Astronomy 422

Advanced Concepts in Astrophysics II

Lecture 1: The Interstellar Medium
Course Logistics

Goals:
- Improve knowledge of astrophysics
- Develop research skills

Main Areas of Study:
- Interstellar medium (ISM)
- The Milky Way Galaxy
- Galaxies and galactic evolution
- Active Galaxies
- Cosmology
- The Early Universe

- Lecture topics and reading can be found on the syllabus
- Term paper (and presentation) will be a significant part of the course (see handout)
- Problem solving (homeworks and in class)
Opportunities

UNM astrophysics seminars Thursdays at 2pm

Synthesis Imaging Summer School 2016
- June 1-8 in Socorro
- registration opens soon

NRAO REU program 2016, Deadline Feb 1
- graduate students and advanced undergrads
- 10-12 weeks

Arecibo Observatory, Deadline Jan 25

ASTRON/JIVE summer student program 2016, Feb 1

See me for more details
The Interstellar Medium (ISM) of the Milky Way Galaxy
Or: The Stuff (gas and dust) Between the Stars

Why study it?

Stars form out of it.
Stars end their lives by returning gas to it.
We have to look through it.

The ISM has:

a wide range of structures
a wide range of densities \((10^{-3} - 10^7 \text{ atoms / cm}^3)\)
a wide range of temperatures \((10 \text{ K} - 10^7 \text{ K})\)
Key concepts:

ISM phases

Cold Neutral Medium

Column densities
The Interstellar Medium (ISM)

General properties:

- Mainly confined to galactic disks
- Enormous range in temperature $T \sim 10-10^7$ K
- Enormous range in density $n \sim 10^{-3}-10^7$ cm$^{-3}$
- Even the most dense regions are close to vacuum (cf $n_{\text{air}} \sim 3 \times 10^{19}$ cm$^{-3}$)
- Far from thermal equilibrium $\Rightarrow$ complex processes
The ISM is both complex and dynamic.
Schematic of a kiloparsec-scale region

- WIM (Warm ISM)
- older cluster
- GMC
- HI
- HI regions, young star cluster
- SNR
- hot gas
- GMC
- H$_2$
- H$_2$
- older cluster
- GMC
- HI
• Dust is found in each type of region

• Cosmic rays also widely distributed

• Magnetic fields present, generally stronger in denser regions

• Stars energize and heat the ISM:
  • enrich with metals
  • cause of turbulence and shocks

• ISM cools by radiation, can collapse and then form stars
Energy flow between ISM and stars etc.

ISM energy: Kinetic, thermal, chemical, magnetic, cosmic ray

Stars: self gravity, nuclear energy

Extragalactic background photons

Stellar ejecta kinetic energy

Starlight photons

Radiative cooling

Self gravity (cloud contraction)

Cold sky
Overview of the ISM
The ISM is comprised of the gas and dust between stars:

- Hydrogen is the most abundant element (~90% by number, ~70% by mass is hydrogen)
- The rest is mostly He, and "metals" ~1-2%.
- Composition similar to Solar System
- Regions classified by state of hydrogen
  - Ionized atomic hydrogen (HII)
  - Neutral atomic hydrogen (HI)
  - Molecular hydrogen (H₂)
- Transition regions are thin
Diffuse phases:

HI      CNM (Cold Neutral Medium)
        \(n \sim 10\text{cm}^{-3}, \ T \sim 40\text{-}200\ \text{K}\)

WNM (Warm Neutral Medium)
        \(n \sim 1\text{cm}^{-3}, \ T \sim 4000\text{-}8000\ \text{K}\)

HII     WIM (Warm Ionized Medium)
        \(n \sim 0.1\text{cm}^{-3}, \ T \sim 8000\ \text{K}\)

HIM (Hot Ionized Medium)
        \(n \sim 10^{-3}\ \text{cm}^{-3}, \ T \sim 5\times10^5\ \text{K}\)
The diffuse phases have low density, fill a large fraction of the ISM volume. ISM components are in rough pressure equilibrium:

\[ P_{\text{WNM}} \sim P_{\text{WIM}} \]

WNM cloud confined by surrounding WIM, not much tendency to expand and extract.

Ideal gas \( \Rightarrow n_1 T_1 = n_2 T_2 \)

NB: we don't always have pressure equilibrium! For example SN shock plowing into the ISM.
Dense phases:
Includes Giant Molecular Clouds (GMCs) and HII regions.

