What is a Galaxy?

Solar System

Distance from Earth to Sun
= 93,000,000 miles
= 8 light-minutes

Size of Solar System
= 5.5 light-hours
What is a Galaxy?

Stellar Region

Sun (solar system too small to be seen on this scale)

30 light-years
What is a Galaxy?

Galaxy

a massive collection of stars, gas, and dust kept together by gravity

200,000 light-years

Sun’s Stellar Region
What is a Galaxy?

If our solar system was the size of a cell in the human body, our galaxy would still measure over one mile across.
Types of Galaxies

Spiral: Disk-like appearance with arms of stars and dust forming a spiral pattern.

Barred Spiral: Similar to spirals but with a bright bar of stars and gas through the center.

Elliptical: Elliptically-shaped, with less gas and dust than spirals; no disk or "arms".

Irregular: Neither elliptical nor spiral in shape; gas and dust as in spirals but no defined "arms".

Peculiar: Distorted; may be one of the above types, often due to collision with another galaxy or similar catastrophic event.
The Hidden Lives of Galaxies
Galaxy Formation

Galaxies form from the primordial density fluctuations that arise after the big bang and grow under inflation.

These density fluctuations form filaments, and galaxies form in knots along the filaments.
Spirals vs. Ellipticals

Final type of galaxy depends on initial rate of star formation:
- If stars form quickly, then galaxy becomes elliptical. Stars form within initial distribution of gas, and follow their initial orbits.
- If stars form later, the gas has time to collapse into a disk. Most stars from within the disk. The galaxy becomes a spiral.
In clusters, galaxies can pass close to one another.

- Galaxies can become distorted, and often merge.
- Mergers often lead to giant elliptical galaxies at the heart of large clusters.
Spirals in Grazing Encounter

Galaxies NGC 2207 and IC 2163
Antennae Galaxies

Colliding Galaxies NGC 4038 and NGC 4039

HST • WFPC2

PRC97-34a • ST ScI OPO • October 21, 1997 • B, Whitmore (ST ScI) and NASA
“Invisible” Light from Galaxies

Electromagnetic Spectrum
“Invisible” Light from Galaxies
“Invisible” Light from Galaxies

X-ray Objects in Galaxies:
• stars
• supernova remnants
• X-ray binaries
This X-ray image of an elliptical galaxy reveals hot, fast-moving gas even in the outer reaches of the galaxy. The visible mass of the galaxy is insufficient to hold onto it.

(The dark circle shows the size of the galaxy when photographed in visible light. The X-ray image shows mass far outside the visible image.)
So, we have a Problem:

- This gas gives off X-rays, which means it’s *hot*!

- Hot gas moves at high velocities - we can measure and confirm this

- The velocity of the gas is greater than the escape velocity of the galaxy, if we calculate the galaxy’s mass by adding up all the mass we can see at all wavelengths of light

- So why hasn’t the gas escaped? There *must* be more mass we *can’t* see!
Another way to look at the problem:
We can determine the mass of an object by measuring the motion of bodies in orbit around it.

Newton’s Second Law:

\[ F = ma \]

F = Force of Gravity
a = acceleration due to circular motion

\[ \frac{GMm}{r^2} = \frac{mv^2}{r} \]
From previous slide, we have Newton’s Second Law of Motion assuming a gravitational force and acceleration due to circular motion:

\[
\frac{GMm}{r^2} = \frac{mv^2}{r}
\]

Simplifying gives:

\[
v^2 = \frac{GM}{r}
\]

So, if \(GM\) is constant, then velocity is proportional to the inverse square root of distance. For example ...
Hidden Mass in Galaxies

Rotation Curve - A Plot of Object Velocity vs. Distance

![Rotation Curve of Solar System](image)
Activity #6a: Evidence for Hidden Mass

There are **nine** solar system planets presented on the graph. The planets, from the closest to the sun to the furthest, are **Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto**. Using the graph, the velocities of the solar system planets, from the lowest value to the highest value, are **approximately 48, 35, 30, 24, 13, 10, 7, 5, and 4 km/sec**. Using the graph, the distances of the planets from the Sun are, from least to greatest, **0, 110, 150, 250, 800, 1500, 2800, 4500, and 6000 million km**. In general, the further a planet is from the sun the **slower** its velocity. The closer a planet is to the sun **faster** its velocity.
Hidden Mass in Galaxies

