Lecture 20: The Milky Way

Astronomy 111
The Milky Way

- Diffuse band of light crossing the night sky.
- All human cultures have names for it:
  - Celestial River
  - Celestial Road or Path
- “Milky Way” from Latin by way of Greek:
  - Greeks: Galaxias kuklos = “Milky Band”
  - Romans: Via Lactea = “Road of Milk”
Panoramic view of the Milky Way
The Starry Messenger

- **1610**: Galileo observed the Milky Way with his new telescope.
- Published his findings in his pamphlet, *Siderius Nuncius* (The Starry Messenger):
  - “For the Galaxy is nothing else than a congeries of innumerable stars distributed in clusters.”
Philosophical interlude

- **Thomas Wright (1750):**  
  - Picture motivated by theological considerations  
  - Wright made no new observations.

- **Model:**  
  - Milky Way is a thin spherical shell of stars with Sun about midway inside the shell.  
  - Look along the tangent: broad band of stars  
  - Look along thin part: few stars
Wright’s Milky Way (1750)

Few Stars

Many stars
Theory of the heavens

- **Immanuel Kant (1755):**
  Misread a newspaper account of Wright’s model.
  Also made no observations.

- **Model:**
  - Lens-shaped disk of stars rotating about its center.
  - Other “nebulae” are distant, rotating milky ways like ours.
The Herschels’ star gauges

- William & Caroline Herschel (1785):
  Counted stars along 683 lines of sight using their 48-inch telescope.
  Assumed all stars are the same luminosity, and that they could see to the edges of the system.
- Model:
  - Flattened Milky Way ("grindstone")
  - Sun very near the center.
The Herschels’ Milky Way map
The Kapteyn universe

- **Jacobus Kapteyn (1901-1922):**
  - Used photographic star counts
  - Estimated distances *statistically* based on parallaxes & proper motions of nearby stars.
  - Neglected interstellar absorption of starlight.

- **Model:**
  - Flattened disk 15 kpc across & 3 kpc thick with the Sun slightly off center.
Kapteyn model (1922)

\[ \text{kpc} = \text{kiloparsec} = 1000 \text{ pc} \]
Harlow Shapley (1915-1921)

- Harvard Astronomer
- Noticed two facts about Globular Clusters:
  - Uniformly above & below the Milky Way.
  - Concentrated on the sky toward Sagittarius.
- Observations:
  - Globular Cluster distances from RR Lyrae stars
  - Mapped the cluster distribution in space.
Shapley’s Globular Cluster distribution
Globular cluster distances

• GCs easily identified
  – Much denser concentration of stars than disk
• ~150 GCs in the Milky Way
  – Mostly in halo
  – ¼ in disk
• Use RR Lyrae variable stars in GCs
  – P-L relation gives distances
The greater Milky Way

- **Shapley’s Results (1921):**
  - Globular clusters form a subsystem centered on the Milky Way.
  - The Sun is 16 kpc from the MW center.
  - MW is a flattened disk ~100 kpc across

- **Right basic result, but too big:**
  - Shapley ignored interstellar absorption
  - Caused him to overestimate the distances.
The problem of absorption

- Absorption of starlight by interstellar dust:
  - Interstellar space is filled with gas and dust
  - Dust absorbs/scatters light, making distant objects look *fainter*.
  - *Overestimate* Luminosity distances.

- Plagues all maps of the Milky Way:
  - Shapley & Kapteyn thought it was small.
  - Trumpler (1930) showed it was significant.
Present picture

• Largely Shapley’s model, corrected for the effects of interstellar absorption.
  – A flattened disk of stars with a central bulge.
  – ~25 kpc in diameter and ~1 kpc thick
  – Sun is ~8 kpc from the center in direction of Sagittarius
  – Galactic Center and much of the disk is obscured by dust in the plane of the Galaxy
Sky: Optical
Sky: Infrared
But what does the Milky Way look like?

• Milky Way is difficult to image since we are inside of it!
  – Imagine knowing what you look like with a mirror, or what Earth looks like without leaving its surface

• Best we can do is find a nearby galaxy with similar properties to ours
Andromeda (M31)

- Nearest bright galaxy to the Milky Way:
  - Distance \( \sim 700 \text{ kpc} \)
- Many similarities to the Milky Way
  - Both large spiral galaxies
  - Similar stellar and gas content
- Andromeda gives us an approximate outside view of our own Galaxy.
Walter Baade (c. 1944)

- Took deep red & blue photos of Andromeda:
  - Disk looked blue
  - Spheroid looked red
  - Could detect many individual stars in both
- Made H-R diagrams of disk & spheroid stars:
  - Disk stars had H-R diagrams like open clusters
  - Spheroid stars had H-R diagrams like globular clusters.
Stellar ages (revisited)

• Massive Stars live short lives:
  – Massive main-sequence stars must be young
  – Low-mass M-S stars can be young or old

• Star Cluster H-R Diagrams:
  – Young Clusters: blue main-sequence stars
  – Old Clusters: no blue main-sequence stars

• “Old” = ~10 Gyr or more
Stellar populations

• Baade divided stars into two “Populations”:

• **Population I:**
  – Disk and Open Cluster stars

• **Population II:**
  – Spheroid and Globular Cluster stars

• Distinguished by:
  – Location, age, and chemical composition
Population I

- **Location**: Disk and in Open Clusters
- **Age**: Mix of young and old stars
- **Composition**: Metal rich (roughly solar)
  - 70% Hydrogen
  - 28% Helium
  - ~2% “metals”
- **Environment**: Often gas rich, especially for the young stars.
Population II

