Interstellar Gas

Interstellar Atoms and Molecules
Star Formation
Molecular Clouds

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Interstellar dust & gas

- Refresher on spectral lines
- Interstellar atoms and molecules
- Molecular clouds and gravitational stability
- Cloud collapse and star formation

**Reading:** Kutner Ch. 3.1–3.4 & 14.4–14.5, Ryden Ch. 5.1–5.3, 16.2-16.3, and Shu Ch. 11
Nomenclature of spectral lines

Much of the evidence for the presence of interstellar gas comes from the detection of \textbf{atomic} and \textbf{molecular} emission and absorption lines.

In astronomy, the ionization states of atoms are indicated with Roman numerals.

- Neutral hydrogen (H) is denoted $\text{H}^\text{I}$ (“H-one”).
- Ionized hydrogen (a free proton) is $\text{H}^\text{II}$ (“H-two”); compare to the usual chemical notation $\text{H}^+$.  
- Do not confuse $\text{H}^\text{III}$ with $\text{H}_2$, which is molecular hydrogen.

Other examples: Doubly-ionized oxygen ($\text{O}^{++}$) is $\text{O}^\text{III}$. In the $10^6$ K solar corona, it is common to observe $\text{Fe}^\text{IX}$ and $\text{Fe}^\text{X}$ (iron atoms that have lost 8 or 9 electrons).
Spectrum of Hydrogen

Recall that electron transitions in H give rise to radiation of discrete wavelengths.

**Lyman:** transitions to \( n = 1 \)

**Balmer:** transitions to \( n = 2 \)

And so on.

Lines within a series are sometimes labeled by Greek letters. E.g., the \( n = 2 \to 1 \) transition is called Lyman-\( \alpha \), \( n = 3 \to 1 \) is Lyman-\( \beta \), etc.
Astronomically significant Hydrogen lines

The Lyman-α line (121.567 nm) is commonly used in cosmology since it is redshifted into the visible spectrum.

Hα is the 656.28 nm line in the $n = 3 \rightarrow 2$ Balmer transition. It shows up a lot in HII regions due to atomic recombination.

The 21 cm HI line is due to an electron transition in the hyperfine levels of the 1s ground state. It is a tracer of neutral hydrogen.
Fine and hyperfine structure in the spectrum

When you look with increasing precision at the H spectrum, you find that the energy levels are **split** into sub-levels.

In QM, we approximate the interactions inside the atom to varying degrees of accuracy.

**Lowest order approximation**  Coulomb force

“**Fine structure”** corrections for relativistic motion of the electron.

“**Hyperfine structure”** interactions between electron orbital angular momentum and nuclear spin angular momentum (**spin-orbit coupling**)

The dominant interaction in the hydrogen atom (Coulomb attraction of e and p) gives rise to the energy levels. Sub-dominant interactions cause splitting of the levels, observed as “fine” and “hyperfine” structure.
Atomic excitation
Atoms can be excited via one of two methods:

\[ n = 2 \]
\[ \rightarrow \]
\[ h\nu \]
\[ n = 1 \]

(a)  

\[ \rightarrow \]
\[ \Delta E \]

(b)

Photoexcitation (or absorption) occurs when the atom absorbs a photon with an energy exactly equal to the difference between energy levels.

Collisional excitation occurs when the atom collides with another particle (normally a free electron). Some of the free particle’s kinetic energy will transfer to the internal energy of the atom.
Atomic de-excitation

Atoms can drop down to lower energy levels via one of three methods:

### (a) Spontaneous emission
- Occurs when the atom releases a photon with energy equal to the difference between energy levels (the inverse of photoexcitation).

### (b) Stimulated emission
- Occurs when the atom encounters a photon with energy equal to the difference between the energy levels.

### (c) Collisional de-excitation
- Occurs when the atom’s de-excitation is triggered by a collision with another free particle.
Atomic de-excitation

- **Spontaneous emission** is directly related to the instability of the excited states.

