Interstellar Medium - Fall 2013

These lecture notes provide an overview of the material covered. These few pages provide more descriptive material and some links to relevant figures. Note that most of the notes will be handed out in class and not posted.

I. Introduction

Why should we care about the Interstellar Medium (ISM) in galaxies? Several reasons come to mind:

a. the ISM is the building block for new star formation, and also the repository of gas expelled from stellar atmospheres and outer layers in the end phases of the life of stars. It also may include in-falling ("accreted") gas from the intergalactic medium. We often refer to the latter as the IGM. It appears unlikely we will find any pristine gas (i.e. still as metal poor as the gas formed in the early universe). Studies of the IGM show that even in the early Universe some metal enrichment has already taken place. The physical processes going on in the ISM and IGM will be quite similar, though not identical. This is mostly related to the density of the gas (which tends to be lower in the IGM), and the physical processes that occur. E.g. photo ionization by star light is likely more prevalent in the ISM, although in the early universe, an as yet TBD source was responsible for the re-ionization of the IGM.

b. The hot diffuse gas phase in the IGM may be the dominant repository of baryonic material in the Universe, containing more mass than stars and ISM inside galaxies. This medium is though to be a part of the "cosmic web" between galaxies.

c. While the astrophysics of gaseous nebulae is not simple, in many cases we can find beautiful demonstrations of basic concepts in e.g. radiative processes in the ISM which are easier to understand than the more complex processes in stellar or planetary atmospheres. There are several good examples where the physical processes separate out, one being the dominant over the other.

d. The ISM provides one of the best probes for the study of galactic dynamics, especially in the outer parts of galaxies. Radial velocity measurements using radio and sub-mm lines found in the ISM are far more accurate than stellar velocities from optical spectra. Gas often extends much farther out in the halo than that stars can be traced, especially in external galaxies, and gas will more closely follow circular orbits due to its tendency to settle in disks as it collides with other gaseous material. That means that at least in principle an analysis of the gas kinematics is inherently simpler than that of stellar kinematics, where triaxial distributions may be common.

e. The ISM provides a richness of probes, through continuum emission, absorption lines, and emission lines that allows chemical abundances to be determined in many different places. It is the best current probe of chemical composition as a function of redshift. In spite of its overall small density, the probes are very sensitive.

The ISM is almost a perfect vacuum if we compare it with the best vacuum achievable in laboratories on earth. The typical average density is 1 hydrogen atom per cm^3. This corresponds to a mass of about 2400 kg for an object with the volume of the Earth. The medium is highly structured, however, especially in the colder phases. Structure is found down to the smallest scales that have been investigated.

In any direction we look from our location in the Milky Way, we will find ISM along the line of sight. Lockman described this as "Looking for nothing in the ISM and not finding it". The traditional approach towards ISM research, both observationally and theoretically has been almost exclusively based on understanding of the Galactic ISM, in particular that in the solar neighborhood. However, observational techniques have reached the point where we can begin to address the physical parameters of the ISM in various external systems, greatly enhancing the richness in environments and conditions present. In addition, external galaxies offer a much better vantage point for determining the global, galaxy-wide properties of ISM parameters.

Subjects we will discuss in this course include:

- Brief historical overview
- Basic overview of ISM components, and the environment the ISM finds itself in.
- Physical processes
    - validity of laws of statistical mechanics
    - atomic and molecular physics
    - radiative transport and processes
    - collisional & radiative ionization and excitation
- Phases of the ISM: neutral, molecular, ionized
- Dust grains: extinction and IR emission
- Magnetic fields, cosmic rays, synchrotron emission
- The balance between the ISM phases: heating and cooling
- Violent ISM: supernovae and stellar winds

Even if we manage to cover all this, it is good to keep in mind what we left out: astro-chemistry (the formation and destruction of (complex) molecules, much of the detail on molecular spectroscopy and molecular cloud physics, most of magnetic field physics, the entire field of star formation, etc.

II. Brief Historical Overview

It took quite some time for people to realize there was an ISM.

1904
Discovery by Hartmann of narrow, stationary, Ca^+ absorption lines in spectrum of a spectroscopic double star. These lines did not take part in the motion of the other lines, which suggested their origin was outside the stars.

Questions:

How would one discover these lines are interstellar and not circumstellar?
What is the significance of the fact that the lines are narrow?

1913
Discovery of increasing ionization rate above 1 km in Earth's atmosphere. This was attributed to some unknown form of radiation ("Hoehenstrahlung"), probably not solar in origin.

1927
Clay found that Hoehenstrahlung is less important at the equator than at the poles of Earth; attributed it to charged particles approaching Earth from interstellar space, hence "cosmic rays" from then on (Millikan, 1927).

