THE MILKY WAY GALAXY

Type: Spiral galaxy composed of a highly flattened disk and a central "elliptical" bulge. The disk is about 100,000 light years (30kpc) in diameter.

The term spiral arises from the external appearance of our galaxy. Seen from a distance, the stars in the disk appear to be concentrated in a spiral like pattern.

Number of Stars: 100 billion (10^{11})

Mass : 5 x 10^{11} Solar masses.

Size of Disk: 100,000 Light Years (30 kpc)

Age: 15 billion years (3 times age of Sun)

The Sun lies in the disk of the Galaxy, about 8.5kpc from its center.

The Large-Scale Structure of the Galaxy

On a large-scale the Galaxy can be broken up into 3 different parts:

1. **The Nuclear Bulge.**

   Contains the galactic nucleus densely packed old stars (Population II), and interstellar gas and dust. This is the center of the Galaxy. Overall this region has a flattened spherical shape which is about 5000pc in diameter. It does not exhibit spiral structure.

2. **The Disk**.

   Outside the bulge is the pancake-like (or pinwheel-like) structure called the Galactic disk. It is very thin (its thickness is 2% of its diameter) and it exhibits concentrations of stars in a spiral pattern. The disk contains interstellar gas and dust, and young stars (Population I), with the youngest stars often residing in the spiral arms. Approximately 80000 ly in diameter.

3. **The Halo**.

   This is a large spherical region about 130,000 light years in diameter that surrounds the Galaxy and contains old stars (Population II), globular clusters (also Population II), and some interstellar gas. The amount of gas in the large halo is small compared to the amount of gas in the thin disk.

   There is probably also an outer halo, composed of non-luminous matter, with a diameter of 200,000 to 300,000 light years. It is . We know this matter is present only because of its gravitational attraction on luminous matter.

Contents of the Milky Way Galaxy

1. Gas and dust.

A great deal of gas lies between the stars, and is referred to as the **INTERSTELLAR MEDIUM**.

2. Stars

Main sequence, red giants, white dwarfs, neutron stars, black holes.

3. Clusters

Galactic clusters.

Globular clusters.

4. Emission Line Nebulae.

Objects which contain gas that gives off electromagnetic radiation at specific energies (or wavelengths).

Examples:

- Supernovae remnants.
- Planetary nebulae.
- HII regions.

The nebula can appear red or green, depending on the wavelength of the dominant emission line.

5. Reflection Nebulae.

Objects which contain dust that **reflects** the light of nearby stars. A spectrum of a reflection nebula looks like the spectrum of the starlight it is reflecting.

6. Dark Nebulae.

Objects which contain dust that hinders our view of background stars. Thus, a dark nebula might look like a blank region of the sky where few or no stars are seen (except for foreground stars). A dark nebula is a visually non-luminous body.

7. Dark Matter

Probably makes up 80-90% of our Galaxy's mass. **We don't know what the dark matter is!**

Possibilities:

- Brown dwarfs
- Small black holes
- Neutrinos (if they have mass)

While we can't see the dark matter, we know it exists since its GRAVITY influences the motion of the visually luminous stars. **Most of the Dark Matter resides in the Halo.**

Stellar Populations

Two stellar populations which give information on the birth of our galaxy.

Population I

Age: 10^6 to 5 x10^9 years.
Regarded as young stars.

Composition: Hydrogen, Helium but 2-3% (by mass) is metals (Oxygen etc).

Location: Lie in the disk.
Circular orbits in disk. Orbit galactic center.

Sun: Population I
All O and B stars are Population I.

Population II

Age: 10^{10} years (or older).
Regarded as old stars.

Composition: Hydrogen, Helium but less than 0.05% (by mass) is metals (Oxygen etc).

Location: Lie in the halo and bulge.
Move in elliptical orbits not confined to the disk. also have higher space motions than Pop. I stars.

Type: Red stars (generally).

Clusters of Stars

A star cluster refers to a region in space in which there is a large concentration of stars.

Two types of clusters:

1. **Open Clusters** (sometimes called Galactic Clusters).
2. **Globular Clusters**.

Clusters are important for two reasons:

1. All stars in a cluster are approximately the same distance from us. This means that a HR diagram can be plotted for a cluster more easily, without making corrections for variations in distance.

2. All stars in a cluster formed at approximately the same time, and had the same initial composition. They are therefore excellent candidates for comparing with stellar evolution models (compare theoretical and observed H-R diagrams).

Open Clusters (also called Galactic Clusters)

Have the following properties:

1. No regular shape.
2. Contain hundreds of stars.
3. Found in the Galactic disk.
4. Spectral analysis shows that they have chemical compositions like the Sun (Population I type stars).
5. They have long main sequences on the HR diagram which indicate that they are young (e.g., many contain young hot O and B type Population I stars).