- In **stimulated emission**, the emitted photon has the same phase and direction as the stimulating photon, thereby amplifying the original photon signal. The rate of stimulated emission is proportional to the intensity of the radiation field at the relevant frequency.

- No photon is emitted in **collisional de-excitation**, as the free particle carries away the energy difference as additional kinetic energy.
Ionizing gas in the interstellar medium

When an atom absorbs a photon with energy greater than the ionization potential for its electron(s), the electron will be stripped from the atom. Photoionization results in the now free electron having a kinetic energy equal to the energy difference of the incoming photon and the ionization potential.

Collisional ionization can also occur, when a free electron with total kinetic energy greater than the ionization potential collides with the atom. The final speeds of the two free electrons is based on conservation of energy and momentum.

Free electrons can be captured by the ions, with a photon carrying away the excess energy. Recombination can result in the electron being located in any of the available energy states (ground or excited).
Kirchoff’s Laws of Spectroscopy

- **a** Continuous spectrum
- **b** Absorption line spectrum
- **c** Emission line spectrum
Evidence for interstellar gas

Apparent through spectral lines seen in absorption against stars or in emission elsewhere.

“Nebulae:” hydrogen emission lines, plus a variety of other bright lines not readily identifiable in the laboratory.

- **Bowen 1928:** extra lines are mostly **forbidden** lines in the spectrum of the ions, mostly neutral, singly or doubly ionized, of the more abundant elements:
  - Oxygen (O/H \(\approx 7 \times 10^{-4}\))
  - Nitrogen (N/H \(\approx 1 \times 10^{-4}\))
  - Carbon (C/H \(\approx 3 \times 10^{-4}\))

It was obvious right away that the lines must originate in very low density diffuse material, which is difficult to reproduce in labs on Earth. Best vacuum on Earth is now \(\sim 10^3 \text{ cm}^{-3}\); in space \(\sim 0.1 – 1 \text{ cm}^{-3}\).
Forbidden lines

What are **forbidden lines**? And how can we see them if they are forbidden? In short, the term is a bit of a misnomer.

► Atomic and molecular transitions are governed by selection rules that tell us what changes in quantum states are allowed during the transition. The selection rules are determined by the physical process governing the transition.

► But we approximate these interactions to varying degrees of accuracy, with the lowest-accuracy ("first-order") effects dominating and then sub-dominant "higher-order" effects added as corrections.

► Selection rules that apply to first-order effects may forbid certain transitions, but the higher-order interactions may allow the transitions (albeit at low rates). These are the "forbidden transitions" which produce **forbidden lines**.
Planetary Nebula NGC 7662 & its visible spectrum

NGC 7662: the Snowball Nebula (or “Blue Snowball Nebula”)

Almost all of the emission is in the form of spectral lines: H and He recombination lines and forbidden lines of heavier elements.

Color image taken at Mees Observatory in AST 111.

Visible spectrum from Pic du Midi Observatory.
Role of interstellar gas in the galaxy

Interstellar gas is the reservoir of material for star formation and star death.
- Stars form by gravitational collapse of interstellar clouds.
- Dying stars return fusion-processed material to the ISM, enriching it in heavier elements and providing material for new stars.

Many properties of interstellar gas clouds are measurable with high precision: density, temperature, pressure, elemental/molecular abundance, etc.
- For the purpose of studying galactic structure, dynamics, and evolution, the gas in the ISM is a useful complement to the information available from stars.
The Stellar Life Cycle

- Sun-like Star
- Massive Star (more than 8 to 10 times the mass of our Sun)
- Protostars
- Red Supergiant
- Star-Forming Nebula
- Red Giant
- Planetary Nebula
- Neutron Star
- Supernova
- White Dwarf
- Black Hole
Milky Way stars, dust, and interstellar gas

Starlight, extinction

Starlight

Dust (emission)

Molecular gas

Neutral atomic gas
The components of the ISM

Diffuse ISM  neutral atomic clouds embedded in ionized medium

Dense ISM  neutral molecular clouds

Ionized nebulae  HII regions, planetary nebulae, SN remnants

H II region NGC 604 in Triangulum (NASA/HST).
The components of the ISM
Diffuse ISM

Clouds of mass $10^3 - 10^6 M_\odot$, 10 – 100 pc in size, 10 – $10^4$ K in temperature.

