Interstellar Medium (ISM)
Interstellar Extinction
Star Formation
Interstellar Medium (ISM): A Global Picture

- “The stuff between the stars”
- Initially all of the baryonic content of the universe is a gas; and the baryonic dark matter probably still is
- Stars are formed out of the ISM, and return enriched gas to it via stellar winds, PNe, SNe - a cosmic ecology
- A complex physical system with many components and structures
Basic ISM Phenomenology

• Interstellar gas and dust, usually mixed
• Generally concentrated in the disk of the Galaxy
• Distinct clouds within the ISM are called nebulae:
  – Dark (opaque)
  – Emission line (H II regions, powered by the UV emission from young stars)
  – Reflection (from the dust grains)
A Basic Tool: Spin-Flip (21 cm) Line of H I

In emission generally originates from warm (T ~ 100 - 6000 K) ISM, which accounts for ~ 30 - 65% of the total ISM volume in the Galactic disk. In absorption, it probes a cooler ISM (can be also self-absorbed).

A major advantage: it is not affected by the dust absorption!
Global Distribution of H I in the Milky Way

Concentrated in the Galactic Plane, but high-latitude features exist. These are believed to be remnants of SN and star formation driven shells and bubbles.
L-V Diagrams

A radio telescope measuring a line (e.g., 21 cm line of H I, or a molecular line such as the CO) provides intensity as a function of velocity at any given pointing. If the resulting map is compressed in one spatial direction (e.g., latitude), the result is an “L-V diagram”, which shows the line intensity in a plane of velocity and the other coordinate (typically the Galactic longitude).

If one has a rotation curve of the Galaxy, this can then be translated into a 3-D distribution of gas and its kinematics.
Multi-Phase ISM

The ISM has a complex structure with 3 major components:

1. **Cold** ($T \sim 30 - 100$ K), dense ($n_{\text{HI}} > 10$ cm$^{-3}$) atomic (H I) and molecular (H$_2$, CO, ...) gas and dust clouds
   - Only $\sim 1 - 5 \%$ of the total volume, but most of the mass
   - Confined to the thin disk
   - Low ionization fraction ($x_{\text{H}^{\text{II}}} < 10^{-3}$)
   - Stars are born in cold, dense clouds

2. **Warm** ($T \sim 10^3 - 10^4$ K) neutral & ionized gas, $n \sim 1$ cm$^{-3}$
   - Energized mainly by UV starlight
   - Most of the total ISM volume in the disk

3. **Hot** ($T \sim 10^5 - 10^6$ K), low density ($n \sim 10^{-3}$ cm$^{-3}$) gas
   - Galactic corona
   - Almost fully ionized, energized mainly by SN shocks
Actually, it is a bit more complicated … There are five thermal phases of the ISM:

- **Molecular clouds:** $T \sim 10\text{-}20$ K, $n > 10^3$ cm$^{-3}$, $< 1\%$ of the volume, $\sim 30\text{-}60\%$ of the mass, gravitationally bound (protostellar) clouds with $M \sim 10^3\text{-}10^6$ M$_\odot$

- **Cold neutral medium (CNM):** H I absorption, $T \sim 100$ K, $n \sim 20\text{-}60$ cm$^{-3}$, $\sim 1\text{-}5\%$ of the volume, in pressure equilibrium

- **Warm neutral medium (WNM):** H I emission, $T \sim 6000$ K, $n \sim 0.3$ cm$^{-3}$, $\sim 30\text{-}60\%$ of the volume

- **Warm ionized medium (WIM):** H II emission, $T \sim 6000\text{-}12000$ K, $n \sim 0.1$ cm$^{-3}$, only $\sim 10\%$ is in bright H II regions

- **Hot ionized medium (HIM):** X-ray and far-UV absorption, soft X-ray emission, $T \sim 10^5\text{-}10^6$ K, $n < 0.01$ cm$^{-3}$

- There is a constant and complex exchange of mass, energy, and momentum among these phases, with an input from stars as well (and AGN, if present)
Absorption of Light (In General)

