Interstellar Medium
ASTR 2110
Sarazin
Interstellar Medium

Put you in contact with dead relatives on other planetary systems?

NO
Interstellar Medium

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

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Dust

1780 – W. Herschel – dark nebulae
1847 – Struve – due to absorption, ~1 mag/kpc
  1 kpc = 1000 pc
1930 – Trumpler – uses open star cluster sizes to measure distance, finds flux < L/(4πd^2)
\[ f = \frac{L}{4\pi d^2} \] no absorption

\[ \theta = \frac{D}{d} \] angular diameter

\[ D = \text{diameter of cluster} \]

\[ f = \frac{L}{4\pi D^2 \theta^2} \]
Dust Extinction

\[ f = \frac{L}{4\pi d^2} e^{-\tau} \text{ absorption} \]

\[ \tau = \int \kappa \rho \, dl = \kappa \rho d \propto d \]

further stars fainter

\[ \tau \approx \frac{d}{\text{kpc}} \approx A \]

\[ A \equiv m(\text{obs}) - m(\text{no dust}) \]

\[ A \equiv \text{extinction} \]

\[ A = -2.5 \log \left( \frac{f(\text{obs})}{f(\text{no abs})} \right) = -2.5 \log(e^{-\tau}) \]

\[ A \approx 1.08 \tau \]
Dust Extinction

$$A_V \equiv V_{\text{obs}} - V_{\text{emit}}$$

$$m = M + 5 \log d_{\text{pc}} - 5 + A$$
Reddening

1940 – Stebbins & Whitford – photoelectric photometry, reddening, extinction curve

Extinction reddens starlight
Extinction curve

$A_\lambda \propto 1/\lambda \rightarrow$ small, solid, dielectric particles = dust grains
Dust Extinction and Reddening

Reddening and Extinction

Long wavelength (redder light)

Less intensity

Dust

Most of the long wavelength light makes it through. The original light is “de-blued.”

Short wavelength (bluer light)

Most of the short wavelength light is scattered away from its original direction.
Dust Extinction and Reddening

\[
A_V \equiv V_{\text{obs}} - V_{\text{emit}} \\
m = M + 5 \log d_{\text{pc}} - 5 + A \\
E_{B-V} \equiv (B - V)_{\text{obs}} - (B - V)_{\text{emit}} \\
A_V \approx 3 E_{B-V} \equiv R E_{B-V}
\]
Example:

B0 V (main sequence) star, observed with $V = 9.60$ and $B-V = 0.90$. Assume $R = 3$. What is distance (in pc)?
Example:

B0 V (main sequence) star, observed with \( V = 9.60 \) and \( B-V = 0.90 \). Assume \( R = 3 \). What is distance (in pc)?

\[
M_V = -4.00, \quad M_B = -4.30 \quad \text{(Table A.5)}
\]

\[
E_{B-V} = (B-V)_{\text{obs}} - (B-V)_{\text{em}} = (B - V) - (M_B - M_V)
\]
\[
= 0.90 - (-4.30 - -4.00) = 0.9 + 0.3 = 1.20
\]

\[
A_V = R \times E_{B-V} = 3 \times 1.2 = 3.6
\]

\[
V = M_V + 5 \log d_{pc} - 5 + A_V
\]

\[
5 \log d_{pc} = V - M_V + 5 - A_V
\]
\[
= 9.6 - (-4.0) - 3.6 + 5 = 15
\]

\[
d = 10^3 \text{pc} = 1 \text{ kpc}
\]
Extinction curve

\[ A_\lambda \propto \frac{1}{\lambda} \rightarrow \text{small, solid, dielectric particles = dust grains} \]
Dust Composition

UV 2200 Angstrom bump, graphite or other carbons

Infrared
Silicates 10, 18 µ
Ices 3.1 µ (H₂O, NH₃, etc.), dense cold clouds
Polycyclic Aromatic Hydrocarbons (PAHs)
A typical dust grain (note the tiny scale!).
ISO spectrum of NGC7023
(D. Cesarsky et al. 1996)

\[ I_v (\text{MJy sr}^{-1}) \]

\[ \lambda (\mu\text{m}) \]

- C skel
- In-plane C-H bend
- Out-of-plane C-H bend

Peaks at:
- 6.25
- 7.62
- 8.6
- 11.3
- 12.0
- 12.7
- 13.55
Benzene

Coronene $C_{24}H_{12}$

Quartet

Anthracene $C_{14}H_{10}$

Trio

Mono

Circumcoronene $C_{54}H_{18}$

Hexabenzocoronene $C_{42}H_{18}$
Dust Scattering
Dust Scattering

Reddening and Extinction

Long wavelength (redder light)

Less intensity

Most of the long wavelength light makes it through. The original light is “de-blued.”

