Isothermal Model : Galaxies formed first, then clusters, and superclusters.

Problem : Not enough time to form superclusters

- Adiabatic Model : superclusters formed first, which fragmented to clusters and then galaxies

Problem : Galaxies would have formed in the too recent past.

Universal Expansion

1912 - V. M. Slipher found that most galaxies were moving away from the solar system.

1924-1929 : Hubble obtained distances to nearby galaxies. Discovered recession velocity $\propto$ distance. Hubble's law : $v = H \times d$ where H = Hubble's constant = 50 to 100 km/s/Mpc

Expansion uniform in all directions (isotropic) and linear. No center for the expansion.

- Measurement of distances of galaxies

1) Measure redshift $z = \Delta\lambda / \lambda = (\lambda_{obs} - \lambda_{emit}) / \lambda_{emit}$

2) Calculate radial velocity vr

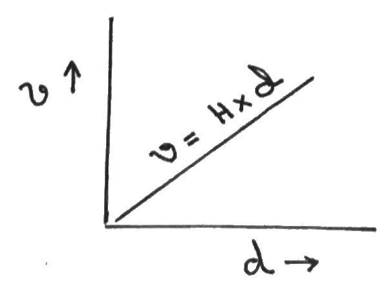
If $z << 1$ then $v_r / c = z$ [non-relativistic doppler formula]

If z is close to 1 or greater use relativistic doppler formula

$$z = \sqrt{\frac{1 + v_r/c}{1 - v_r/c}} - 1$$

$$v_r / c = \frac{(1+z)^2 - 1}{(1+z)^2 + 1}$$

3) Use Hubble's law to obtain distance $d = v_r / H$



- Universal expansion implies an origin in time
  - Time = distance / velocity
  - Age of the universe = d / v = d / (H x d) = 1 / H
  - If H = 100 km/s/Mpc   Age = 10 billion years
  - If H = 50 km/s/Mpc   Age = 20 billion years

- Universal expansion implies an inital explosion
  - Big Bang Hypothesis
  - Expansion began ~ 15 billion years ago

Big Bang Model

- The expansion began approximately 15 billion years ago. 10^{-43} to 10^{-35} seconds after the explosion there was rapid expansion (inflation). The volume of the universe increased by 10^{25} times.
- The universe was filled with hot radiation billions of °k mostly in the form of γ-ray photons.
- Matter formed from the radiation.
- As the universe expanded the γ-ray radiation cooled to x-ray that further cooled to ultraviolet.
- During the first 10^6 years radiation was constantly absorbed and re-emitted by the matter present. Most of the hydrogen was ionized and the universe was opaque to radiation.
- When the temperature dropped to 3000°k the protons and electrons combined to form hydrogen atoms. There was little interaction of radiation with matter. This phase of the universe is called the epoch of decoupling. The universe became transparent after that.
- As the universe continued to expand the radiation cooled to the present day temperature of 2.7°k.

- This cosmic background radiation was discovered by Arno Penzias and Robert Wilson (1965).
- The radiation is thermal. [The radiation can be characterized by a blackbody curve. Applying Wien's Law to this background radiation the λ_{max} is found to be 1.1 mm which is in the microwave part of the spectrum.] The radiation is also isotropic which means it has the same intensity no matter which direction you look.
- There is a small anisotropy due to the earth's motion. This enables one to obtain the velocity of the sun w.r.t. the microwave background radiation which is 400 km/s.