If the radiation travels through a medium which absorbs (or scatters) radiation, the energy in the beam will be reduced:

\[
\begin{align*}
I_0 & \rightarrow I_0 + dI_0 \\
\text{dA} & \quad \text{dS}
\end{align*}
\]

Number density of absorbers (particles per unit volume) = \( n \)

Each absorber has cross-sectional area = \( s \) (units cm\(^2\))

If beam travels through \( ds \), total area of absorbers is:

number of absorbers \( \times \) cross-section = \( ndAds \)
Fraction of radiation absorbed = fraction of area blocked:

\[
\frac{dI}{I} = \int n \, dA \, ds = \int n \, ds
\]

\[
dI = \int n \, I \, ds = \int I \, ds
\]

**absorption coefficient** (units cm\(^{-1}\))

Can also write this in terms of mass:

\[
\equiv \int I \, ds
\]

\(\equiv\) is called the mass absorption coefficient or the **opacity**.

Opacity has units of cm\(^2\) g\(^{-1}\) (i.e. the cross section of a gram of gas).

*(From P. Armitage)*
Equation of radiative transfer for pure absorption:
Rearrange previous equation:
\[
\frac{dI}{ds} = aI
\]

Different from emission because depends on how much radiation we already have.

Integrate to find how radiation changes along path:
\[
\left[ \ln I \right]_{s_0}^s = \int_{s_0}^s I ds
\]

\[
I(s) = I(s_0)e^{\int_{s_0}^s I ds}
\]

(From P. Armitage)
e.g. if the absorption coefficient is a constant (example, a uniform density gas of ionized hydrogen):

\[ I_{n}(s) = I_0 e^{-a_n s} \]

Specific intensity after distance \( s \)

Initial intensity

Radiation exponentially absorbed with distance

Radiative transfer equation with both absorption and emission:

\[ \frac{dI_n}{ds} = \nabla I_n + j_n \]

(absorption) (emission)

(From P. Armitage)
Optical depth

Look again at general solution for pure absorption:

\[ I(s) = I(s_0) e^{-\alpha s} \]

Imagine radiation traveling into a cloud of absorbing gas, exponential defines a scale over which radiation is attenuated.

When:

\[ \int_{s_0}^{s} \alpha(s) ds = 1 \]

…intensity will be reduced to \( 1/e \) of its original value.

(From P. Armitage)
Define **optical depth** $\tau$ as:

$$
\tau(s) = \int_{s_0}^{s} \kappa(s') ds'
$$

or equivalently $d\tau = \kappa ds$

A medium is **optically thick** at a frequency $\nu$ if the optical depth for a typical path through the medium satisfies:

$$
\tau \geq 1
$$

Medium is said to be **optically thin** if instead:

$$
\tau < 1
$$

Interpretation: an optically thin medium is one which a typical photon of frequency $\nu$ can pass through without being absorbed.

*(From P. Armitage)*
Interstellar Dust Grains

Probability of interaction with a photon increases for photons whose wavelength is comparable to or smaller than the grain size; longer wavelength photons pass through. Thus interstellar extinction \( = f(l) \). (Note: this breaks down for high-energy photons)
The bump at $\lambda \sim 2200 \, \text{Å}$ is due to silicates in dust grains. This is true for most Milky Way lines of sight, but not so in some other galaxies, e.g., the SMC.
Interstellar Extinction in Standard Photometric Bandpasses

