GALAXIES

Galaxy

Collection of stars in orbit. Each star is held within the galaxy by the combined force of all the other stars. A galaxy can contain anywhere from 10^8 to greater than 10^{12} stars.

Their properties vary greatly in terms of their total mass, their total luminosity, the amount of gas and dust present, their age and chemical composition, their stellar population, their large-scale shape and symmetry, and their rotation.

Classification of Galaxies

Based on the galaxy's appearance ---- classification scheme introduced by Hubble in 1925.

4 principal types:

Elliptical

S0 (pronounced S-zero)

Spiral

Irregular.

NB Hubble's classification scheme for galaxies is normally represented in terms of the so-called `tuning-fork diagram.' **This is not an evolution diagram**.

Rotation:

Used to indicate whether the stars orbit the center of the galaxy in a coherent manner.

eg:

The stars in the disk of the Milky Way stay in the disk as they orbit the center of our galaxy. All the disk stars rotate in the same direction and in the same plane. The rotation rate can be used to estimate the mass of the galaxy.

In elliptical galaxies the individual stellar orbits are randomly orientated so that at any point in the galaxy there is a significant range of velocities. In this case the amount of random motion (velocity dispersion) gives an indication of the galaxy's mass.

Mass to Light Ratio

Defined as the ratio of the mass of an object (in solar masses) to its luminosity (in solar luminosities).

The Sun has a mass to light ratio of 1.

Massive stars have a mass to light ratio **less than** 1

Low mass stars on the main sequence, white dwarfs, neutron stars etc have mass to light ratios **greater than** 1.

The mass to light ratio gives a crude indication of the amount of recent star formation, and of the importance of dark matter.

Types of Galaxies

1. Elliptical Galaxies.

Mass: 10^6 M_{sun} to 10^{13} M_{sun}

Shape: Elongated (elliptical), or Spherical

Stellar Population: Old (no young stars)

Gas and dust: Little, if any.

Rotation: They rotate very slowly or not at all.

Mass to light ratio: 100

Notes:

Giant Ellipticals are very rare, often reside in the center of a cluster of galaxies, and have a diameter comparable to the Milky Way (10^5 parsecs).

Dwarf Ellipticals are much more common, and may be only 2000 parsecs across.

2. S0 Galaxies.

Mass: 10^9 M_{sun} to 10^{11} M_{sun}

Shape: Prominent bulge with disk. Little evidence for spiral structure.

Stellar Population: predominantly old stars.

Gas and dust:: Very little gas and dust

Notes:

S0 galaxies have some of the properties of spirals, and some of the properties of ellipticals.

3. Spiral Galaxies.

Mass: 10^9 M_{sun} to 10^{12} M_{sun}

Shape: Disk like, with a central bulge, They also have an outer (but faint, and hence difficult to detect) spherical halo.

Stellar Population: Mixed. Both old and young stars.

Gas and dust: Gas and dust present in varying amounts.

Rotation: Fast rotators

Mass to light ratio: 2-20

Notes:

Andromeda and the Milky Way Galaxy are spiral galaxies.

The amount of gas and dust is one of the criteria for sub-classifying spiral galaxies.

Some spiral galaxies exhibit a bar-like structure across their disks (barred spirals), while others don't (normal spirals).

4. Irregular Galaxies.

Mass: 10^8 M_{sun} to 10^{11} M_{sun}

Shape: Irregular

Stellar Population: Young and old stars

Gas and dust:: Large amounts of gas, and sometimes dust.

Mass to light ratio: 1

Notes:

The Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC), two satellite galaxies of our own galaxy, are (dwarf) irregulars.

LMC's mass is about 10^{10} M_{sun}.

SMC's mass is about 10^9 M_{sun}.

Irregular galaxies exhibit various degrees of star formation.

Peculiar Galaxies

About 10% of the external galaxies cannot be classified according to these normal types, and are called peculiars.

Some peculiar galaxies look as if explosions occurred in them, but that is probably not what happened.

Some peculiar galaxies have rings of stars and gas and dust encircling them in unusual directions.

Peculiar galaxies may be the result of collisions or mergers between galaxies.

Galaxy Formation

Subject of intense debate but obviously GRAVITY plays a major role in leading to the collapse of gas into a galaxy full of stars.