- **Location**: Spheroid and in Globular Clusters
- **Ages**: oldest stars, 10–15 Gyr
- **Composition**: metal poor (0.1–1% solar)
  - 75% Hydrogen
  - 24.99% Helium
  - ~0.01% metals
- **Environment**: gas poor, no star formation
Stellar Orbits

- A galaxy is bound together by the mutual gravitational attraction of all of its parts.
- Stars orbit about the center of mass of the galaxy.
  - **Milky Way**: measure the proper motions and radial velocities of individual stars
  - **Andromeda**: measure the combined Doppler motions of large numbers of stars.
Stellar Kinematics

• **Disk Stars:**
  – Ordered, roughly circular orbits in a plane.
  – All orbit in the same general direction.
  – Orbit speeds similar at a given radius.

• **Spheroid Stars:**
  – Disordered, elliptical orbits at all inclinations.
  – Mix of prograde and retrograde orbits
  – Wide ranges of orbital speeds.
## Pop I vs. Pop II

<table>
<thead>
<tr>
<th>Population I</th>
<th>Population II</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Disk &amp; Open Clusters</td>
<td>• Spheroid &amp; Globulars</td>
</tr>
<tr>
<td>• Young &amp; old Stars</td>
<td>• Oldest stars</td>
</tr>
<tr>
<td>• Metal-rich</td>
<td>• Metal-poor</td>
</tr>
<tr>
<td>• Blue M-S stars</td>
<td>• No blue M-S stars</td>
</tr>
<tr>
<td>• Ordered, circular orbits</td>
<td>• Random elliptical orbits</td>
</tr>
<tr>
<td>• Gas-rich environment</td>
<td>• Gas-poor environment</td>
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Chemical Evolution

• Metals form by fusion inside of massive stars
  – Supernova explosions enrich the interstellar medium with metals.
  – The next generation of stars form out of the metal-enriched interstellar gas.
  – Successive generations get more metal rich.

• *Higher* metal content in *later* generations.
Clues to galaxy formation?

- Chemical evolution only affects populations.
  - Fusion occurs in the deep interiors of stars.
  - Except for CNO elements, surface composition remains effectively unchanged over a star’s life.
  - Once a star forms, its chemical composition is mostly fixed for life.

- Metal content gives us a clue to the formation history of populations of stars.
Phase I: spheroid formation

- Start with slowly rotating, metal-poor gas clouds
  - First generation of stars are metal-poor spheroid & globular cluster stars (Pop II)
  - Massive Pop II stars go supernova and enrich the gas with metals.
  - Low-mass Pop II stars are still around today.
  - Star formation stops early-on in the spheroid.
Phase II: disk formation

- Metal-enriched gas settles into a rotating disk.
  - Next generation (old Pop I) stars have more metals, and ordered disk rotation
  - Massive old Pop I stars go supernova, enriching the disk gas further
  - Following generations (young Pop I) have even more metals (e.g., the Sun).
  - Star formation is still going on in the disk
Galactic formation mechanism

(1) 

(2) Globular clusters 

(3) 

(4)
Modern Galactic studies

- Kinematic studies to better understand Galactic formation mechanisms
- Rotation curve of Galaxy
- Existence of Dark Matter
- Black hole at the Galactic center?
21 cm radiation

- Long wavelength observations of interstellar hydrogen
  - See through dust
- Measure rotation curve of Milky Way
- Milky Way is a normal giant barred spiral galaxy
  - Type SBbc
21 cm map of Milky Way
Dark matter

- From 21 cm observations, we can measure rotation curve of Milky Way.
- Flat rotation curve implies existence of dark matter.
Dark matter

• We know that normal matter (that produces visible light) dominates inside of Milky Way
• Outer reaches of Milky Way must be made of mostly dark matter
What is dark matter?

- MACHOS: MAAssive Compact Halo Objects
  - e.g., white dwarfs, M dwarfs, planets, neutron stars, black holes
- WIMPS: weakly interacting massive particles
  - Neutrinos, an as yet undiscovered particle, micro black holes

We don’t know yet!
The Galactic center

- Observations of the Galactic center over time show stars orbiting a very massive but small object—must be a black hole!
- $3.7 \times 10^{-6} \, M_\odot$
Black hole

• Radio and infrared observations of the Galactic center show a bright source
  – Sgr A
• Black hole is unseen because it’s black
  – Sgr A*
Summary

• The **Milky Way** is our Galaxy
  – Diffuse band of light crossing the sky
  – Galileo: Milky Way consists of many faint stars

• The nature of the Milky Way
  – Philosophical speculations: Wright & Kant
  – Star counts: Herschels & Kapteyn
  – Globular cluster distribution: Shapley
Summary

- Disk & spheroid structure of the Galaxy
- Pop I Stars:
  - Young, metal-rich, disk stars
  - Ordered, nearly circular orbits in the disk
- Pop II Stars:
  - Old, metal-poor, spheroid stars
  - Disordered, elliptical orbits in all directions
- Gives clues to the formation of the Galaxy
Summary

• 21 cm observations give rotation curve of Galaxy
• Rotation curve says that Milky Way contains dark matter
• Observations show there is a (small) black hole at the Galactic center