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$E(\lambda - V)/E(B - V)$</th>
<th>$A_\lambda/A_V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U$</td>
<td>1.64$^a$</td>
<td>1.531</td>
</tr>
<tr>
<td>$B$</td>
<td>1.00$^b$</td>
<td>1.324</td>
</tr>
<tr>
<td>$V$</td>
<td>0.0$^b$</td>
<td>1.000</td>
</tr>
<tr>
<td>$R$</td>
<td>$-0.78^b$</td>
<td>0.748</td>
</tr>
<tr>
<td>$I$</td>
<td>$-1.60^b$</td>
<td>0.482</td>
</tr>
<tr>
<td>$J$</td>
<td>$-2.22 \pm 0.02$</td>
<td>0.282</td>
</tr>
<tr>
<td>$H$</td>
<td>$-2.55 \pm 0.03$</td>
<td>0.175</td>
</tr>
<tr>
<td>$K$</td>
<td>$-2.744 \pm 0.024$</td>
<td>0.112</td>
</tr>
<tr>
<td>$L$</td>
<td>$-2.91 \pm 0.03$</td>
<td>0.058</td>
</tr>
<tr>
<td>$M$</td>
<td>$-3.02 \pm 0.03$</td>
<td>0.023</td>
</tr>
</tbody>
</table>

Note:
This is the ratio of extinction in magnitudes!

Dramatically lower extinction in IR! Which is why we use IR imaging to see through the dust…
Stars form out of dense, cold, often dusty, molecular gas. In spiral galaxies, star formation is concentrated along spiral arms, where gas is compressed.
Part of Orion molecular cloud complex

Same is true on smaller scales. Observe:

**Giant molecular clouds**

$M \sim 10^6 M_{\text{Sun}}, R \sim 10 \text{ pc}$

$\rightarrow$ star clusters

...on large scales, down to:

**Molecular cloud cores**

$M \sim \text{few Solar masses}$

$R \sim 0.1 \text{ pc}$

$\rightarrow$ one or a few stars

*(From P. Armitage)*
Star-forming regions appear when a giant molecular cloud is compressed.

This can be caused by the cloud’s passage through a spiral arm, by a SN explosion, or by other mechanisms.
Most young stars seem to have formed in clusters, ranging from relatively small groups such as Taurus to much larger clusters such as Orion. Ionizing radiation from massive stars provides a strong feedback, and tends to blow away the leftover gas...

Most stars today probably form in environments similar to this.

(From P. Armitage)
Protostars form in cold, dark nebulae

- Star formation begins in dense, cold nebulae, where gravitational attraction causes a clump of material to condense into a protostar.
- As a protostar grows by the gravitational accretion of gases, Kelvin-Helmholtz contraction causes it to heat and begin glowing.
Summary: star formation on large scales

1) Stars form out of molecular gas which is assembled into dense molecular clouds in spiral arms.

2) Molecular clouds have a complex, often filamentary structure. Individual stars, or small groups, form from the smallest scale structures, cloud cores of size ~0.1 pc.

3) Molecular clouds probably have lifetimes of $10^6$ to $10^7$ yr, which is only a few dynamical times. Star formation is a fairly rapid process once molecular clouds have formed.

4) If massive stars form within a young cluster, their ionizing radiation / stellar winds / supernovae destroy the molecular cloud on a short time scale.

5) Most stars (~80%) form in clusters at least as rich as Orion.

(From P. Armitage)
Basic physics of star formation

Consider the forces acting on a `star forming unit’ within a molecular cloud - a molecular cloud core:

- Gravity - act to collapse the cloud
- Pressure
- Magnetic fields
- `Bulk motions’ - sources of support against collapse to form a star

If somehow we form a core in which gravity dominates over all other forces, collapse will occur on the dynamical or free-fall time:

\[
\nu_{\text{esc}} = \sqrt{\frac{2GM}{R}}
\]

\[
\tau_{\text{dyn}} = \frac{R}{\nu_{\text{esc}}} = \sqrt{\frac{R^3}{2GM}} \sim \frac{1}{\sqrt{G\rho}}
\]

…for a cloud of mass M, radius R, and mean density \( \rho \).

(From P. Armitage)
The Jeans Mass

Ignore for now magnetic fields and bulk motions. The Jeans mass is the minimum mass a cloud must have if gravity is to overwhelm pressure and initiate collapse.