- Mostly neutral atomic material embedded in a much less dense and very hot (> $10^5$ K) ionized medium.
- Mostly in the form of dark clouds with $n_H = 0.1 - 10 \text{ cm}^{-3}$ and $T = 10 - 100$ K.
- Dark because the extinction by dust they contain can be as high as $A_V \sim 3$.
- The neutral diffuse ISM fills 40%–80% of the volume of the Milky Way.
- There is about $10^9 - 10^{10} M_\odot$ of neutral diffuse ISM in the Galaxy!
- Spectral line tracers: H\textsc{i} 21 cm line; C\textsuperscript{+} line at 157.7 $\mu$m.
The components of the ISM

Dense ISM

H — neutral and mostly molecular instead of atomic — in the form of clouds with densities $n_{\text{H}_2} = 10 - 10^6 \text{ cm}^{-3}$. Temperature is $10 - 100 \text{ K}$, mass is $10^3 - 10^6 M_\odot$.

▶ As much mass (total in Galaxy) as the diffuse ISM, $10^9 - 10^{10} M_\odot$ but volume is small in comparison.

▶ **Molecular cloud complexes** are usually physically connected to complexes of diffuse atomic clouds.

▶ The visual extinction through a molecular cloud is $\gg 1$.

▶ Best spectral line tracers are rotational lines of CO. H$_2$ radiates too poorly and is excited too inefficiently to be an effective tracer.

▶ 180 molecular species have been detected so far in interstellar clouds. Smallest molecule: H$_2$; largest: C$_{70}$ fullerene.

▶ See Al Wootten’s list of reported ISM molecules at NRAO
The components of the ISM

Ionized nebulae

Include H\textsc{ii} regions, planetary nebulae, and supernova remnants.

- Hydrogen is fully ionized in ionized nebulae; other elements may be multiply ionized.
- These objects have negligible mass on the galactic scale but they are very bright at visible and radio wavelengths.
- They are the most easily noticed components of the ISM.
- Spectral line tracers: hydrogen recombination lines, “forbidden” lines of relatively abundant ions and atoms (C, N, O, etc.).
- Electron densities are usually around $n_e = 10 - 10^4$ cm$^{-3}$. Temperatures are about $10^4$ K in H\textsc{ii} regions and planetary nebulae.
The components of the ISM

Ionized nebulae

Planetary nebulae consist of gas ejected and ionized by stars with core masses below the SAC mass that are becoming white dwarfs.

HII regions are associated with young, massive O-type stars in star forming regions.

- They always seem to occur on the edges of giant molecular cloud complexes. The Orion clouds are the nearest and best example.

Supernova remnants are what their name implies. Their ionization traces the advance of the blast wave into the ISM rather than photoionization by UV starlight.

- The matter in SNRs tends to be in lower ionization states than in HII regions and planetary nebulae.
Heating and cooling of the ISM
HII regions and planetary nebulae

Heating **Photoionization** by starlight; UV light with $E > 13.6$ eV ionizes hydrogen, imparting kinetic energy to the electrons produced.

Cooling **Collisional excitation** followed by emission of forbidden lines by ions of C, N, and O (mostly). The more metals, the more efficiently the cooling.

Atomic energy levels $E$

$e$ - atom inelastic collision $h\nu$
Heating and cooling of the ISM
Neutral, Diffuse ISM

**Heating**  UV light \((h\nu = 5 - 13 \text{ eV})\) in background starlight, known as the interstellar radiation field (ISRF).
- Heating occurs via the photoelectric effect on dust grains.
- Carbon can be ionized by \(E = h\nu = 11 \text{ eV}\) photons and thus is usually singly ionized (C II) in the diffuse ISM even when hydrogen is neutral and atomic.

