The Milky Way Galaxy

Our Home Away From Home
Galaxies

Group of stars are called galaxies

Our star, the Sun, belongs to a system called

The Milky Way Galaxy

The Milky Way can be seen as a band of stars in the night sky
The Milky Way Galaxy

The Milky Way is basically a disk of stars with a large central bulge

The central bulge contains the galactic nucleus

Most of the stars in the Milky Way are contained within the Galactic Disk

The plane of the Galactic Disk is almost perpendicular to the plane of our Solar System
Milky Way Dimensions

The central bulge which contains densely packed older stars is ~ 16,000 light years in radius.

The radius of the galactic disk is ~ 50,000 light years.

The disk contains mainly young stars as well as interstellar gas and dust.

The thickness of the galactic disk is ~ 2,000 light years.
Where is Our Solar System?

Initial attempts to find our solar system's location were to simply count the numbers of stars in various regions of the sky.

What was found was that there were equal numbers of stars in all regions.

Therefore, the solar system is at the center of the galaxy.

This is incorrect!
Where is Our Solar System?

Why is this result incorrect?

Assumed that space was a vacuum

However there is a large amount of interstellar dust

This interstellar dust absorbs the light from the stars and if a star is far enough away, its light is totally absorbed -

Interstellar Extinction

Interstellar dust is also denser towards the center of the galaxy

So how did we find our location?
Where is Our Solar System?

The globular clusters that surround the Milky Way were the Key

Within these globular clusters are Cepheid variable stars
Cepheid Variable Stars

Cepheid Variable stars are stars whose luminosity varies precisely as a function of time

Typical classical Cepheids pulsate with periods of a few days to months

Variability comes from a dynamic balance between gravity and pressure - they have large oscillations around stability
Cepheid Variable Stars

The usefulness of these stars comes from their period–luminosity relation
Where is Our Solar System?

Using the measured variation and the measured apparent luminosity of these Cepheid Variables, it is possible to deduce the distance to these globular clusters.

Then using the known directions and the measured distances it was seen that the globular clusters were spherically centered about some point that was not the Earth.
Where is Our Solar System?

It was found that the Solar system was \( \sim 30,000 \) light years from this central point

We are not at the Center
Our Galactic Year

It has been determined that our Sun is moving at a speed of ~200 km/sec.

Using this speed and an orbital radius of 28,000 light years, it takes the Sun 250 million years to make one complete trip around the center of the galaxy.

This time of 250 million years is called the *Galactic Year*.

Using the time it takes to go around the galaxy and the age of our Sun, we have gone around ~60 times.
Structure of the Milky Way

The general shape is a flat disk, 2000 light years thick and 100,000 light years in diameter, with a central bulge.

Is there any internal structure to the Milky Way?
Are the stars spread uniformly or distributed otherwise?

Standard atomic transitions yield visible and ultraviolet radiation.

These wavelengths cannot be used because of interstellar extinction.
Structure of the Milky Way

The key to determining the structure of the Milky Way is atomic hydrogen consisting of an electron orbiting a nucleus made up of only a proton.

Both the proton and the electron have Spin which can be considered as an inherent angular momentum.

The spins of the proton and electron can be aligned in one of two ways:

- **Parallel**
- **Antiparallel**
Structure of the Milky Way

The energy for the state where the spins are parallel is higher than for the state where the spins are anti-parallel.

The hydrogen atom, if it is in the spin parallel state, can make a transition to the spin anti-parallel state releasing energy.

When a transition does occur, energy is released corresponding to a wavelength of 21 cm, which is in the radio portion of the electromagnetic spectrum.

This radiation can pass through the interstellar medium unaffected.

