Interstellar Medium

Most of nearby material is in stars
Interstellar space *nearly* empty (more than lab vacuum)
\[<n> \sim 1 \text{ atom/cm}^3\]
But, not empty
1. Gas
2. Dust = small solid particles
3. Relativistic matter
   1. Light
   2. Cosmic rays = relativistic particles
   3. Magnetic fields
Neutral Atomic Hydrogen Gas

21 cm Hyperfine Line of Hydrogen
1944 – van de Hulst predicts 21 cm line of atomic H
1951 – Ewen & Purcell detect
Molecular Gas

1969 – H$_2$CO detected (Snyder, others)
1970 – CO (3 mm) detected in radio
## Gaseous interstellar and circumstellar molecules (149)

<table>
<thead>
<tr>
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<td>CH₃NH₂</td>
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<td>H₂CO</td>
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<td>HNO</td>
<td>NaCN</td>
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<td>HC₃NH⁺</td>
<td>C₃H⁺</td>
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</table>
Ionized Hydrogen (H II, H\textsuperscript{+})

Photo-ionized Hydrogen

Always at T ∼ 10\textsuperscript{4} K

H II regions around OB stars

Planetary nebulae (?)

Diffuse ionized gas
Emission nebulae:
Emission lines from atomic hydrogen H I, helium He I

Why atomic H in ionized H region?
Made by recombination, $H^+ + e^- \rightarrow H^0$
Collisionally Ionized Gas

Generally at $T \sim 10^6$ to $10^8$ K

Due to shocks from SNe and stellar winds

Supernova remnants

Diffuse hot gas
Interstellar clouds

ISM is inhomogeneous, gas and dust in clouds

1930’s – Beals and others
Pressure Equilibrium

n increases as T decreases

n T ≈ constant

pressure equilibrium?
Tranquil or Violent ISM?

Tranquil (Swan Lake):
Gas slowly cools, condenses into clouds, clouds make stars, stars die, add to ISM. All near equilibrium.

Violent (We Will Rock You):
Supernova blast through ISM, crunch gas into clouds, clouds make stars, OB stars make SN.
Star Formation
Star Formation

Density $\rho$ (stars) $\sim 1 \text{ gm/cm}$
ISM $<\rho> \sim 10^{-24} \text{ gm/cm}$
Stars form from the densest clouds
Star Formation

Internal pressure balances gravity, external pressure $P_{\text{ext}}$

\[
\frac{dP}{dr} = -\frac{GM(r)\rho}{r^2} \quad \text{hydrostatic equilibrium}
\]

\[
\left\langle \frac{dP}{dr} \right\rangle = \frac{\Delta P}{\Delta r} = \frac{P_{\text{ext}} - P_c}{R}, \quad P_c \equiv \text{central pressure}
\]

\[
\rho \sim \frac{M}{R^3}
\]

\[
-\frac{GM(r)\rho}{r^2} \sim -\frac{GM}{R^2} \frac{M}{R^3} \sim -\frac{GM^2}{R^5}
\]
Star Formation

\[ \frac{-GM(r)\rho}{r^2} \sim -\frac{GM^2}{R^5} \]

\[ P_c = \frac{\rho_c kT}{\mu} \sim \frac{MkT}{R^3 \mu} \]

\[ \frac{P_{ext} - P_c}{R} \sim -\frac{GM^2}{R^5} \]

\[ P_{ext} \sim \frac{MkT}{R^3 \mu} - \frac{GM^2}{R^4} \]

\[ P_{max} = \left[ \left( \frac{kT}{\mu} \right)^4 \frac{\pi}{G^3 M^2} \right] \]
Star Formation

Unstable (collapse) if:

- External pressure too strong

\[ P_{\text{ext}} \geq P_{\text{max}} = \left[ \left( \frac{kT}{\mu} \right)^4 \frac{\pi}{G^3 M^2} \right] \]

- Gravity too strong

\[ M \geq M_{\text{Jeans}} = \left[ \left( \frac{kT}{\mu} \right)^4 \frac{\pi}{G^3 P_{\text{ext}}} \right]^{1/2} \]
Star Formation

Triggers:

1. Clouds coalesce, grow until $M > M_{\text{Jeans}}$, collapse, form star or stars

2. External pressure on cloud increases suddenly
   1. Nearby supernova
   2. Nearly HII region, heating by OB stars
   3. Spiral arm shocks in galaxies
   4. Collapse and formation of galaxy or merger of galaxies

Fragmentation of large cloud => stars form in clusters
Star Formation

Angular momentum: forms a disk
Magnetic field: helps remove angular momentum, disk makes a jet
Star Formation

- a. Dark cloud
- b. Gravitational collapse
- c. Protostar
- d. T Tauri star
- e. Pre-main-sequence star
- f. Young stellar system
ALMA Image of Disk around HL Tau
Star Formation
The Milky Way
Our Galaxy - Love It or Leave It!
ASTR 2110
Sarazin
The Milky Way – Our Galaxy
“In” the Milky Way

- Stars
- Open star clusters
- Gas
  - Emission nebulae
  - Atomic hydrogen
  - Molecular hydrogen
- Dust
  - Dark nebulae
  - Reflection nebulae
“Out of” the Milky Way

- Globular star clusters
- Galaxies
  - Spiral nebulae
  - Elliptical nebulae
Is the Milky Way the Whole Universe?

