Chapter 23

- Our Parent Galaxy
- Measuring the Milky Way
  - Star Counts
  - Distances
  - Shape
- Galactic Structure
- Formation of the Milky Way
- Spiral Arms
- Mass of the Milky Way
- The Galactic Center
A galaxy is a collection of stellar and interstellar matter, i.e.,:

- Gas
- Dust
- Stars in all stages of life
- White Dwarfs, Neutron Stars and Black Holes

All the matter may add up to about 500 billion to 2 trillion Solar Masses.

Not all of this huge mass is “luminous” matter!

The Milky Way is the galaxy in which we live.
The Milky Way

- We know of its existence because (Fig. a):
  - we see few stars when looking out of the galaxy (red arrows)
  - we see many stars when looking in (blue and white arrows).
- Fig. b shows a real optical view from Earth
- Fig. c shows an artists conception of what it may look like from the top.
The Milky Way is a **spiral galaxy**. Here are three similar galaxies.

![Image of the Milky Way and other galaxies](image-url)
The Milky Way

- This artist’s conception shows the various parts of our galaxy and the position of our own star.

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Measuring the Milky Way

One of the first attempts to measure the Milky Way was made by William Herschel (who discovered Uranus in 1781), using visible stars. Herschel simply counted the stars he observed in different directions and concluded that the sun was at the center of a disk shaped collection of stars.

He was not aware that most of the Galaxy, particularly the center, is blocked from view by vast clouds of gas and dust.
Measuring the Milky Way

- Looking perpendicular to the plane the view is not as obscured by gas and dust.
- Perpendicular to the plane we see two kinds of objects, *viz.*, 
  - Globular Clusters, and 
  - “Spiral Nebulae”
- To know if something we see “belongs” to our galaxy, we must be able to measure the distance to it.
- Thus, we can have no idea if Globular Clusters and Spiral Nebulae “belong” to our galaxy without being able to measure the distances to them.
A useful analogy to light's dependence on distance is a traffic light that is distant and dim... compared to one that is nearby and bright.
The Distance Ladder

• The key idea in extending the distance ladder is to use particular types of variable stars – stars whose luminosity varies in a regular fashion (over hours or days) and have left the main sequence.
• The period of variation is closely linked to the star’s mass.
• If the mechanism for the variation is understood then the Luminosity (or absolute brightness) of the star can be predicted theoretically with a great deal of accuracy.
• The absolute brightness can be compared with the apparent brightness via the inverse square law to determine the distance to the star.
We have already encountered variable stars:
- Eclipsing binaries
- Novae
- Supernovae, and related phenomena (e.g. pulsars). These are called cataclysmic variables.

Stars whose luminosity varies in a regular way, and not for the above reasons, are called intrinsic variables.

Two types of intrinsic variables are very well understood:
- RR Lyrae stars and
- Cepheids Variables
Variable Stars

- The names come from the first discovered star in each constellation: RR Lyrae means “like” the variable star “RR” in the constellation Lyra.
  - RR Lyrae variables are type A or F stars that have left the main sequence and are settled on the Horizontal Branch.
  - Type I Cepheid variables are very massive, metal rich stars, typically 4 to 20 times more massive than the sun, that have left the main sequence and have reached the “asymptotic giant” stage. In this stage they are about 100,000 times more luminous than the sun.
  - Type II Cepheids are typically metal poor, small stars (about ½ the mass of our sun)
Variable Stars

• The variability of these stars comes from the \( \kappa \) opacity mechanism. This has to do with the change in the opacity of the star’s interior as it evolves.

• “Opacity” is the lack of transparency to the passage of photons (light).

• In a normal star, an increase in the temperature (and therefore the density and pressure) generally causes a decrease in the opacity, allowing photons to escape more rapidly and resulting in equilibrium.

• In some stars, however, an increase in the temperature (and the density and pressure) causes an increase in the opacity, which prevents the energy being produced from escaping and leads to an unstable situation.
Variable Stars

• Helium is the element thought to be most responsible for the process (this is why all variable stars are post main-sequence).
• Doubly ionized He is more opaque than singly ionized He and the more He is heated, the more opaque it becomes.
• When the temperature is low, the opacity is also low and radiation escapes freely. This causes the core to shrink, which increases the fusion rate in the core, causing the temperature to rise.
• This increases the Luminosity of the star as well as its opacity, since more He gets doubly ionized.
Variable Stars

• As the opacity rises, more of the radiation from the core is trapped and the radiation pressure increases. This causes the core to expand and cool, in turn reducing the Luminosity (and the opacity).
• Thus the stars luminosity increases, then decreases and increases again, in a periodic fashion.
• The phenomenon is similar to Hydrostatic equilibrium, but for photons.
• It causes the core to expand and contract in a regular way, much like the “breathing mode” of a sun-like star, except with much more dramatic effects on the star’s luminosity.
Variable Stars