GMCs:
- occupy a small volume of ISM, but roughly half of the ISM mass.
- are confined by their own gravity, not by pressure of the surrounding gas.
- May reach 1 million solar masses

Other ISM components:
- Dust (silicates or carbonaceous material)
- Starlight (combined light of bright stars produces average interstellar radiation field)
- Cosmic rays, X-rays
- Magnetic fields
Viewing the ISM of Galaxies

The Sombrero galaxy seen by Hubble (left; visible light) and by Spitzer (right, Infra-red). Images courtesy of NASA.
Physical principles of the ISM

In thermodynamic equilibrium at temperature T, the Maxwell, Boltzmann and Planck distributions will apply.

- Maxwell distribution of velocities:

\[ n_v dv = n \left( \frac{m}{2\pi kT} \right)^{3/2} e^{-mv^2/2kT} 4\pi v^2 dv \]

- Boltzmann distribution of population of energy levels:

\[ \frac{N_b}{N_a} = \frac{g_b}{g_a} e^{-(E_b - E_a)/kT} \]
• The Planck function of radiation:

\[ B_\nu(T) = \frac{2\hbar \nu^3}{c^2} \frac{1}{e^{\hbar \nu/kT} - 1} \]

- Rayleigh-Jeans limit \( \hbar \nu \ll kT \)

\[ B_\nu(T) = \frac{2\nu^2 kT}{c^2} \]

- Wien limit \( \hbar \nu \gg kT \)

\[ B_\nu(T) = \frac{2\hbar \nu^3}{c^2} e^{-\hbar \nu/kT} \]

These equations hold in stellar atmospheres, but NOT in the ISM!
Why is the ISM not in TE?
Thermal equilibrium requires *detailed balance*, ie, each process occurs as often as the inverse process.

- This is often not true in the ISM. For example, collisional excitation is followed by radiative decay due to low density.
- Example is OIII in HII regions

![Energy level diagram showing transitions between 1s, 1D, and 3P states with wavelengths 4363 Å, 2321 Å, and 5007 Å.](image)
The interstellar radiation field is far from thermal equilibrium. Peaks at 2000 Å => $T_{\text{col}} = 10^4$ K, but the energy content $\sim 1\text{eV cm}^{-3} = 3\text{K}$. 


does not resemble a black body...
Which distributions are valid in ISM?

• Maxwell: Yes!
  – Elastic collisions are sufficiently frequent to thermalize the velocity distribution.
  – Usually $T_{\text{kin}} = T_e = T_i$

• Boltzmann: No!
  – We define an excitation temperature $T_{\text{ex}}$ by

\[
\frac{N_b}{N_a} = \frac{g_b}{g_a} e^{-(E_b - E_a)/kT_{\text{ex}}}
\]

  – Usually $T_{\text{kin}} \neq T_{\text{ex}}$

• Planck: No!
Statistical equilibrium

Because the radiation field cannot be described by the Planck function, thermal equilibrium does not hold if both radiative processes and collisions are important.

Continue by assuming statistical equilibrium:

• Sum of rates of all processes populating level \( j \) = sum of rates of all processed depopulating level \( j \)

\[
\frac{dn_i}{dt} = \sum_j (-R_{ij} n_i + R_{ji} n_j) = 0
\]
Cold Neutral Medium (CNM)
Composed of neutral hydrogen (HI).
Would you expect Balmer emission lines in the optical?
Cold Neutral Medium (CNM)
Composed of neutral hydrogen (HI).
Would you expect Balmer emission lines in the optical?

Would need to populate $n=3$ level by collisions.

$$n=3 \Rightarrow 12\text{eV above the ground state.}$$

$$12\text{eV} = kT \Rightarrow T \sim \frac{12\text{eV}}{8.6 \times 10^{-5} \text{eV K}^{-1}} = 10^5 \text{K}$$

HI gas is not that hot.
We instead detect HI in the $n=1$ state by 21-cm radiation.
Hyperfine structure in H:

e and p spin either parallel (higher energy) or anti-parallel (lower energy). Corresponds to $m_s \pm 1/2$.

$\Delta E$ corresponds to a 21-cm photon.
• The lifetime in the upper state ~ 11 million years.