The age of a cluster can be determined from the spectral types of its most massive (or luminous) *main sequence* stars. e.g.

If an open cluster has O stars, it must be less than 10^7 years old, since otherwise the O stars would have used up their hydrogen fuel and evolved off the main sequence.

An open cluster with no main sequence stars earlier than B5 (ie no O to B4 stars) must be approximately 10^8 years old.

Globular Clusters

Have the following properties:

1. A regular spherical shape (round) with the stars more closely packed toward the center.
2. Contain 10^4 to 10^6 stars per cluster.
3. Spatial densities (ie stars per cubic parsec) are much higher (million times) than near the Sun.
3. They are found in the Galactic halo.
4. Spectral analysis shows that they have a smaller amount of heavy elements than the Sun (hence Pop. II).
5. They have short main sequences on the HR diagram which indicate that they are old (i.e., *they do not contain* O, B, A, and F Population II stars).

The clusters must be old (greater than 10^{10} years) because, if they were not, F stars would still be present on the main sequences.

Neutral hydrogen emission (21-cm Emission)

A powerful way to study the hydrogen in the Galaxy is to make radio observations using 21 cm wavelength line radiation of neutral hydrogen. Both emission and absorption of 21 cm radiation from neutral hydrogen can be studied.

1. A neutral hydrogen atom will **emit** 21 cm radiation when the spin of the electron and proton in the atom ***changes*** (flips) from ***both spinning in the same direction to spinning in opposite directions***.

   The atom may be excited by collisions with electrons or other atoms. After being excited, an atom will typically wait 10^7 years before decaying back to the ground state.

2. A neutral hydrogen atom will **absorb** 21 cm radiation when the spin of the electron and proton in the atom ***changes*** (flips) ***from spinning in opposite directions to both spinning in the same direction.***

Note

The spinning is due to the fact that both electrons and protons carry a property called “spin” which makes them behave as tiny magnets.

HI observations are used to probe:

The motion of material about the center of our Galaxy.

The structure of the disk, and hence the disks spiral structure.

In addition to HI, modern radio telescopes also use molecules as probes of the interstellar medium.

eg,

CO (carbon monoxide) is often used to study molecular clouds since the hydrogen is molecular, and difficult to detect.

Other molecules used include CH, OH, NH_3.

In some regions conditions are such that a particular molecule “masers”. Maser refers to **microwave amplification by stimulated emission of radiation.** (Laser = light amplification ...).

Another type of radio emission (which occurs over a continuous set of radio wavelengths) is synchrotron emission. This arises when electrons circle around under the influence of the Galactic magnetic field.

Synchrotron emission is often termed **non thermal emission** as it tells you nothing about the temperature of the gas.

The Spiral Structure of the Galaxy

The spiral structure of the Galaxy can be traced by observing the locations of galactic clusters, young O and B stars, and HII regions which are concentrated in the spiral arms.

There are two reasons why spiral structure may be present in a galaxy.

1. Supernovae explosions will sweep up gas into elongated string-like structures where new stars will form. The rotation of the galaxy, which can be observed by studying stellar proper motions and Doppler shifts, then orders these concentrations of stars into a spiral-like pattern.

2. The density wave theory of spiral structure predicts that the rotation and gravity of the mass in the galactic disk itself will cause the formation of spiral patterned regions where stars form and spend more time. While stars revolve around the galactic center they move more slowly in the spiral arms than when they are out of the spiral arms.

Because of star formation, our galaxy is constantly changing. As noted previously the spiral arms are delineated by massive stars and HII regions. Since massive stars live for less than 10^8 years, the stars that trace the spiral arms are forever changing.

One scenario for changes over time:

- Because of gravitational attraction or gas swept up by a supernova explosion, a region in space becomes very dense but is cool. This region will contain large amounts of molecules and dust. If no stars are nearby we see a dark nebula, but if stars are nearby we see a reflection nebula.
- After millions of years gravity may cause the gas and dust to collapse enough to begin fragmentation into protostars. Eventually the gravitational collapse causes the densities and temperature to become hot enough to start nuclear fusion, and very hot (O type) main sequence stars form.
- The hot stars ionize the existing gas and dust, and eventually there are only ions (near the star) and atoms left. Now we see an emission line nebula known as a HII region.

Measuring the Mass of the Galaxy

The mass of the Galaxy can be measured by observing the rotation velocity of gas and stars about the Galactic center.

The mass can be deduced from the rotation rate using Newtons theory of gravity. Newtons theory allows 2 assumptions to be made.

(a) All the mass inside a stars orbit acts as though it were concentrated at 1 point.

(b) The mass outside the orbit can be ignored.

If we know an objects orbital velocity, and its distance from the galactic center, we can deduce the mass interior to its orbit. As we increase the interior mass an object has to revolve around its center of motion faster to keep itself from falling inward due to the forces of gravity.

