Interstellar Gas, Dust & Star Formation

Reddening and polarization of starlight Interstellar Atoms and Molecules Molecular Clouds Gravitational Collapse Free-Fall Timescale Pre-MS stars and the Hayashi Track

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Interstellar gas, dust & star formation

Topics:

- Polarization of starlight
- Refresher on spectral lines
- Interstellar atoms and molecules
- Molecular clouds and gravitational stability
- Collapse of a spherical cloud: free-fall time
- Synopsis of star formation
- The initial mass function
- Formation of protostellar disks and jets
- Pre-MS stars and the Hayashi track

Reading: Kutner Ch. 15, Ryden Sec. 17.1



Pillar and Jets HH 901/902 Hubble Space Telescope • WFC3/UVIS

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NASA, ESA, and M. Livio and the Hubble 20th Anniversary Team (STScI)

STScI-PRC10-13a

Starting from the **Beer-Lambert Law** $f = f_0 e^{-\tau}$, we can express extinction in terms of magnitudes:

$$m_{obs} - m_0 = 2.5 \log \left(\frac{f_0}{f_0 e^{-\tau}}\right) \\ = 2.5 \log (e^{\tau}) \\ = 2.5 \tau \log e = 2.5 \tau (0.434) \\ m_{obs} = m_0 + 1.086 \tau$$

Thus we can define a wavelength-dependent extinction term $A(\lambda) = 1.086\tau(\lambda)$ such that

$$m_{\rm obs}(\lambda) = m_0(\lambda) + A(\lambda)$$
 $m_{\rm obs} - M = 5\log r - 5 + A$

In other words, the effect of extinction is to make stars look fainter than they should given their distance.

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The effect of extinction is to reduce the flux at shorter wavelengths. This makes the color of the object redder, and it reduces the overall brightness of the object (making it appear further away).



For a color index such as B - V, the individual magnitudes will be shifted by a passband-dependent extinction term:

$$V = V_0 + A_V \qquad \qquad B = B_0 + A_B$$

Hence the observed color will be

$$B - V = (B - V)_0 + (A_B - A_V) = (B - V)_0 + E(B - V)$$

The term E(B - V) is called the **color excess**. In terms of optical depth, the color excess is

$$E(B - V) = A_B - A_V = 1.086(\tau_B - \tau_V) = 1.086\tau_V \left(\frac{\tau_B}{\tau_V} - 1\right)$$

The wavelength dependence of extinction is written in terms of *R*, the ratio of total to selective extinction:

$$R_V = \frac{A_V}{E(B-V)} = \frac{1}{\frac{\tau_B}{\tau_V} - 1}$$

Since $\tau \sim \lambda^{-n}$ with n > 0, extinction is larger at shorter wavelengths (**reddening**). In other words, stars look redder than they should given their temperature. For particles with size $a \approx \lambda$, $\tau \sim \lambda^{-1}$ and

$$R_V = rac{1}{rac{ au_B}{ au_V}-1} = rac{1}{rac{\lambda_{ ext{eff},V}}{\lambda_{ ext{eff},B}}-1}pprox 4.2$$

for $\lambda_{\text{eff},B} = 445$ nm and $\lambda_{\text{eff},V} = 551$ nm.

For diffuse dark clouds, $R_V \approx 3.1$ and $\tau_V = 2.76E(B - V)$. And for dense molecular clouds, $R_V \approx 5.5$ and $\tau_V \approx 5.1E(B - V)$.

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Extinction correction

Recipe:

- 1. Reduce every B V by the same amount E(B V)
- 2. Reduce every V by the visual extinction A_V
- 3. The whole H-R diagram shifts to bluer and brighter values.
- You will be applying these corrections in future homeworks and recitations.



Extinction and reddening by real dust grains

Most interstellar grains are not just dielectric, they absorb light as well. Empirically,

$$au_a \sim \lambda^{-1.85}$$
 $\lambda = 0.5 - 20 \ \mu {
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except for certain special wavelengths (see below).

Reddening, or differential extinction, is defined by **color excesses** E(U - B) and E(B - V) where

$$\frac{E(U-B)}{E(B-V)} \approx 0.72$$



Empirical **color-color** *relation for unextinguished zero-age main sequence stars.*

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The reddening correction



Take observations at three wavelengths (e.g., *U*, *B*, *V*). Compare the color-color plot to unextinguished stars. Shift the plots until they fit. The amounts by which the cluster shifts are E(B - V) and E(U - B), in this case 0.32 and 0.18.

Polarization of light by nonspherical dust grains

Interstellar dust grains are actually not spherical; they tend to be needle-shaped or flake-like. Thus they can absorb or scatter light with some polarizations — the components of the electric field **E** along the long axis of the grain — better than others.



Polarization of light by dust grains

Interstellar dust grains are often aligned with their long axes along some given direction. That direction can be determined by external magnetic fields and/or gas motions.

 Most common alignment: B perpendicular to the long axis of spinning dust grains (Davis & Greenstein 1951).



Stellar dust grain polarization in the Galaxy (ESA & the Planck Collaboration).

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Nomenclature of spectral lines

Much of the evidence for the presence of interstellar gas comes from the detection of **atomic** and **molecular** emission and absorption lines.

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

- Neutral hydrogen (H) is denoted HI ("H-one").
- Ionized hydrogen (a free proton) is HII ("H-two"); compare to the usual chemical notation H⁺.
- ▶ Do not confuse HII with H₂, which is molecular hydrogen.

Other examples: Doubly-ionized oxygen (O^{++}) is OIII. In the 10^6 K solar corona, it is common to observe FeIX and FeX (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 = 1Balmer: transitions to n = 2And so on.

Lines within a series are sometimes labeled by Greek letters. E.g., the $n = 2 \rightarrow 1$ transition is called Lyman- α , $n = 3 \rightarrow 1$ is Lyman- β , 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 at cosmologically-important distances.

H α 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:



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:



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

Stimulated emission occurs when the atom encounters a photon with energy equal to the difference between the energy levels. **Collisional de-excitation** occurs when the atom's de-excitation is triggered by a collision with another free particle.

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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.

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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).

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Kirchoff's Laws of Spectroscopy



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 $\approx 5 \times 10^{-4}$)
 - ▶ Nitrogen (N/H $\approx 2 \times 10^{-5}$)
 - 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 $\sim 10^3$ cm⁻³; in space $\sim 0.1 - 1$ 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**.

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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.



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