**Cooling**  Excitation of excited carbon (C II) by collisions with H atoms and electrons, followed by radiation in the forbidden 157.7 \(\mu\text{m}\) line.
Heating and cooling of the ISM

Molecular Clouds

**Heating** Not well understood, but we know it cannot be starlight directly. Best candidates:

- **Turbulence** driven by stellar winds and outflows.
- **Cosmic rays** ions accelerated to $10^{15}$ eV in supernova remnants.

**Cooling** Collisional excitation followed by radiation in the rotational lines of the more abundant molecules like CO, OH, H$_2$O.

- Molecular clouds are frequently dense and cold enough to be unstable and collapse under their own weight.
- As we will see, the gravitational instability of molecular clouds is the principal means by which stars are formed in the galaxy.
Molecular clouds: Internal structure

- Molecular clouds are **clumpy**; they tend to consist of denser clumps in a range of sizes and masses, blending into a less-dense background.

- Molecular clouds are **cold**; they tend to have $T < 20$ K.

- Molecular clouds are **turbulent**: the random internal velocities are typically $\sim 1$ km/s, much larger than the average molecular speeds in a quiescent gas in equilibrium at the same temperature.

- Molecular clouds (and clumps) generally **rotate** slowly.

- Molecular clouds are **magnetized**: they are threaded by the same magnetic flux present when the material was diffuse and atomic. Now it has been compressed to a much smaller size, and the fields are correspondingly larger.
Molecular clouds & star formation

As a result:

- Clumps get massive enough and cold enough that the gas pressure cannot hold up their weight, and they collapse.
  - As clumps collapse they heat in their cores.
  - If they are sufficiently massive and collapse to a small enough scale, temperatures can reach the fusion ignition point and a star is formed.

- The clumps are constantly being rearranged, compressed, or distended by turbulence.

- Collapse does not happen with spherical symmetry; often collapse is easier along the axis of rotation because of centrifugal forces.
Collapse of a clump: the Jeans mass

Consider a constant-density clump and its central pressure:

\[ P_c \approx \frac{GM^2}{R^4} \quad \text{from weight} \]

\[ = \frac{\rho kT}{\mu} \quad \text{from ideal gas law} \]

Balancing the pressure gives

\[ \frac{GM^2}{R^4} = \rho \frac{GM}{R} = \frac{\rho kT}{\mu} \quad \implies \quad \frac{M}{R} = \frac{kT}{\mu G} \]

and assuming the mass is uniformly distributed gives

\[ \rho = \frac{3M}{4\pi R^3} \quad \implies \quad R = \left( \frac{3M}{4\pi \rho} \right)^{1/3} \]

\[ \therefore \, M = \frac{kT}{\mu G} \left( \frac{3}{4\pi \rho} \right)^{1/3} M^{1/3} \quad \implies \quad M = \left( \frac{kT}{\mu G} \right)^{3/2} \left( \frac{3}{4\pi \rho} \right)^{1/2} \]
Collapse of a clump: the Jeans mass

Define the Jeans mass $M_J$ as the critical mass for collapse:

$$M = \left( \frac{kT}{\mu G} \right)^{3/2} \left( \frac{3}{4\pi \rho} \right)^{1/2}$$

If a clump’s mass exceeds the Jeans mass for its density, temperature, and composition, it will collapse under its weight.

**Example: A pure molecular Hydrogen cloud**

For a cloud of $\text{H}_2$:

$$\mu = 3.3 \times 10^{-24} \text{ g}$$
$$T = 20 \text{ K}$$
$$n = 1.4 \times 10^5 \text{ cm}^{-3}$$

\[\therefore \ M_J = 1M_\odot\]