Everybody knows their place in it?
What is the Size and Shape of the Milky Way?

Where are we located in it?

Early 1900’s -> this is the whole Universe?
Kapteyn Model & Star Counts

Plot # of stars brighter than some flux or magnitude [N(>f)] vs. the flux f

Assume

1. All stars have the same luminosity (OK, just do average)
2. No extinction (wrong)
Star Counts

\[ f = \frac{L}{4\pi d^2} \Rightarrow d = \sqrt[3]{\frac{L}{4\pi f}} \]

If flux > \( f \), \( \Rightarrow \) distance < \( d \)

\[ n \equiv \frac{\text{# stars}}{\text{volume}}, \text{ assume uniform} \]

\[ N(< d) = n \frac{4\pi d^3}{3} \]

\[ N(> f) = \frac{4\pi}{3} n \left[ \left( \frac{L}{4\pi f} \right)^{1/2} \right]^3 = \frac{4\pi}{3} n \left( \frac{L}{4\pi f} \right)^{3/2} \]

\[ N(> f) \propto f^{-3/2} \]
Kapteyn Model & Star Counts

1. Found $N(>f)$ stops sooner (fewer faint stars) out of MW plane
2. Same number of stars in all directions within the plane

Milky Way is flattened disk, Sun close to center?

Pre-Copernicus?
Globular Cluster Distribution

Centered in Sagittarius

This is center of Milky Way

But, how far away?

Shapley
Cepheid Variable Star Distances

Pulsating variable stars
\[ P_{\text{pul}} \approx (G \rho)^{-1/2} \]
Giants → bigger = lower density, longer period, and brighter

Henrietta Leavitt
Cepheid Variable Star Distances

- **Cepheid Variables**
  - Brighter Cepheid Variables
  - Fainter Cepheid Variables

- Graph showing the relationship between luminosity ($L_{\text{sun}}$) and period (days):
  - Luminosity scale: $10^2$ to $10^4$
  - Period scale: 1 to 100 days
Cepheid Variable Star Distances

Complication: two kinds of Cepheid variable with similar luminosities and periods
Distance to Galactic Center

$R_0 = 8\text{ kpc}$

Shapley
Structure of Milky Way
Structure of Milky Way
Milky Way – IR COBE Picture
Structure of Milky Way - Bar
Galactic Coordinates

l = longitude, measure from Galactic Center
b = latitude, measured from Galactic plane
Is the Milky Way the Whole Universe?

Everybody knows their place in it?
What are Spiral and Elliptical Nebulae?

- Part of Milky Way, small objects, Milky Way is the whole Universe?
- Similar to Milky Way ("island universes"), big objects, very big big Universe?
Edge-On Spirals $\approx$ Milky Way?
Curtis-Shapley Debate

Heber Curtis
U.Va. grad alumus

Harlow Shapley

National Academy of Sciences, 1920
**Curtis-Shapley Debate**

<table>
<thead>
<tr>
<th>Shapley – Spirals local</th>
<th>Curtis – Spirals distant</th>
</tr>
</thead>
<tbody>
<tr>
<td>M101 rotates, proper motion (Von Maanen) → ( v&gt;c ) if distant</td>
<td>Observation wrong</td>
</tr>
<tr>
<td>Spiral spectra ≠ stars</td>
<td>Mixture of stars and bad spectra</td>
</tr>
<tr>
<td>Novae seen in spirals → close</td>
<td>Not novae (1930’s → supernovae)</td>
</tr>
<tr>
<td>Spirals brighter than Milky Way</td>
<td>Absorption in Milky Way</td>
</tr>
<tr>
<td>Spirals avoid MW → part of it, ejected from disk</td>
<td>Absorption in Milky Way</td>
</tr>
<tr>
<td>Spirals redshifted, receding from us (Slipher) → ejected from MW disk</td>
<td>Huh?</td>
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Shapley won “debate”
Edwin Hubble (1923)

Andromeda Galaxy (M31)
• Resolved into stars

• Measured Cepheids $\rightarrow$ distance = 800 kpc
It’s a Big Universe!
It’s a Big Universe!

- ~ $10^{12}$ galaxies in visible Universe
- ~ 5000 Mpc or ~ 13 billion light years in size