Borderline case is one where the cloud is in hydrostatic equilibrium:

\[ \frac{dP}{dr} = -\frac{Gm}{r^2} \]

To derive an estimate of the Jeans mass, consider a cloud of mass M, radius R:

- approximate derivative dP/dr by -P / R
- assume pressure is that of an ideal gas:

\[ P = \frac{R_g}{T} \]

…where \( R_g \) is the gas constant (avoid confusion with radius)

(From P. Armitage)
Substitute: 

\[ \frac{R_g}{R} \frac{T}{R} = \frac{GM}{R^2} \]

\[ M = \frac{R_g}{G} TR \]

Can eliminate R in favor of the density \( \rho \) using: 

\[ M = \frac{4}{3} R^3 \rho \]

\[ M = \frac{R_g}{G} T \left( \frac{3}{4} \right)^{1/3} M^{1/3} \left( \frac{1}{3} \right)^{1/3} \]

Tidy this up to get a final expression for the **Jeans mass**:

\[ M_J = \frac{R_g}{G} \left( \frac{3}{4} \right)^{3/2} T^{3/2} \]

Basic formula for star formation. Numerical constants don’t matter and vary depending on the details of the derivation.

*(From P. Armitage)*
Mass scale of star formation

Observationally, stars form from cold dense molecular gas:
  • \( \rho \sim 10^{-19} \text{ g cm}^{-3} \)
  • \( T \sim 10 \text{ K} \)

Use these numbers in the Jeans mass formula, and take \( \mu = 2 \) for molecular hydrogen:

\[
M_J = 7.6 \mu 10^{32} \text{ g} \mu 0.4 M_{\odot}
\]

…which matches the typical mass of stars in the Galaxy!

Level of agreement here is `too good to be true’ - however can conclude that the Jeans mass in these conditions is about a Solar mass and sets the basic mass scale for star formation.

(From P. Armitage)
Can likewise define a characteristic length scale (the Jeans length), by eliminating mass rather than radius from the previous expression:

\[ \frac{4}{3} \frac{\mu}{R^3} = \frac{R_g}{G} TR \]

\[ R_J = \left( \frac{R_g}{G} \frac{1}{2} \frac{3}{4} T^{1/2} \right)^{1/2} \]

For the same density / temperature as before, \( R_J = 10^4 \) AU

Free-fall timescale for a cloud of this density is:

\[ \frac{1}{\sqrt{G}} = 10^{13} \text{ s} = 4 \times 10^5 \text{ yr} \]

Conclude: star formation in these conditions ought to yield Solar mass stars within a few hundred thousand years.
Collapse of a Protostellar Cloud

Another manifestation of the gravothermal "catastrophe", or core collapse
Collapse of a Protostellar Cloud

Dramatic increase in central density leads to the onset of thermonuclear reactions; deuterium burns first.
What happens during the collapse?

Jeans mass formula: \( M_J \propto T^{3/2} \rho^{1/2} \)

Initially: gas is optically thin and can cool efficiently due to radiation from molecules such as carbon monoxide.

Collapse is **isothermal** during the early stages (\( T \) constant).

If \( T \) stays constant while \( \rho \) increases:

- Gravity becomes even more dominant over pressure
- \( M_J \) drops - allows for possibility that the cloud might break up into smaller fragments during the collapse itself

*(From P. Armitage)*
Protostars and pre-main-sequence stars

Jeans’ mass - minimum mass of a gas cloud of temperature $T$ and density $\rho$ that will collapse under gravity:

$$M_J = \frac{R_g^{3/2}}{\sqrt{4G}} \frac{3}{T^{3/2}}$$

Several stages of collapse:

- Initial isothermal collapse - still optically thin
- Collapse slows or halts once gas becomes optically thick - heats up so pressure becomes important again
- Second phase of free-fall collapse as hydrogen molecules are broken up - absorbs energy and robs cloud of pressure support
- Finally forms protostar with radius of 5 - 10 $R_{\text{sun}}$

All this happens very rapidly - not easy to observe

(From P. Armitage)
Observationally, classify young stellar objects (YSOs) by looking at their **spectral energy distributions** (SEDs). Four main classes of object have been identified:

![Graph](image)

**Class 0 source**

Observationally, this is a source whose SED peaks in the far-infrared or mm part of the spectrum. No flux in the near-infrared (at a few microns). Effective temperature is several 10s of degrees Kelvin.