Mathematically we have (revised form of **Kepler's 3rd law**)

$$(M_1 + M_2) / M_S = (a / a_E)^3 \ (P_E / P)^2$$

where M_1 is the mass of the 1st body, M_2 the mass of the 2nd body, P is the orbital period, and a is the semi-major axis (radius) of the orbit of one object about the other.

Consider the mass inside the Sun's orbit around the galactic center.

Distance of Sun from galactic center (a)

=8500 parsecs

=2.6×10^{22} cm

=1.75×10^{9} astronomical units

Orbital velocity (v)

=230 km/s

=2.3×10^{7} cm/s

=7.2×10^{14} cm/year

Hence

P = [Length of orbit] / [Sun's rotational velocity]

$= 2\pi a / v$

$= 2 \times 3.14 \times [2.6 \times 10^{22}$ cm] / [7.2×10^{14} cm / year]

$= 2.3 \times 10^{8}$ years

$M_{int}/M_{sun} = (a / a_E)^3 / (P / P_E)^2$

$= (1.75 \times 10^{9}$ A.U. / 1 A.U.$)^3$ / $(2.3 \times 10^{8}$ yr/ 1 yr$)^2$

$= 1.0 \times 10^{11} M_{sun}$

Thus the mass of our galaxy contained **inside** the Sun's orbit is approximately $10^{11} M_{sun}$

Doppler shifts of stars and gas and proper motions of stars are used to study motions in our galaxy. 21 cm observations and radio observations of molecules provide a powerful way to study the rotation of the disk to large distances from the galactic center.

The measurements of orbital velocities in a galaxy are graphed for each radius studied to form a **rotation curve** for the galaxy. From the rotation curve the mass of the galaxy interior to each radius can be determined.

Studies of rotation curves (in the Galaxy and external galaxies) suggest that as much as 80% to 90% of the mass of the Galaxy is non-luminous dark matter.

The Galactic Center

Observations of the galactic center are important as they allow us to study the central regions of a galaxy with a high spatial resolution. Other galaxies are too distant to study with the same spatial resolution.

Some of the phenomena occurring in the galactic center may give us insights into active galaxies and quasers (Chapter 16).

Conditions in the Galactic Center are very different from Solar neighborhood.

1 Million stars packed into a cubic light year

(Only 1/100 star in a similar volume near Sun.)

Problem

Our view of the galactic center is severely hindered by interstellar extinction. Since our Sun is located in the outer part of the very dusty galactic disk we cannot see the galactic center in visible or ultraviolet light.

Astronomers study the galactic center by making observations at infrared and radio wavelengths since the absorption at these wavelengths is considerably less than at optical (and ultraviolet) wavelengths.

Radio observations can be made easily from the ground. Unfortunately ground-based infrared observations can only be made in a few select windows of the spectrum. At other wavelengths the Earths atmosphere is opaque. Observations at these other infrared wavelengths can be made from aircraft (eg The Kuiper Airborne Observatory) or by satellites (eg IRAS).

The nature of the galactic center is the subject of an intense debate. The galactic center may contain

(a) A massive black hole with a mass a million times that of the Sun.

If such a black hole exists, it must be the intense non-thermal radio source Sgr A*. Sgr A* is a point like radio source located at the center (or almost) of our galaxy. Some astronomers argue that any black hole in the central region must have a mass less than 100 Solar masses.

(b) A cluster of young stars.

To explain the level of ionization in the galactic center (the hydrogen in the inner most region is ionized) some of the stars must be O stars. Since O stars live for only 10^7 years, many of the stars in the cluster must have formed less than 10^7 years ago.

From infrared observations we now have direct evidence for hot young stars in the galactic center.

It is very difficult to study the hot stars since we can only study them at infrared wavelengths where very little of their energy is emitted. From Wiens law we know hot O type stars emit most of their radiation at ultraviolet wavelengths. Unfortunately all the ultraviolet and optical energy emitted by the stars is absorbed by the intervening interstellar dust.

Formation of Milky Way

Basic scenario.

Cloud of gas with mass greater than 10^{11} Solar masses. Poor in metals.

Collapses due to a gravitational instability (Time scale --- 100 Million years?)

First stars formed and exploded, enriching gas with some heavy metals. These are known as Pop III stars, but have not been detected.

New stars formed. They contain some trace of heavy elements, and are the Population II stars we see today.

Star formation was not very efficient, and some gas collapsed to form a rotating disk. This gas was (relatively) rich in metals coming from Pop. II supernovae.

Gas in disk began to fragment, forming Pop. I stars. These stars lie in the disk, like the gas from which they formed.

Formation of Milky Way still not well understood. Many problems with the simple scenario outlined above?

e.g. No Pop III stars found.

Halo stars have a range of abundances and ages.