- The conditions for this phenomenon can only be found in post main sequence stars.
- In the H-R diagram, there is a region (outside the main sequence) called the **Instability Strip** in which stars will oscillate.
- Some stars will cross this region on their way out of the main sequence.
Large stars and smaller stars will cross the instability strip after leaving the main sequence.
Variable Stars

- **RR Lyrae stars** have essentially the same luminosity curve, with periods from 0.5 to 1 day.
- **Cepheid variables** periods range from about 1 to 100 days.
- High mass stars evolve horizontally across the H-R diagram. When their paths cross the instability strip they become **Cepheid Variables**.
The usefulness of these stars comes from their period–luminosity relationship.
RR Lyrae stars all have about the same luminosity; knowing their apparent magnitude allows us to calculate the distance.

Cepheid Variables have a luminosity that is strongly correlated with the period of their oscillations; once the period is measured, the luminosity is known and we can proceed as above.

- Recall that to measure the distances we use the inverse square law:

\[ F = \frac{L}{4\pi R^2} \]
The Distance Ladder

- Many RR Lyrae stars are found in globular clusters. These clusters are not in the plane of the Galaxy, so they are not obscured by dust and can be measured.
- This yields a much more accurate picture of the extent of our Galaxy and our place within it.
We have now expanded our cosmic distance ladder one more step.
Our knowledge of the galactic structure is based on detailed optical, infrared and radio observations of stars and gas.

The extent of the halo is based on observations of variable stars in globular clusters and stars in the halo. For halo objects light obscuration is not an issue as there is little gas and dust outside the disk.

Because of the large amounts of gas and dust in the disk, optical and infrared observations take us out to only about 10 kpc. Our detailed knowledge of the disk is based mainly on radio observations, particularly the 21 cm. line.
Galactic Structure

- Galactic halo
- Galactic disk
- Galactic bulge
- Galactic center
- Sun
- Emission nebula
- Open cluster
- Globular clusters
- O, B stars
- Gas and dust

Dimensions:
- 4 kpc
- 8 kpc
- 30 kpc

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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 in the halo.

The Galactic disk extends about 30 kpc and it is where the youngest stars are, as well as star formation regions—emission nebulae, large clouds of gas and dust. The disk is between 300 and 600 pc thick.

Surrounding the Galactic center is the Galactic bulge, which is roughly spherical, about 6 kpc across and 4 kpc perpendicular to the plane and contains a mix of older and younger stars. The older stars are on the outside and the younger stars on the inside of the bulge.
Galactic Structure

- Stars are formed in nebulae within the disk, so most of the O and B stars and young star clusters are found in the disk. They are rich in metals and heavy elements from the ISM and are called **Population I stars**. The disk itself therefore appears bluish.

- Once they are formed, stars tend to drift out of the disk and perpendicular to it due to interactions with other stars. Therefore, the regions above and below the disk are populated with older stars. Including these older stars the disk is about 2 - 3kpc thick. These regions appear reddish.

- Old, halo stars are poor in heavy elements and are known as **Population II stars**.
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 the gas and dust.
Orbital Motion

- Stellar orbits in the disk are in the plane of the disk and in the same direction;
- Stellar orbits in the halo and bulge are random.
Orbital Motion

- Within the disk, Stars and Interstellar clouds show systematic Doppler shifts.
- We can infer their velocities from these Doppler shifts.

The curved arrows denote the speed of the disk material, which is greater closer to the center.

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Orbital Motion

• Observations of stars give us a good idea of the rotation rate of our galaxy in the solar neighborhood (within a few hundred parsecs of the sun).

• To measure the rotation at greater distances, astronomers use radio emissions from atomic hydrogen clouds, specifically the 21 cm line.

• However, it is hard to measure the distance to molecular clouds, so the observations have to be combined with theory (Newton’s theory of gravity) to get an accurate map of the distribution of gas in the galactic plane.
Radio emissions (21 cm line) are used to map out the atomic Hydrogen clouds in the galaxy.
Orbital Motion

• A careful study of the motion in the disk leads us to conclude that
  – The entire disk is rotating
  – Stars, gas and dust all move in roughly circular paths around the galactic center
  – The period of rotation depends on the distance from the galactic center. It is shorter closer to the center and longer farther from the center, i.e., stars near the center are moving faster.
  – This is known as Differential Rotation.

• However, the orbital velocities have led to BIG questions about the matter content of the galaxy.
Galactic Spiral Arms

- Measurement of the position and motion of gas clouds shows that the Milky Way has a spiral form.
Galactic Spiral Arms

- The spiral arms cannot be tied to the rotation, i.e., rotate along with the Galaxy -- they would “wind up.”