Possible Galaxy Formation Scenarios:

1. Large masses may naturally undergo gravitational instabilities and collapse to form clusters of galaxies, voids, and individual galaxies.
2. Supernovae of extremely massive objects might cause gas to be swept up, triggering the gravitational collapse of the gas cloud.
3. Ellipticals contain only Pop. II stars. Such a system may have undergone only one major, but very efficient, star formation episode. Spiral galaxies, on the other hand, may undergo more one than stage of star formation (e.g. Pop. I and Pop. II in Milky Way).
4. Small galaxies might form first. Larger galaxies may then form through mergers. Studies have shown that colliding spiral galaxies may merge to become ellipticals. During such a merger, gas and dust are converted to stars rapidly (so after a time there are no young stars) and the rotational motion of the spirals is dissipated. Models of interacting galaxies (based on the theory of gravity) show that some of the structures seen in external galaxies are explainable in terms of an interaction.

Clusters of Galaxies

The Milky Way Galaxy belongs to a group of about 30 galaxies known as the Local Group. The size of the Local Group is about 3 million light years.

The Local Group is a member of the Local Supercluster of galaxies which is about 100 million light years across. The Local Supercluster contains many groups and clusters of galaxies.

Clusters of galaxies are larger than groups of galaxies. Typically they have 100's to 1000's of members.

Clusters and superclusters are arranged in flattened or filamentary-like large-scale structures. In between the clusters are **voids** where very few galaxies are found. The large-scale structure of the voids is bubble-like, and the clusters and superclusters form the boundaries (surfaces) of the voids. **The large-scale structure was unexpected, and is one of the most important discoveries of the last decade.**

From the motions of the individual galaxies in a cluster, the mass of the cluster can be determined. These studies indicate that as much as 95% of the mass of the Universe is non-luminous (ie dark) matter. We do not know what the dark matter is made of.

Types of Clusters

1. **Poor Clusters**.

   Irregularly shaped and contain a mix of all galaxy types (spirals, ellipticals, etc.).

   e.g. Local group

2. **Rich Clusters.**

   Spherically shaped, with most massive members near the center.

   They contain mainly ellipticals. and S0's. Spiral galaxies are rare in the inner region of the cluster.

   Mergers and interactions in regular clusters are common. This probably explains why they don't contain spirals.

   Rich clusters of galaxies often contain a large amount of hot ionized gas that emits x-rays. The mass of the hot gas may exceed the total mass of the individual galaxies which make up the cluster.

The Expansion of the Universe

When we look at the spectra of distant galaxies (ie those not in the local group) features (eg absorption and emission lines) are seen to occur at larger wavelengths than we expect based on laboratory measurements.

Since the features occur at larger wavelengths, we say that the spectra are **REDSHIFTED**. We can interpret this redshift as a Doppler shift. Since the spectra are redshifted, distant galaxies are moving away from us.

By measuring the (relative) change in wavelength of a feature, we can determine the velocity with which an object is moving away from us. For a given object, the deduced velocity is the same no matter what spectral region is used (eg radio, optical, x-ray etc).

More distant galaxies have the highest velocities. Imperically we find the distance of the galaxy (d) and its recessional velocity (v) are linearly related.

$$v = \text{constant} \times d$$

This is **Hubble's law.**

Notes:

The redshift of the galaxies is caused by the expansion of the Universe. An expanding Universe means that the volume or size of the Universe is increasing with time.

Strictly speaking the REDSHIFT is not due to the motion of the galaxies. Rather it is caused by the expansion of the universe. *As light traverses space the universe grows, stretching the light out and hence INCREASING its wavelength.*

Space is growing at a rate such that two points separated by one million light years are, on average, becoming 20 km (12 miles) further apart each second. Alternatively, two points in space separated by 1 km (0.6 miles) are, on average, becoming further apart by the thickness of a piece of notebook paper every 1,500 years.

The fact that all galaxies appear to be moving away does not imply that our Galaxy is in a privileged position. We would see the same effect no matter where we were in our universe. (Balloon experiment)

The galaxies (and dense clusters) do not partake in the expansion. The galaxies are controlled by their own gravitational field. *Rather it is the space between the clusters of galaxies that is increasing*.

The Andromeda galaxy has a blue shift (features shifted to shorter wavelengths). The Andromeda galaxy is part of the local group. The local group does not partake in the expansion of universe.

Hubble's Law

Hubble's law states that the recessional velocity (v) is related to the distance (d) by

$$v = H d$$

where H is a constant called **Hubble's constant**. Thus if we know H we can determine the distance to any (non local group) galaxy (since **d=v/H**).

The measurement of Hubble's constant is currently a major goal of observational astronomy. The best estimate for the Hubble constant is either

50 km/s/Mpc

or

100 km/s/Mpc

(km/s/Mpc = kilometers per second per mega [million] parsecs)

Problem.

