I. Introduction

- Neutral gas, molecular gas, general viewpoint -6-
- Dust -8-
- Ionized Gas -9-
  - photoionization
  - collisions
  - cosmic rays
- Phases of interstellar gas -12-
- Magnetic fields and cosmic rays -13-
- Pressure sources -14-

II. Validity of the laws of statistical physics in ISM conditions

-16-

Four major laws of statistical physics:

1. **Maxwellian** velocity distribution
2. **Boltzmann distribution** of energy levels in atoms and molecules
3. **Saha equation** for ionization equilibrium
4. **Planck function** for radiation

-19-

These four laws hold under thermodynamic equilibrium (TE) However, this is not often the case for the ISM. TE does not hold for two reasons:

1. It requires **detailed balancing**
2. The strong dilution of the radiation field.

Detailed Balancing

Each process is as likely to occur as its inverse. For example, consider the 3727 Å emission from O^+. This is a forbidden transition (actually a doublet). The excitation of the electron level occurs through collisions with electrons, in most conditions in the ISM.

...

Statistical equilibrium

-22-

In general, assume **statistical equilibrium**: $\frac{\mathrm{d}n_i}{\mathrm{d}t} = 0$ -23-

III. Radiative Transfer -24-

IV. Radiative transfer equation -26-

V. Einstein coefficients -28-

VI. Line profile function, $\phi(\nu)$

-31- See RL chapter 10.6 and Draine 6.4

Natural line width

Key point: A small Einstein coefficient A results in a *narrow* line.

The natural line width of most transitions is quite small, and broadening due to other effects is more important.

Doppler broadening

- Thermal velocities
- Bulk motion (turbulence)

Collisional broadening

$\sim$ Pressure broadening, which is not generally important in the ISM because the density is so low…mostly occurs in stellar atmospheres. This still produces a Lorenzian profile, but with:

$$\phi(\nu) = \frac{4\Gamma^2}{16\pi^2(v - v_o)^2 + \Gamma^2}$$

VII. Atomic H in the ISM

-33- Draine Ch 8, 29; Ch 17.1, 17.3

Wherever HI dominates the ISM, all atoms are found in the **ground state**.

ISM is too cool for collisions to happen often and cosmic rays are rare. Possible tracers of HI gas:

1. 21 cm HI transition (=hyperfine transition) in emission or absorption.
2. Lyman absorption lines against hot background stars.

Only the ^{2}S level is populated. HI is hard to find in the ground state; fine structure $\rightarrow$ different angular momentum.

See Draine Ch 4 (& 5) on notation of energy levels and atomic

Excitation and radiative transport for the 21-cm line

Spin of proton and electron:

- Parallel (upper energy)
- Anti-parallel (lower energy)

(Spin is around particle's own axis, not to be confused with angular momentum). Motions specified by maxwellian velocity distribution, and collisions dominate the level populations (excite and de-excite).

Energy difference (very small):

$$h\nu = 9.4 \times 10^{-18}\,\text{erg}$$
$$\nu = 1420.4\,\text{MHz}$$
$$\lambda = 21.11\,\text{cm}$$

Spontaneous emission probability is *very* small:

$$A_{kj} = 2.86 \times 10^{-15}\,\text{sec}^{-1}$$
$$\rightarrow \text{lifetime} = 1.10 \times 10^{7}\,\text{years}$$

Simple case of a single layer of gas

VIII. Atomic Structure

- electron spin -I6-
- spin-orbit coupling -I8-
- atoms with multiple electrons -I10-
- transition rules
- x-ray emission, Zeeman effect -I20-

IX. HII Regions -51-

- Stromgren Theory -52-
- HII Region spectra
  - Continuum Radiation -63-
    - 2-photon
    - free-free
    - free-bound
    - dust
  - Line Radiation -69-
    - Recombination lines -69-
      - radio -71-
      - optical and IR -72-
    - Collisionally excited lines -79-
- Types of HII Regions -85-
  - "Blister model" – cavity inside GMC
  - "Champagne model" – half cavity at edge of GMC
  - Compact – only visible at radio and FIR wavelengths

X. Spectra in the ISM -89-

- Interstellar absorption lines in stellar and quasar spectra -89-
- Theory of formation of (interstellar) absorption lines -90-
  - Equivalent width (W) -90-
- Growth curves in practice -94-
- UV absorption lines from H and H_2 -96-

XI. Dust -104-

- Far infrared emission from dust -104-
  - General properties of dust -104-
  - Absorption efficiency: the Q parameter -105-
  - Calculating dust mass from FIR fluxes -106-
    * Spectrum emitted by dust grains → modified blackbody spectrum -108-
  - Dust temperatures -109-
- Interstellar extinction -116-
  - The extinction law -117-
- Interstellar reddening -118-

XII. Molecular Hydrogen and CO -124-

- Molecular gas and CO as a tracer -128-
- Collisional Excitation and Ionization -142-
- Properties of hot ionized gas and spectrum -145-

XIII. Heating and Cooling -151-

- General
  - Primary heat source: photoionization -152-
  - Primary cooling source: inelastic collisions -153-
- HII regions (ionized) -154-
  - Heating -154-
  - Cooling -155-
- HI gas (neutral) -160-
  - Dominant cooling line from CII (IP = 11.26 eV)
  - HI naturally cool, but observe very warm HI!

- General players:
  - Cooling function -160-
  - Heating function -161-