- There are two theories for the formation of the spiral arms.
Density Wave Model: They could be density waves, with stars moving in and out of them much as cars move in and out of a traffic jam.
Self-Propagating Star Formation: As clouds of gas and dust move through the spiral arms, the increased density triggers star formation. This may contribute to propagation of the arms.
Galactic Spiral Arms

- The origin of the spiral arms is not yet understood. For example:
  - What produces the density waves required in the density wave model? People have suggested:
    - Gravitational effects of our satellite galaxies,
    - Instabilities in the gas near the central bulge, and
    - The bar-like shape of the central bulge may have something to do with it.
  - Is the Self-Propagating model able to produce extended spirals, or is it limited to *isolated* spirals?
Any theory of galaxy formation should be able to account for all the properties below.

<table>
<thead>
<tr>
<th>Table 14.1 Overall Properties of the Galactic Disk, Halo, and Bulge</th>
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</thead>
<tbody>
<tr>
<td>Galactic Disk</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Highly flattened</td>
</tr>
<tr>
<td>Contains both young and old stars</td>
</tr>
<tr>
<td>Contains gas and dust</td>
</tr>
<tr>
<td>Site of ongoing star formation</td>
</tr>
<tr>
<td>Gas and stars move in circular orbits in the Galactic plane</td>
</tr>
<tr>
<td>Spiral arms (Sec. 14.5)</td>
</tr>
<tr>
<td>Overall white coloration, with blue spiral arms</td>
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</tbody>
</table>
The formation of the halo of the Galaxy likely involved the merger of smaller galaxies.

Disk formation is believed to be similar to the formation of the solar system, but on a much larger scale.
The orbital speed of an object depends only on the amount of mass between it and the Galactic center. Measuring the Galactic orbital speed allows astronomers to calculate the Galactic mass contained within the orbit.
The Mass of the Milky Way

- Once all the Galaxy is within an orbit, the velocity should diminish with distance, as the dashed curve shows. Keplerian motion predicts $v = \sqrt{GM/R}$.

- It doesn’t; roughly 87% of the mass of the Galaxy would have to be invisible to reproduce the observed curve!
To account for the velocity curves, the mass of the galaxy would have to be more than 6 times the mass observed in luminous matter.
The Mass of the Milky Way Galaxy

- What could this “dark matter” be? It is dark at all wavelengths, not just the visible part of the spectrum.
  - Stellar-mass black holes?
    - Probably no way enough could have been created.
  - Brown dwarfs, faint white dwarfs, and red dwarfs?
    - Currently the best star-like options
  - Subatomic particles?
    - Could be, although no evidence so far and they would have to be very hard to detect.
The Mass of the Milky Way Galaxy

• The bending of space-time can allow a large mass to act as a gravitational lens:
  – Observation of such events suggests that low-mass white dwarfs could account for about 30% - 50% of the mass needed.
  – The rest is still a mystery.
Galactic Dark Matter

- Even the visible portion of the galaxy has more dark matter than ordinary matter.
- Still, we find flat rotation curves out to about 40 kpc from the center and so our galaxy is in reality very much bigger than (roughly 3-4 times) the luminous portion would have us believe!
- As a consequence, our galaxy is expected to have a total mass of roughly 1.5 trillion solar masses and extend to about 100-120 kpc from the center.
- About 1.0 trillion solar masses would lie beyond the visible galaxy!
The Galactic Center

- This is a view toward the Galactic center, in visible light. The two arrows in the inset indicate the location of the center; it is entirely obscured by dust.
The Galactic Center

- These images, in infrared, radio, and X-ray, offer a different view of the Galactic center.
The Galactic center appears to have
- a stellar density a million times higher than near Earth,
- a strong X-ray source at the center,
- a rotating ring or disk of matter a few parsecs across,
- a ring of molecular gas 400 pc across, and
- strong magnetic fields
• Apparently, there is an enormous black hole at the center of the Galaxy, which is the source of X-rays.

• An accretion disk surrounding the black hole emits enormous amounts of radiation.
• The stars shown on the right are very close to the Galactic center.

• The orbit on the right of star S2 is the best fit; it has a period of about 15 years. Calculations assume a central black hole of about 4 million solar masses.
Summary

- A galaxy is stellar and interstellar matter bound by its own gravity.
- Our Galaxy is spiral.
- Variable stars can be used for distance measurement, through period–luminosity relationship.
- True extent of a galaxy can be mapped out using globular clusters.
- Star formation occurs in disk, but not in a halo or a bulge.
Summary

• Spiral arms may be density waves.
• Galactic rotation curve shows large amounts of undetectable mass at large radii, called dark matter.
• Activity near Galactic center suggests presence of a 3.7 million-solar-mass black hole.