Assume a galaxy has a redshift of 5000 km/s and H=100 km/s/Mpc. What is its distance?

Use Hubble's law

d = v / H

= (5000 km/s) / (100 km/s/Mpc)

= 50 Mpc = 50 x10^6 parsecs = 160 x 10^6 light years

NB. H has units of time^{-1} ! 1/H gives an estimate for the age of the Universe.

Measurement of Hubble's Constant

To determine Hubble's constant we need to determine the distance to galaxies by some method other than Hubble's law.

Virtually all methods rely on bootstrapping. eg.

1. Radar is used to determine the distance of the Earth from the Sun
2. Trigonometric parallax is used to determine the distance to nearby stars. To do this we need the Earth - Sun distance.
3. For more distant stars we can use spectroscopic parallax. The spectroscopic parallax method has to be calibrated, however, using trigonometric parallax.
4. We can use Cepheids (ie a standard candle) to determine the distance to nearby galaxies. The use of Cepheids again relies on distance determinations made using trigonometric parallaxes.
5. Using nearby galaxies we can calibrate other standard candles (eg the brightest planetary nebulae, the maximum brightness obtained by a type 1 supernova) to determine the distance to more distant galaxies.

Given the uncertainties that can accumulate at each step, it is easy to see why the Hubble constant is uncertain to a factor of 2.

(A few methods don't rely on the bootstrapping technique, but have other uncertainties, and often can only be applied to a few galaxies.)

“Look Back Time”

Since the speed of light is finite (300,000 km per second or 186,000 miles per second), astronomers see distant objects as they appeared in the past. The higher the redshift of an object, the further we see back into the past.

The value of studying objects at different redshift is to probe changes in the Universe over time (e.g. galaxy formation, evolution of the Universe). High redshift objects allow us to probe what the Universe was like when it was less than about 10% of its current age.

Objects at the highest redshifts are often said to be at the “edge of the known Universe.“ However, this is a very simplistic statement given our knowledge of cosmology (the Universe has no center).

Active Galaxies

When energetic activity such as strong radio, optical or x-ray emission is associated with a galaxy (or a small region in a galaxy) that object is called an active galaxy.

As we look back into time to larger and larger redshifts (e.g., when the Universe was 50% of its current age), energetic activity associated with galaxies was much more frequent than it is now.

Activity in galaxies may be caused by collisions between them (mergers) or large amounts of matter falling into massive black holes in the galaxy’s center.

There are 3 overlapping Classes.

Radio Galaxies

Seyfert galaxies

Quasers

Radio Galaxies

Emit large amounts of non-thermal radio energy.

Generally associated with Elliptical galaxies.

May show single, or nearly symmetrical radio lobes. These lobes may span hundreds of millions of light years (i.e. greater than 1,000 times diameter of Milky Way).

Energy produced by electrons spiralling along magnetic field lines.

Seyfert Galaxies

A spiral galaxy whose nucleus is abnormally luminous.

A Seyfert may emit the luminosity of the entire Milky Way galaxy, but from a region much less than a light year across.

The brightness of the nucleus can fluctuate on timescales of minutes.

Seyfert galaxies, unlike normal spirals, show an intense emission line spectrum superimposed on the normal galaxy spectrum.

The line spectrum provides direct evidence for gas motions in excess of 10,000 km/s.

QUASARS

Extremely luminous and extremely active distant galaxies.

Show a strong emission line spectrum --- Allows us to deduce that they are ejecting hot gas from their centers.

They are **high redshift objects** that appear as ***unresolved*** points of light. This gives their name --- QSOs or quasi-stellar objects. Recent photos show that they often lie in what appear to be galaxies.

Quasars are very luminous (typically 1000 times brighter than the Milky Way), and hence can be seen at very large redshifts. With modern detectors and telescopes, quasars can be used to probe the Universe back to a time when it was only 1 or 2 billion years old (about 10% of its current age).

Quasers are believed to be at cosmological distances (i.e. at the distance implied by using their redshift and Hubble's law).

NB.

Distant (large) galaxies can usually be resolved with large telescopes, even though the resolution of an optical telescope is limited by seeing. Initially no galaxies were observed to be associated with a quaser. The surrounding galaxy is extremely difficult to detect because of the glare of the bright quaser.

