1B23
Modern Physics, Astronomy, and Cosmology

Partial Notes, Astronomy Set 2 – Galaxies

Normal Galaxies

Galaxies were first systematically categorized by Edwin Hubble who in 1929 classified them according to shape: the **Hubble Classification Scheme** or **Tuning Fork Diagram**

Elliptical galaxies ('Early type')
E0 – E7 (0 spherical, 7 most distorted):

S0 These galaxies are intermediate between E0 and Sa – they have disks but no spiral structure.

Spiral galaxies ('Late type')
Classified Sa – Sc; the subclass refers to how tightly wound arms are and size of nucleus

- Sa – large nucleus, tightly wound arms
- Sc – small nucleus, open spiral arms

Also have *barred* spiral galaxies, SBa – SBc (though bars are normal!)

Irregular galaxies
IrI and IrII – disorganised

Note that more detailed schemes have since been developed, but the basic Hubble classification remains widely used.

Properties

Ellipticals contain old stars (Pop. II) and have very little interstellar material.

Spirals contain young and old stars (Pop I and II) and have large amounts of interstellar material.

It is thought that ellipticals formed most of their of stars early on, using up all their interstellar gas, and so did not collapse to form a disk.

Star formation proceeded more slowly in spirals, allowing the huge rotating proto-galaxy cloud to collapse to form a disk, before the bulk of stars was formed.

HST observations (Deep Field etc.) indicate that lots of star-forming, irregular galaxies were present when universe was very young. The suggestion is that modern-day galaxies were built up by mergers.

	Ellipticals	Spirals
Luminosity ($L_\odot$)	$10^5 - 10^{11}$	$10^8 - 10^{11}$
Diameter (kpc)	3–100	5–50
Visible Mass ($M_\odot$)	$10^5 - 10^{13}$	$10^9 - 5 \times 10^{11}$

The Milky Way Galaxy

Our own Galaxy is a spiral galaxy and consists of following principal components:

Disk:
50 kpc in diameter with a thickness of 1 kpc. The sun is located in disk, 8.5 kpc from Galactic centre. The disk contains young stars (i.e. those with composition of 2% elements heavier than H, He = Population I stars) in spiral arms.

Bulge:
Contains old stars (composition of 0.1% elements heavier than H, He = Population II).

Halo:
has a diameter of $\sim$ 100 kpc and contains globular clusters . These are spherical clusters with diameters 10–20 pc containing about 10^5 old Population II stars. They are the oldest systems in the Galaxy with ages 13–15 $\times 10^9$ yr.

The Galactic Nucleus:
Obscured visible at optical wavelengths, but visible in the IR. The dynamics of stars in the central region indicates a supermassive black hole (M $> 10^6$ $M_\odot$).

Galactic Dynamics

The sun has a rotation velocity V of 270 km/s and a rotation period P of 2.4×10^8 yr.

To measure the mass of a galaxy, we can use the form of Kepler's 3rd law (for circular orbits), $V_{\rm rot}^2 = GM/R$ to determine the mass (M) inside a star at orbital radius (R), given a rotation velocity ($V_{\rm rot}$). (M as $\sim 10^{11}$ $M_\odot$ for our Galaxy.)
Plotting V against R gives the **rotation curve** of the Galaxy.

Our own galaxy, in common with other spiral galaxies, is observed to have a flat rotation curve – indicating large amounts of dark matter.

Active Galaxies

Normal galaxies emit thermal radiation and their optical spectra consist of absorption lines arising from their constituent stars.

Active galaxies have the following general properties:

(1) Much higher energy output $> 10^{37}$ W (Milky Way nucleus emits 10^{35} W) enabling them to be seen at much larger distances.

(2) Non-thermal (synchrotron) emission with excess energy at UV, IR, radio and X-ray wavelengths.

(3) Variability over time-scales from few hours to few years – indicates emitting region is few light years across.

(4) Often have jets emerging from nucleus.

(5) Have emission line spectra.

Examples are Radio Galaxies, Seyfert Galaxies and Quasars.

Seyfert Galaxies

These are spiral galaxies which show evidence for violent activity in their nuclei and are generally classed as
Active Galactic Nuclei (AGN).

Discovered in the 1940s by Carl Seyfert and appear as normal spirals but with very bright nuclei and emit strong non-thermal spectrum.

The visible spectrum contains broad (5 000–10 000 km/s) emission lines indicating clouds of gas moving at very high speeds in the nucleus of the galaxy.

1% of spiral galaxies are Seyfert galaxies.

The light output and spectrum are highly variable on short time-scales of days to months → activity is confined to a small region at most a few light-months in diameter.

Quasars

In 1960 optical spectra of two faint stellar-like objects were obtained which were sources of radio emission – called
3C 48 and 3C 273.

Spectra showed strong emission lines which were finally interpreted in 1963 as the Balmer series of hydrogen redshifted by an unprecedented amount of 100 nm for 3C 273 ($z = 0.16$).