Short wavelength (bluer light)

Most of the short wavelength light is scattered away from its original direction.
Scattering = Blue Sky

Blue light scatters more than red light. When the Sun is high in the sky you will see all of the colors if you look right at the Sun. But looking in other directions, you will see just the blue colors because some of the blue sunlight will be scattered back to you. When the Sun is near the horizon, the blue sunlight is scattered away leaving only the red and orange sunlight---the Sun appears red.
Dust Polarization

extinction also polarizes light

non-spherical dust grains, aligned by magnetic field

in ISM
Dust Temperatures

Dust not evaporate

$T \lesssim 1000 \text{ K}$

Heating from star light
Dust Temperatures

\[
\left( \frac{dE}{dt} \right)_{\text{absorbed}} = \left( \frac{dE}{dt} \right)_{\text{emitted}}
\]

\[ F \equiv \text{flux of starlight (erg/cm}^2/\text{sec)} \]

\[
\left( \frac{dE}{dt} \right)_{\text{absorbed}} = (\pi a^2) F \epsilon_{\text{absorption}}
\]

\[
\left( \frac{dE}{dt} \right)_{\text{emitted}} = (4\pi a^2) \sigma T^4 \epsilon_{\text{emission}}
\]

Blackbody = perfect emitter and absorber

\[ \epsilon_{\text{absorption}} = \epsilon_{\text{emission}} = 1 \]

Real grains, \( \epsilon \approx a/\lambda \)

\[ T \approx 30 \left( \frac{F}{\text{erg/cm}^2/\text{sec}} \right)^{1/5} \text{ K} \]

Far from star, \( F \approx 0.02 \text{ erg/cm}^2/\text{sec} \) background

\[ T \geq 10 \text{ K} \]
Dust Temperatures

Dust not evaporate

\[ T \lesssim 1000 \text{ K} \]

Heating from star light

\[ T \gtrsim 10 \text{ K} \]
Dust Infrared Emission

$\lambda = 0.3 \text{ cm} / T \text{ Wien Law}$

$T \sim 10 - 1000 \text{ K}$

$\lambda = 300 \text{ to } 10 \text{ microns}$

absorbed starlight re-radiated in IR
Orion – visible and IR
Galactic IR Emission

\[
\frac{\lambda I_{\lambda}}{N_H} \text{ (erg s}^{-1} \text{ sr}^{-1} \text{ H}^{-1})
\]

\[
10^{-27} \quad 10^{-26} \quad 10^{-25}
\]

\[
\lambda \text{ (\mu m)}
\]

\[
3 \quad 5 \quad 10 \quad 20 \quad 30 \quad 50 \quad 100 \quad 200 \quad 300 \quad 500 \quad 1000
\]

- IRTS
- IRAS
- COBE DIRBE
- COBE FIRAS

21% 14% 65%

Total power/H = 5.1 \times 10^{-24} \text{ erg s}^{-1} / \text{H}
Origin of Dust Grains

nucleated in stellar outflows (winds, PNe, giants, novae, SNe, . . .)

Ices freeze onto dust in cold clouds
destroyed in shocks, star formation, in hot gas
expect continuum, molecules $\rightarrow$ grains (PAHs)
Relation to Gas

strong correlation = mixed well together

\[ N_H \equiv \int n_H \, dl = \text{number density of H atoms} \times \text{distance} \]

\[ N_H \approx 2 \times 10^{21} \, \text{cm}^{-2} \, A_V \, \text{(mag)} \]

\sim 1\% \text{ of mass of ISM in grains}

Grains not mainly H, He

mass grains \sim \text{mass of heavy elements (\sim 2\%)}

much of heavy elements are in grains
Elemental Depletions in Gas in ISM
Gas element depletions

Volitiles (C, N, O, . . .) ~ 50%

Refractories (Fe, Al, . . .) > 90% depleted
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Interstellar Medium - Gas
ASTR 2120
Sarazin
Interstellar Gas

ISM consists of different **phases** of gas, different temperatures and densities

Classify based on physical state of **hydrogen**

Molecular $\text{H}_2$

Atomic $\text{H} \ I = \text{H}^0$

Ionized $\text{H} \ II = \text{H}^+$

$<n_{\text{H}}> \sim 1 \text{ atom/cm}^3$

Very inhomogeneous

Almost no gas at $<n_{\text{H}}>$. 