Quasar Redshifts

The redshift, usually designated by the letter z, is calculated by dividing the shift in wavelength of some emission or absorption line ($\lambda - \lambda_o$) by its true (rest, or laboratory) wavelength (λ_o).

$$z = (\lambda - \lambda_o) / \lambda_o$$

By using the Special Theory of Relativity, the redshift can be used to calculate the speed (v) at which a quasar appears to be moving away from an observer. For small redshifts (ie z much less than 1)

$$z = v / c$$

(where c is the speed of light).

z is a directly measurable quantity, and is usually quoted by Astronomers when discussing very distant objects.

Z can be converted to a "distance" and hence "look back time". This conversion is usually done for the popular press, but has less use for astronomers since **the conversion depends on the adopted cosmological model.**

The redshifts of some quasars are very high, corresponding to velocities of approximately 90% the speed of light. This implies that some quasars are as far away as 15 billion light years (exact number depends on cosmological model).

The Discovery of Quasars

Quasars were discovered in 1963. Cyril Hazard (now a Mellon Professor at the University of Pittsburgh) was trying to identify the exact location in the sky of a bright radio source. Since single-dish radio telescopes have poor resolution, he recorded the exact time when the radio source was covered by the nearby Moon. By doing this he was able to determine the position of a point-like (star-like) bright object which emitted the strong radio waves. The object is called 3C273. Martin Schmidt (at Caltech) took a spectrum of 3C273 and discovered its high redshift.

Processes in Quasars

Extremely energetic processes may be seen in quasars at all wavelengths.

Strong x-ray, ultraviolet, optical, infrared and radio continua may be generated by accretion disks and synchrotron emission (rapidly moving electrons in a magnetic field)

Broad emission lines and absorption lines arise due to mass motions near or exceeding one-tenth the speed of light.

Jets and apparent superluminal velocities (seen with VLBI) indicate mass ejections near the speed of light.

Observations of quasers show that some quasers can double their luminosity on the time scale of a day. When combined with their cosmological distance, this means that quasers are capable of generating as much energy as 1000 Milky Way Galaxies in a volume not much bigger than the size of the Solar System!

The Basic Model

Basic model for active galaxies is a massive (10^6 to 10^9 M_{sun}) **black hole with an accretion disk**. The energy which is generated ultimately comes from the incredibly strong gravitational field of the black hole.

Galaxy - galaxy collisions are also probably an important process in some part of the active galaxies phenomenon.

Star formation is also believed to be playing a role in some active galaxies phenomena.

A fundamental problem in active galaxies research involves understanding the geometry of the various regions which emit radiation. Since quasars are not spherical objects (they have accretion disks), they do not emit the same amounts of electromagnetic radiation in all directions. Modern research often centers on trying to understand if the different properties of active galaxies are due to orientation effects or are real.

(There is probably no single model that can account for all quasers and active galaxies.)

Gravitational Lenses

Some quasars have been found to be gravitationally lensed, in agreement with predictions of Einstein's General Theory of Relativity.

Gravitational lensing occurs when light from a distant, high redshift object is bent around a lower redshift, foreground object like a galaxy. This gives rise to multiple quasar images.

Since the paths that light must follow to form each quasar image are slightly different, making light curves for the various images of a gravitationally lensed quasar will potentially allow the Hubble constant to be determined.

The gravity of the matter in, for example, the foreground lensing galaxy can be studied by observing such configurations. This includes the non-luminous dark matter.

Quasar Absorption Lines as Probes of the Universe

The light from distant quasers passes through intervening galaxies and gas clouds. This gives rise to absorption lines in the spectrum which can be used to study the properties of the intervening material. This material occurs at lower redshifts.

By studying quasar absorption line spectra we can probe the properties of faint galaxies, gas and dust which existed in the Universe when it was much younger than it is today. For example, we can study the abundances of the chemical elements in these clouds which provides clues to star formation, and the origin of the elements, in the early Universe.

The types of objects studied in this way include: intergalactic clouds, clouds embedded in clusters of galaxies, galactic halos, galactic disks, galactic halos in formation and galactic disks in formation.

(David Turnshek, a professor at Pitt, is actively involved in many facets of Quasar research.)

Some fundamental (and unanswered) questions regarding galaxies are:

- What determines whether an elliptical or spiral galaxy is formed?
- At what redshift do galaxies first form?
- How does the clustering of galaxies change with redshift?
- What causes the voids?
- How does the activity in galaxies change with redshift?
- What determines the mass and size of galaxies?
- Do stars or galaxies form first?
- What is the (important) role of non-luminous matter, whose nature is unknown but which may account for 95% of the mass of the universe, in galaxy formation?

We attempt to answer these questions by looking at objects at high redshift, by running theoretical models, and by studying the microwave background radiation.