*(From P. Armitage)*
What are Class 0 sources?
- Still very cool - not much hotter than molecular cloud cores. Implies extreme youth.
- Deeply embedded in gas and dust, any shorter wavelength radiation is absorbed and reradiated at longer wavelengths before escaping.
- Fairly small numbers - consistent with short duration of the initial collapse.
- Outflows are seen - suggests a protostar is forming.

Earliest observed stage of star formation...

(From P. Armitage)
Class 1 sources also have SEDs that rise into the mid and far infrared. But they differ from Class 0 in having detectable near infrared flux.

Still not seen at visible wavelengths.

(From P. Armitage)
Structure of Class 1 sources:

Still can’t see the star itself, but dust has cleared enough to see the hot gas and dust close to the star.

Absorption and reradiation of this near-infrared flux by the dust in the envelope produces the far-infrared peak.

(From P. Armitage)
A Schematic View of a Protostar With a Bipolar Outflow

Observed line profiles
A protostar accretes from a disk, and ejects along the rotation axis (a way to bypass the Edington limit?)
Clumps of glowing gas called Herbig-Haro objects are sometimes found along these jets and at their ends.
Class 2 sources: Classical T Tauri stars

Flat or falling SEDs in the mid-infrared
Optically visible pre-main-sequence stars

Also called classical T Tauri stars, after the prototype star T Tauri in the Taurus star forming region.

(From P. Armitage)
By this stage almost all of the collapsing cloud has settled onto the star or onto a disk surrounding the star.

From most angles we can see the young star directly.

Disk slowly drains onto the star over several million years.

(From P. Armitage)
Class 3 sources: Weak-lined T Tauri stars

Fairly normal stellar SEDs, but more luminous than main sequence stars of the same effective temperature (ie they lie above the main sequence).
Also more active (eg in X-ray emission) than ordinary main sequence stars.

(From P. Armitage)
The more massive the protostar, the more rapidly it evolves

(a) Mass more than about $4 \, M_\odot$: Energy flows by convection in the inner regions and by radiation in the outer regions.

(b) Mass between about $4 \, M_\odot$ and $0.8 \, M_\odot$: Energy flows by radiation in the inner regions and by convection in the outer regions.

(c) Mass less than $0.8 \, M_\odot$: Energy flows by convection throughout the star’s interior.
Young stars descend onto the zero-age main sequence (ZAMS) along the Hayashi tracks.

They leave the MS along nearly the same tracks when they become red giants.
Protostars Evolve Into Main-Sequence Stars

- A protostar’s relatively low T and high L place it in the upper right region on an H-R diagram.
- Further evolution of a protostar causes it to move toward the MS.
- When its core T become high enough to ignite steady H burning, it becomes a MS star.
HR diagram for young stars

Filled circles: class 2 sources (classical T Tauri stars)
Open circles: class 3 sources (weak-lined T Tauri stars)

(From P. Armitage)
Fraction of stars with near-infrared excess emission (disks) as a function of the age of the cluster they are in.

(From P. Armitage)
Star Formation Feedback: A Self-Regulating Process?

• The most massive young stars (O, B) emit strong UV radiation that ionizes H in the remaining cloud, creating an H II region, and preventing subsequent star formation.

• Radiation pressure and stellar winds from the O and B stars also create shock waves, which may also disrupt star formation, or enhance it by compressing the gas and triggering the formation of more protostars.

• Eventually SN explosions clear out the gas.

• Thus, only a few % of the initial cloud mass may be turned into stars.

• However, if star formation proceeds rapidly, a large fraction of the cloud may be converted into stars - this is the starburst mode of star formation.