In 1951 the first radio telescope was built to detect the 21 cm radiation from the hydrogen transition.
Structure of the Milky Way

The key to using this 21 cm radiation is the Doppler shift

A hypothesis is first formulated as to the structure of the galaxy

Then predictions are made and then compared to the experimental data
Structure of the Milky Way

Simplest Hypothesis:
Galaxy is a uniform non-rotating disk

All the radiation will be 21 cm
Measure the energy as a function of direction
Relative intensity as a function of direction gives the relative densities
Should then correlate with known densities as a function of position

This is not what is seen
Structure of the Milky Way

Slightly more complicated hypothesis:
Uniform density with galaxy rotating

Radiation will be Doppler shifted by an amount dependent on the radial velocity along the line of sight

Since the density is uniform, the energy received will be at uniformly distributed wavelengths

Again this is not what is seen
Structure of the Milky Way

More complicated hypothesis:
Galaxy is rotating and has non-uniform density

Radiation is Doppler shifted by an amount dependent upon the velocity along the line of sight
Since Density is non-uniform, prominent peaks in the energy distribution as a function of wavelength

This is in fact what is seen
The Spiral Milky Way Galaxy

From the shifted wavelengths, the components of the velocities along the line of sight can be determined.

From these radial velocities, the fact that the Milky Way Galaxy is a spiral structure was determined.
Galactic Structure

This artist’s conception shows the various parts of our galaxy, and the position of our Sun
Galactic Structure

The **galactic halo** and **globular clusters** formed very early.

The **halo** is essentially spherical.

All the stars in the halo are very old, and there is no gas and dust.

The **galactic disk** is where the youngest stars are, as well as star formation regions.

Emission nebulae and large clouds of gas and dust.

Surrounding the galactic center is **the galactic bulge**, which contains a mix of older and younger stars.
Galactic Structure

This infrared view of our galaxy shows much more detail of the galactic center than the visible-light view does, as infrared is not absorbed as much by gas and dust.
Galactic Structure

Stellar orbits in the disk move on a plane and in the same direction.

Orbits in the halo and bulge are much more random.
The Formation of the Milky Way

Any theory of galaxy formation should be able to account for all the properties below

<table>
<thead>
<tr>
<th>Galactic Disk</th>
<th>Galactic Halo</th>
<th>Galactic Bulge</th>
</tr>
</thead>
<tbody>
<tr>
<td>highly flattened</td>
<td>roughly spherical—mildly flattened</td>
<td>somewhat flattened and elongated in the plane of the disk (“football shaped”)</td>
</tr>
<tr>
<td>contains both young and old stars</td>
<td>contains old stars only</td>
<td>contains both young and old stars; more old stars at greater distances from the center</td>
</tr>
<tr>
<td>contains gas and dust</td>
<td>contains no gas and dust</td>
<td>contains gas and dust, especially in the inner regions</td>
</tr>
<tr>
<td>site of ongoing star formation</td>
<td>no star formation during the last 10 billion years</td>
<td>ongoing star formation in the inner regions</td>
</tr>
<tr>
<td>gas and stars move in circular orbits in the Galactic plane</td>
<td>stars have random orbits in three dimensions</td>
<td>stars have largely random orbits, but with some net rotation about the Galactic center</td>
</tr>
<tr>
<td>spiral arms</td>
<td>no obvious substructure</td>
<td>central regions probably elongated into a bar; ring of gas and dust near center</td>
</tr>
<tr>
<td>overall white coloration, with blue spiral arms</td>
<td>reddish in color</td>
<td>yellow-white</td>
</tr>
</tbody>
</table>
The formation of the galaxy is believed to be similar to the formation of the solar system, but on a much larger scale.
Galactic Spiral Arms

We have see from measurements of the position and motion of gas clouds, that the Milky Way has a spiral form
Why The Spiral Arms

We have determined that the Milky Way Galaxy has spiral arms.

Other galaxies also have spiral arms, and other galaxies do not.

Some galaxies that have spiral arms, have arms that are poorly defined.

Data show that the stars on the outside edge of our galaxy are moving at approximately the same velocity as stars that are closer inward.
Why The Spiral Arms

If the spiral arms are an actual part of the structure of a spiral galaxy, then the spiral arms should have wound up tightly by now

But they have not!  

