Chapter 10
The Interstellar Medium

Guidepost

In a discussion of bread baking, we might begin with a chapter on wheat and flour. In our discussion of the birth and death of stars, the theme of the next five chapters, we begin with a chapter about the gas and dust between the stars. It is the flour from which nature bakes stars.

This chapter clearly illustrates how astronomers use the interaction of light and matter to learn about nature on the astronomical scale. That tool, which we developed in Chapter 7, “Starlight and Atoms,” is powerfully employed here, especially when we include observations at many different wavelengths.

We also see in this chapter the interplay of observation and theory. Neither is useful alone, but together they are a powerful method for studying nature, a method generally known as science.
### Outline

I. Visible-Wavelength Observations  
   A. Nebulae  
   B. Extinction and Reddening  
   C. Interstellar Absorption Lines  

II. Long- and Short-Wavelength Observations  
   A. 21-cm Observations  
   B. Molecules in Space  
   C. Infrared Radiation from Dust  
   D. X Rays From the Interstellar Medium  
   E. Ultraviolet Observations of the Interstellar Medium  

III. A Model of the Interstellar Medium  
   A. Four Components of the Interstellar Medium  
   B. The Interstellar Cycle  

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### A World of Dust

![Image of a star field, likely a nebula, with stars and dust]
One example of an interstellar gas cloud (nebula) is visible to the bare eye: the Orion nebula.

Three Kinds of Nebulae (1)

1) Emission Nebulae

- Hot star illuminates a gas cloud…
- excites and/or ionizes the gas (electrons kicked into higher energy states)…
- electrons recombining, falling back to ground state produce emission lines.
Three Kinds of Nebulae (2)

- Star illuminates gas and dust cloud;
- star light is reflected by the dust;
- reflection nebula appear blue because blue light is scattered by larger angles than red light;
- Same phenomenon makes the day sky appear blue (if it’s not cloudy).

Scattering in Earth’s Atmosphere

(SLIDESHOW MODE ONLY)
Three Kinds of Nebulae (3)

Dense clouds of gas and dust absorb the light from the stars behind;

3) Dark Nebulae

appear dark in front of the brighter background;

Interstellar Reddening

Red light can more easily penetrate the cloud, but is still absorbed to some extent

Blue light is strongly scattered and absorbed by interstellar clouds

Infrared radiation is hardly absorbed at all

Interstellar clouds make background stars appear redder
**Interstellar Reddening (2)**

The Interstellar Medium absorbs light more strongly at shorter wavelengths.

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**Interstellar Absorption Lines**

These can be distinguished from stellar absorption lines through:

a) Absorption from wrong ionization states

b) Small line width (too low temperature; too low density)

c) Multiple components (several clouds of ISM with different radial velocities)

The interstellar medium produces *absorption lines* in the spectra of stars.

Narrow absorption lines from Ca II: Too low ionization state and too narrow for the O star in the background; multiple components

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Wavelength
Structure of the ISM

The ISM occurs in two main types of clouds:

• HI clouds:
  Cold (T ~ 100 K) clouds of neutral hydrogen (HI);
  moderate density (n ~ 10 – a few hundred atoms/cm³);
  size: ~ 100 pc

• Hot intercloud medium:
  Hot (T ~ a few 1000 K), ionized hydrogen (HII);
  low density (n ~ 0.1 atom/cm³);
  gas can remain ionized because of very low density.

Observing Neutral Hydrogen: The 21-cm (radio) line (I)

Electrons in the ground state of neutral hydrogen have slightly different energies, depending on their spin orientation.

![Diagram of magnetic fields and 21 cm line](image)
The 21-cm Line of Neutral Hydrogen (II)

Transitions from the higher-energy to the lower-energy spin state produce a characteristic 21-cm radio emission line.

=> Neutral hydrogen (HI) can be traced by observing this radio emission.

Observations of the 21-cm Line (1)

All-sky map of emission in the 21-cm line
Observations of the 21-cm Line (2)

HI clouds moving towards Earth
HI clouds moving away from Earth

Individual HI clouds with different radial velocities resolved

Molecules in Space

In addition to atoms and ions, the interstellar medium also contains molecules.