Well over 1000 Quasars (Quasi-stellar radio sources) have now been identified. It is generally accepted that their enormous redshifts are due to the expansion of the Universe.

They are the most distant known objects that we can observe and they allow us to probe the early Universe. The highest redshift quasars known (to-date) have $z = 6.0$ to 6.4

To determine their distances and recession velocities, we need to use the relativistic redshift formula since the classical formula of $v = cz$ gives a recession velocity $> c$ if $z > 1$:

$$d = \frac{cz(1 + z/2)}{H(1 + z)^2}$$

and

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

and

$$v = c\left[\frac{(z + 1)^2 - 1}{(z + 1)^2 + 1}\right]$$

Thus for a $z = 4.0$ quasar, the Lyman-α line of hydrogen will be redshifted from 121.5 nm to 607.5 nm; its recession velocity is $0.923c$ and its distance is 2 880 Mpc (H=50 km/s Mpc^{-1}).

Quasars are variable on time-scales of days to months which indicates that they are very small (< 1 light month or $< 10^{15}$ m).

Their enormous distances indicate that their luminosities are 1000 times that of a normal galaxy or $\sim 10^{12}$ $L_\odot$.

Energy problem – how can so much energy be generated from such a small object?

Super-massive black hole of 10^8 $M_\odot$ has a Schwarzschild radius of 3×10^8 km so size is not a problem.

Energy is converted from gravitational to radiative energy as material spirals in an
accretion disk
around a black hole.

Luminosities of 10^{12} $L_\odot$ (= bright quasar) are possible with an inflow of roughly 1 $M_\odot$/yr.

Radio Galaxies

Elliptical galaxies with very strong radio emission originating from giant lobes either side of the optical galaxy.

Cygnus A is one of the strongest radio sources known with an output of 10^{38} W (distance = 200 Mpc).

Diameter of its lobes = 17 kpc and distance from the nucleus = 50 kpc.

Lobes emit synchrotron radiation i.e. they are clouds of relativistic electrons.

What is the source of the relativistic electrons?

Clue: most radio galaxies show jets connecting the optical galaxy to radio lobes.

Implies source is in the nucleus of the optical galaxy.

The Distribution of Galaxies

Galaxies are not uniformly distributed but are concentrated into
clusters
which in turn form
superclusters.

The Milky Way Galaxy belongs to the
Local Group
which consists of at least 20 galaxies and is about 1 Mpc in size.

Our Galaxy and the Andromeda Galaxy (M31; dist=700 kpc) dominate; the other members are mostly dwarf ellipticals.

Clusters of Galaxies

Contain from 10 – 1000s of galaxies, and are gravitationally bound systems.

Spacing of galaxies is realtively close, ≈ 100 times diameter of galaxy. (For comparison, in our Galaxy the spacing of stars $\approx 10^6$ diameter of a typical star.)

Rich clusters (> 100 members) contain mostly elliptical galaxies and usually have a giant elliptical galaxy (called a cD galaxy) at centre in the gravitational well.

It is thought that the large number of ellipticals is due to galaxy mergers and the cD galaxy originates by devouring other galaxies. Evidence for this is that some cD galaxies have double nuclei and extensive visible halos (up to 1 Mpc in diameter). Diameter of cD galaxy ≈ 200 kpc.

Example of a rich cluster – Coma Cluster with diameter of 7 Mpc and contains thousands of galaxies.

Virgo cluster is a nearby cluster at a distance of 15.7 Mpc and has a diameter of 3 Mpc and covers 7° on sky.

Masses of Clusters

Masses of clusters can be measured from the dynamics of the constituent galaxies; by gravitational lensing; and by X-ray observations.

All three methods indicates masses $\sim 10\times$ the visible mass $\Rightarrow$ dark matter.

Superclusters

Over the last 10–15 years, the 3D structure of the local Universe has been mapped by measuring redshifts of clusters.

It is found that clusters of galaxies are grouped into chains or **superclusters** with large voids in between. The Universe therefore has a cell-like structure.

The superclusters are hundreds of Mpc long. Our Local Supercluster is mostly empty space with the galaxies occupying 5% of the volume.

Hubble's Law

Hubble (1929) discovered that the recession velocity v of a galaxy is proportional to its distance d:

$$v \propto d$$

where

$$v = \frac{(\lambda - \lambda_0)}{\lambda_0} c$$

λ is the measured wavelength of a spectral line and λ_0 is the theoretical wavelength.

Define **redshift** z as

$$z = \frac{(\lambda - \lambda_0)}{\lambda_0}$$

then

$$v = cz = Hd \qquad d \text{ in Mpc; } v \text{ in km/s}$$

where H_0 is Hubble's constant (constant in space, but not in time!). Because of the difficulty in determining distances to galaxies, H is today thought to lie between 70–75 km/s/Mpc.