Rotation Curve - A Plot of Object Velocity vs. Distance

Our Solar System

\[ v \propto \frac{1}{\sqrt{r}} \]

Graph showing the relationship between velocity and distance for the Solar System, with a plot of distance from the Sun in millions of kilometers versus velocity in km s\(^{-1}\).
The previous plot showed data for planets in our solar system, illustrating the equation:

\[ v^2 = \frac{GM}{r} \]

If we solve for \( M \):

\[ M = \frac{v^2 r}{G} \]

We can use real data (the distances and velocities of the planets) and the fact that \( G = 6.67 \times 10^{-11} \text{ m}^3/\text{kg-s}^2 \) to verify that the central mass, \( M \), remains constant..
<table>
<thead>
<tr>
<th>Planet</th>
<th>Distance from Sun (km)</th>
<th>Velocity (km/s)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>$1.5 \times 10^8$</td>
<td>29.8</td>
<td>$2.0 \times 10^{30}$</td>
</tr>
<tr>
<td>Jupiter</td>
<td>$7.8 \times 10^8$</td>
<td>13.1</td>
<td>$2.0 \times 10^{30}$</td>
</tr>
<tr>
<td>Neptune</td>
<td>$4.5 \times 10^9$</td>
<td>5.4</td>
<td>$2.0 \times 10^{30}$</td>
</tr>
</tbody>
</table>
Hidden Mass in Galaxies

What does this have to do with Galaxies???

If we measure the distance and velocity of objects (e.g., stars) orbiting in a galaxy, we’d expect them to obey the same laws. As distance from the center of the galaxy increases, we should get to a point where almost all of the galaxy’s mass is inside the orbit of the furthest objects.

At this point, the central mass would be practically constant, and we would expect a rotation curve similar to that for our solar system.
Hidden Mass in Galaxies

What we expect for a galaxy if all the mass was concentrated in the central region.

Compare expected velocities with actual velocities.
Hidden Mass in Galaxies

If we take the same equation we used for the solar system:

\[ M = \frac{v^2 r}{G} \]

and use the actual distances and velocities observed for this galaxy, we can calculate the enclosed mass at various distances from the galaxy’s center.

(Remember that \( G = 6.67 \times 10^{-11} \, \text{m}^3/\text{kg-s}^2 \) )
# Activity 6b, part 2

<table>
<thead>
<tr>
<th>Distance (kpc)</th>
<th>Velocity (km/s)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>95.0</td>
<td>$2.1 \times 10^{40}$</td>
</tr>
<tr>
<td>10.0</td>
<td>110.0</td>
<td>$5.6 \times 10^{40}$</td>
</tr>
<tr>
<td>15.0</td>
<td>110.0</td>
<td>$8.4 \times 10^{40}$</td>
</tr>
</tbody>
</table>
Hidden Mass in Galaxies

What Happened?!?!?

The central mass never becomes constant, as it did for the Solar System. The fact that the mass is still increasing means we haven’t yet reached a distance where all the mass is contained inside that orbit. But we’ve plotted all *the matter we see!*

There *must* be Missing Mass!!
Hidden Mass in Galaxies

Hot Gas and Rotation Curves show:

- Gas and objects move at velocities greater than can be accounted for from the gravitational effect of the visible mass of the galaxy.
- From these observations we deduce that the visible mass accounts for only 10% of the total mass of the galaxy.
- Recent results from WMAP show ordinary matter makes up only 4% of the universe!
Candidates for the Hidden Mass

- Hydrogen Gas
  - Very abundant, but not enough detected

- MACHOs (Massive Compact Halo Objects)
  - E.g. Black Holes, Neutron Stars, Brown Dwarfs
  - Not enough of them

- WIMPs (Weakly Interacting Massive Particles)
  - E.g. Exotic subatomic particles
  - The best candidate theoretically, but not yet observed.
The Hidden Lives of Galaxies

Presentation available at http://imagine.gsfc.nasa.gov/docs/teachers/galaxies/galaxies.html