• Collisions excite upper state, but they can also de-excite, thus no photons required.

• Timescale for collisions is typically a few hundred years

\[ \tau = \frac{1}{n\sigma v} \]

So, why do we get 21cm photons at all?
Level populations are determined by collisions

\[ \frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-\frac{h\nu}{kT}} \]

Let's look at the behavior of \( e^{-\frac{h\nu}{kT}} \)

Assume \( T \sim 100 \text{ K} \) (range 40-8000 K), which gives

\[ \frac{h\nu}{kT} = \frac{6.63 \times 10^{-34} \text{ [Js]} \ 1.42 \times 10^9 \text{ [Hz]}}{1.38 \times 10^{-23} \text{ [JK}^{-1}\text{]} \ 100 \text{ [K]}} = 7 \times 10^{-4} \]

Small!
Then:

\[ \frac{n_1}{n_0} \approx \frac{g_1}{g_0} \left( 1 - \frac{h\nu}{kT} \right) \approx \frac{g_1}{g_0} \]

Statistical weights: allowed projection of vector sum of spins on an arbitrary axis.

\[ g = 2F + 1 \] where \( F = \) total angular momentum

\( g_1 = 3 \) \( \uparrow \uparrow \) corresponding to three allowed projections of total spin \( \uparrow \uparrow \)

\( g_0 = 1 \) \( \uparrow \downarrow \) projected value of \( F \) always zero \( \uparrow \downarrow \)

\[ \Rightarrow \frac{n_1}{n_0} \approx \frac{g_1}{g_0} \approx 3 \]

First detected by Ewen and Purcell at Harvard in 1951
Some HI is in reasonably well defined clouds. Motions inside the cloud, and motion of the cloud will broaden and shift the observed lines.

Idealized 21cm spectra

Example observed 21cm spectra
**HI densities and column densities**

Basic result: if optically thin, the total emission intensity along the line of sight gives the column density, $N_{\text{HI}}$.

$N_{\text{HI}} = \# \text{ of HI atoms per cm}^2 \text{ in the line of sight.}$

Example:

$$N_{HI} = 7 \text{ cm}^{-2}$$

$$N_{HI} \ [\text{cm}^{-2}] = \int_{0}^{L} n_{HI} dL$$
Recall for blackbody radiation in the radio regime (low frequencies):

\[
\frac{h\nu}{kT} \ll 1
\]

This is the Rayleigh-Jeans limit, so the intensity from a Planck spectrum can be written as

\[
I_\nu = \frac{2kT\nu^2}{c^2}
\]

We define the term \textit{brightness temperature}, \(T_B\), as

\[
T_B = \frac{I_\nu c^2}{2k\nu^2}
\]

\(T_B\) is defined like this for \textit{any} radiation process, not only blackbody radiation.
This is a useful concept, since we can derive the HI column density for optically thin gas:

\[ N_{HI} = 1.82 \times 10^{18} \int_{V} T \tau_T dV \text{ cm}^{-2} \]

Note: this is a useful alternative to eq. 12.7.

Note 2: Units of constant: cm\(^{-2}\)/K km s\(^{-1}\)
21 cm hydrogen in the Milky Way.
HI in the Coma Cluster, overlaid on optical

HI properties of galaxies close to the cluster center are very different from those further out.

In the center, HI disks are smaller than the stellar disks and sometimes they are very asymmetrical. This is probably due to ram pressure stripping.

Many processes can affect the environmental evolution, such as tidal interactions and merging, starvation, and ICM-ISM interactions
HI in NGC4522 (Virgo cluster) overlaid on R-band.

Stellar disk looks smooth and undisturbed, but the gas has been completely removed from the outer disk.

In the inner part we see gas being accelerated toward the cluster mean central velocity.
Binary black hole in 0402+379

Most compact supermassive binary black hole pair
Projected separation between black holes = 7.3 pc
VLBI Results

Line blueshifted $700 \pm 10$ km/s from systemic

Line redshifted $370 \pm 10$ km/s from systemic
Exercise

Suppose we observe an optical depth of 0.025 for the 300 km/s wide line. Assuming $T_{\text{spin}} = 6000$ K, (a) what is the HI column density? (b) If the HI is in a cloud shaped like a giant coke can 50 pc long and with a radius of 10 pc, what is the total HI mass of the cloud?
Next time:

Warm Ionized Medium