[Image of interstellar gas]
Neutral, Atomic Hydrogen (H I, H\(^0\))

~50% of mass in local ISM

Interstellar Clouds

Warm Neutral Intercloud Medium

Most is fairly cold (~100 K), atoms in ground state, no normal atomic emission lines

How to see?
Interstellar gas
Atomic Hydrogen HI

1904 – Hartmann – Interstellar absorption lines
Interstellar Absorption Lines

- Stationary lines from binary stars
- Narrower than stellar lines
- Increase with distance
- $\langle v \rangle = \frac{1}{2} v(\text{star})$

→ Cold neutral gas

Most atomic lines in UV, can’t be seen except from space
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

Poles Aligned (higher energy state)

N
S

Poles Opposite (lower energy state)

N
S

A 21-cm photon is emitted when poles go from being aligned to opposite (a spin flip).
21 cm Hyperfine Line of Hydrogen

\[ \Delta E = 6 \times 10^{-6} \text{ eV} \]
\[ \nu = \Delta E / h = 1.42 \times 10^9 \text{ Hz} = 1420 \text{ MHz} \]
\[ = 1.42 \text{ GHz} \]
\[ \lambda = c / \nu = 21.1 \text{ cm} \]

3/4 of atoms in upper state, 1/4 in lower state

1 decay per 1.1 \times 10^7 \text{ years}
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
Atomic Hydrogen

Standard Clouds

\[ n_H \sim 20 \text{ atoms/cm}^3 \]
\[ T \sim 100 \text{ K} \]
\[ D \sim 10 \text{ pc} \]

Neutral Intercloud Gas

\[ n_H \sim 0.3 \text{ atoms/cm}^3 \]
\[ T \sim 2000 \text{ K} \]
Molecular Gas

Three kinds of energy levels and lines

• Electronic transitions
  – Just like individual atoms
  – Mainly in UV and optical

• Rotational transitions
  – Mainly in mm and submm radio
  – Except H, in IR

• Vibrational Transitions
  – Mainly in mid-IR
  – Except H, in near IR
Molecular Gas

1969 – $\text{H}_2\text{CO}$ detected (Snyder, others)
1970 – CO (3 mm) detected in radio
Molecular Gas $\text{H}_2$

~50% of mass

Often in dense clouds

$n(\text{H}_2) \sim 10^5$ molecules/cm$^3$

$T \sim 10$ K

$A_V > 10$

> 100 molecules now known
### Gaseous interstellar and circumstellar molecules (149)

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</table>

**Notes:**
- N indicates the number of nitrogen atoms.
- Some molecules are marked with a question mark (?) indicating uncertainty in their presence.
Molecular Masers

Tiny sources of VERY bright molecular radio lines

If thermal, would require $T > 10^{12}$ K

OH, H$_2$O, SiO

Require very high densities and/or strong radiation fields

need protostars or old stars (giants, supergiants)
Ionized Hydrogen (H II, H\(^+\))

Photo-ionized Hydrogen

Always at T \(\sim\) 10\(^4\) K

H II regions around OB stars

Planetary nebulae (?)

Diffuse ionized gas
Emission Nebulae

1930’s – Strömgren, Menzel, Baker, Goldberg, . . .

emission nebulae = photoionized hydrogen gas
Why are H II regions sharply defined?

O, B stars make UV which ionizes H.

\( h\nu > 13.6 \text{ eV}, \lambda < 912 \text{ Å} = 91.2 \text{ nm} \)

Optical Depth of ISM to these photons

\[ \sigma \approx 7 \times 10^{-18} \text{ cm}^2 \]

\[ \tau = n_{H^0} \sigma l = n_H \frac{n_{H^0}}{n_H} \sigma l \approx 20 \left( \frac{n_H}{1 \text{ cm}^3} \right) \left( \frac{n_{H^0}}{n_H} \right) \left( \frac{l}{\text{pc}} \right) \]

If neutral, all UV absorbed in \( l < 0.05 \text{ pc} \), then stays neutral

If ionized, \( (n_{\text{HI}}/n_H) \ll 1 \), can stay ionized
Size of H II regions

All ionizing UV photons absorbed in region

Radius = $R_S$ “Strömgren radius”

# absorptions = # ionizations = # recombinations

\[ e^- + p^+ \leftrightarrow H^o + \text{photon} \]

$\frac{\text{# recombinations}}{\text{volume} \cdot \text{time}} \propto n_e n_p = \alpha n_e n_p$

$\alpha \approx 3 \times 10^{-13} \text{ cm}^3 / \text{s}$

Pure H, ionized, $n_e = n_p = n_H$

$\frac{\text{# recombinations}}{\text{sec}} = \alpha n_H^2 \frac{4\pi}{3} R_S^3$

$Q_* = \frac{\text{# ionizing photons}}{\text{sec}}$ from star(s)

$Q_* = \alpha n_H^2 \frac{4\pi}{3} R_S^3$
Emission nebulae:
Emission lines from atomic hydrogen H I, helium He I

Why atomic H in ionized H region?
Made by recombination, $H^+ + e^- \rightarrow H^0$
Emission nebulae:
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Forbidden lines of common elements (O, N, etc.) but only occur at very low densities, never in lab

\[ \text{O II} = \text{O}^+ \]

\[ \text{O III} = \text{O}^{+2} \]
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
Cas A – VLA Radio
Tycho – Chandra X-ray