Why not?
Why The Spiral Arms

The spiral arms are not a physical reality in the normal sense.

What the Milky Way has is a pattern of spiralness that is moving through the galaxy - like waves in water.

There are density waves moving through the stars and interstellar dust, temporarily piling up material.

These density waves are moving at a rate of ~300 km/s.

The interstellar medium can only support waves up to 10 km/s.
Why The Spiral Arms

Shock waves develop in front of the leading edge of the density wave.

The interstellar medium can not move out of the way fast enough.

Matter is compressed to high densities, densities that are high enough for star formation to begin.

The spiral arms will therefore contain young, hot stars, while the region between the arms contains older stars.
Why The Spiral Arms

The origin of the spiral arms is not yet understood
Precessing Orbits

A star's movement through the galaxy is affected by the other stars in the galaxy.

The paths of the stars are not circular, but are elliptical.

These ellipses appear to precess.

The elliptical orbits of the stars are not independent of each other, but are correlated.
Rotation Rates

Not all parts of the galaxy are rotating at the same rate

Differential Rotation

The measurement of stars’ velocities show that the velocities increase rather sharply, like that of a rigid body, and then continue to increase with a slow rise

This behavior for the orbital velocities cannot be accounted for in a straight forward manner

It was expected that the rotation velocities would decrease like Keplerian orbits as a function of distance from center
Galactic Mass

The orbital speed of an object depends only on the amount of mass between it and the galactic center.
Once all the galaxy is within an orbit, the velocity should diminish with distance, as the dashed curve shows.

It doesn’t

More than twice the mass of the galaxy would have to be outside the visible part to reproduce the observed curve.
Galactic Mass

What could this “dark matter” be?

It is dark at all wavelengths, not just the visible

- **Stellar-mass black holes?**
  
  Probably no way enough of them could have been created

- **Brown dwarfs, faint white dwarfs, and red dwarfs?**
  
  Currently the best star-like option

- **Weird subatomic particles?**
  
  Could be, although no direct evidence so far
Galactic Mass

A Hubble search for red dwarfs turned up too few to account for dark matter

If enough existed, they should have been detected
Galactic Mass

The bending of spacetime can allow a large mass to act as a gravitational lens.

Observation of such events suggests that low-mass white dwarfs could account for as much as 20% of the mass needed.

The rest is still a mystery.
Center of Milky Way Galaxy

The center of our galaxy is in the general direction of the constellation Sagittarius.

The Galaxy's center is difficult to observe using visible light because of interstellar extinction.

However we can use radio and infrared wavelengths.
Center of Milky Way Galaxy

These images — in infrared, radio, and X-ray — offer a different view of the galactic center.
Center of Milky Way Galaxy

The center of the Milky Way is very “bright” in the radio wavelengths.

The brightest infrared source comes from Sagittarius A and within this is a very bright radio source Sgr A* which marks the center of the galaxy.
Center of Milky Way Galaxy

The galactic center appears to have

• A stellar density a million times higher than near Earth
• A ring of molecular gas 400 pc across
• Strong magnetic fields
• A rotating ring or disk of matter a few parsecs across
• A strong X-ray source at the center
Center of Milky Way Galaxy

Apparently, there is an enormous black hole at the center of the galaxy, which is the source of these phenomena.

An accretion disk surrounding the black hole emits enormous amounts of radiation.

Observations on three stars that are orbiting the core region at a distance ranging from ~1000 A.U. to ~2700 A.U. seem to show them orbiting a common point.

Measurements indicate that the mass is roughly 3.7 million solar masses – a black hole whose size would extend out to the orbit of Mars.
Center of Milky Way Galaxy

There are other interesting objects at the center of the Milky Way.

Observations have been made of the remnant of a supernova explosion that had occurred near the Sgr A* and that may have at one time fed the black hole.

There is still much to learned about the center of the Milky Way.