Molecules also store specific energies in their

a) rotation

b) vibration

Transitions between different rotational / vibrational energy levels lead to emission – typically at radio wavelengths.
The Most Easily Observed Molecules in Space

- CO = Carbon Monoxide → Radio emission
- OH = Hydroxyl → Radio emission.

The Most Common Molecule in Space:

- H₂ = Molecular Hydrogen → Ultraviolet absorption and emission:

  Difficult to observe!
  But: Where there's H₂, there's also CO.
  Use CO as a tracer for H₂ in the ISM!

Molecular Clouds

- Molecules are easily destroyed ("dissociated") by ultraviolet photons from hot stars.
  
  → They can only survive within dense, dusty clouds, where UV radiation is completely absorbed.

  → "Molecular Clouds":

  Largest molecular clouds are called "Giant Molecular Clouds":
  
  Diameter ≈ 15 – 60 pc
  Temperature ≈ 10 K
  Total mass ≈ 100 – 1 million solar masses
**Interstellar Dust**

- Probably formed in the atmospheres of cool stars.
- Mostly observable through infrared emission.
- Infrared and radio emissions from molecules and dust are efficiently cooling gas in molecular clouds.

**The Coronal Gas**

- Additional component of very hot, low-density gas in the ISM:
  - $T \sim 1$ million K
  - $n \sim 0.001$ particles/cm$^3$
- Observable in X-rays
- Called “Coronal gas” because of its properties similar to the solar corona (but completely different origin!)
- Probably originates in supernova explosions and winds from hot stars
The Four Components of the Interstellar Medium

<table>
<thead>
<tr>
<th>Component</th>
<th>Temperature [K]</th>
<th>Density [atoms/cm³]</th>
<th>Main Constituents</th>
</tr>
</thead>
<tbody>
<tr>
<td>HI Clouds</td>
<td>50 – 150</td>
<td>1 – 1000</td>
<td>Neutral hydrogen; other atoms ionized</td>
</tr>
<tr>
<td>Intercloud Medium</td>
<td>10³ - 10⁴</td>
<td>0.01</td>
<td>Partially ionized H; other atoms fully ionized</td>
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<tr>
<td>(HII)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coronal Gas</td>
<td>10⁵ - 10⁶</td>
<td>10⁻⁴ – 10⁻³</td>
<td>All atoms highly ionized H</td>
</tr>
<tr>
<td>Molecular Clouds</td>
<td>20 - 50</td>
<td>10³ - 10⁵</td>
<td>Neutral gas; dust and molecules</td>
</tr>
</tbody>
</table>

The Interstellar Cycle

Stars, gas, and dust are in constant interaction with each other.

- Stars are formed from dense molecular cloud cores.
- Supernovae trigger shock waves in the ISM that lead to the compression of dense clouds and new star formation.
- Young star clusters leave trails of rarefied ISM behind.
- Young star clusters illuminate the remnants of their “mother” clouds, producing reflection nebulae.
- Supremovae of massive stars produce coronal gas and enrich the ISM with heavier elements.
### New Terms

<table>
<thead>
<tr>
<th>interstellar medium</th>
<th>giant molecular clouds</th>
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<tbody>
<tr>
<td>nebula</td>
<td>infrared cirrus</td>
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<tr>
<td>emission nebula</td>
<td>coronal gas</td>
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<tr>
<td>HII region</td>
<td>local bubble or void</td>
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<tr>
<td>reflection nebula</td>
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<tr>
<td>dark nebula</td>
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<tr>
<td>forbidden line</td>
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<td>metastable level</td>
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<td>interstellar dust</td>
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<td>interstellar extinction</td>
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<td>interstellar reddening</td>
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<td>interstellar absorption lines</td>
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<tr>
<td>HI clouds</td>
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<tr>
<td>intercloud medium</td>
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<td>pressure</td>
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<td>21-cm radiation</td>
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