1930's

Discovery of interstellar extinction. This was not found by Kapteyn (think of Kapteyn model for our Galaxy!) but by Trumpler (1930) & van de Kamp (1932). Trumpler estimated the distance of open clusters from their angular size. He then noticed that the cluster light from the star seemed to dim faster than distance^{-2} with those estimated distances. Van de Kamp discovered that galaxy number counts decreased towards the Galactic plane.

1930's and 40's
Karl Jansky and Grote Reber discovered radio continuum emission from the Milky Way. The emission mechanism was only fully understood later in the 50's and 60's. (What radiation is it?)

1937,40
Swings and Rosenfeld and McKellar find diatomic molecules in interstellar absorption lines (CH, CH$^+$, CN)

1939
Stromgren develops concept of "Stromgren sphere", which is ionized gas region around massive stars. I suspect he did not give it that name.

1944
Prediction by Van de Hulst of the existence of a 21-cm line transition in HI. Observationally verified in 1952 by Ewen and Purcell, first conclusive proof of the existence of neutral hydrogen in the ISM. Possibly the most important prediction and discovery made in ISM research.

1949
Serendipitous discovery by Hall and Hiltner that the polarization of star light is correlated with reddening, hence with extinction. The interpretation of this is that the dust grains may be non-spherical but elongated, and systematically aligned in the interstellar magnetic field to cause polarized scattered light.

1952
Shlovsky predicts synchrotron radiation and its polarization. This provided further evidence for the existence of interstellar magnetic fields and cosmic rays.

1963
Discovery of OH molecule 18-cm emission lines and masers. This was also about the time of the discovery of the first pulsar, and pulsars have turned out to be important background sources for us to learn more about the ionized ISM.

1968 and beyond
Discovery of NH_3, H_2O, H_2CO and subsequently many more complex molecules in ISM.

1960's
Discovery of soft X-ray background, providing direct evidence for hot ISM (million degree) in solar neighborhood.

1972
Copernicus satellite for first time detects UV absorption lines from ISM. Confirmation of existence of molecular hydrogen, and underabundance of many elements (C,N, O,...) in ISM compared to solar abundance. Discovery of OVI absorption lines confirming existence of hot medium in ISM.

1970's
Development of IR astronomy, culminating with flight of IRAS satellite in 1983, which produced Far-infrared maps of Milky Way and other galaxies, of HII regions, and many other objects. Also discovered extensive mid-IR emission from PAHs (polycyclic aromatic hydrocarbons), which are large molecules in the dust, much smaller than the typical dust grains causing interstellar extinction. There were also significant developments in X-ray and even gamma-ray observatories providing new data on the high energy ISM.

We stop our little overview here and will cover more recent discoveries as we go along in this course. Significant space missions since the 70's have included the International Ultraviolet Explorer, the Hubble Space Telescope (ongoing), FUSE satellite, Einstein, ROSAT, Chandra, and XMM in X-ray (the latter two are still operational), COS-B and Gamma Ray Observatory in gammma-ray, and ISO, SPITZER, Herschel, and WISE in infrared. Other missions relevant to ISM include various probes of cosmic microwave background (which detect the Galactic ISM whether they want to or not). Important discoveries of the cool and warm HI, the molecular gas, and the ionized warm gas have come from ground-based telescopes.

III . Overview of the interstellar medium. See also Chapter 1, textbook.

Discuss list of ISM components from text book.

The ISM in a galactic disk on large scales is likely in some sort of equilibrium situation, although on smaller scales it may be subject to various instabilities (e.g. those causing a cloud to collapse and start forming stars). As an example, its vertical scale height and distribution will be determined by the disk potential (defining the vertical force of gravity as a function of height above the plane) and the velocity distribution of the gas in the z-direction. Since the disk potential is due to stars, gas, and dark matter, all of which will have some extended distribution with height above the plane, the situation is not as simple as an atmosphere on a planet, where we can assume that the gas all experiences the same gravitational force. Still, we do often describe the gas distribution in terms of exponential scale heights, even if an exponential density distribution is not necessarily the correct solution to the hydrostatic equilibrium problem.

The second parameter that determines the scale height is of course the velocity dispersion of the gas. This has several contributions, first it can never be less than the thermal velocity width if the gas is at constant temperature. Most of the ISM actually experiences significant bulk motions on top of this thermal motion, the origin of which is still subject to debate. It is clear that mechanical energy input from stars in the form of stellar winds and supernovae stir up the medium. This may produce turbulence down to small scales. In addition, the gas could be subject to its own gravitiational forces (self-gravity) and establish a velocity dispersion between gas clumps in a self-gravitating larger cloud (e.g. for molecular gas). In this case, the disk potential itself matters less, although that was responsible in the first place for establishing the thickness of the gas layer from which the molecular cloud clumps formed. In addition, once the molecular cloud is dispersed due to star formation, the remaining clumps will move in the disk potential and obtain a scale height commensurate with their velocity dispersion.

Some images of ISM in Milky Way and other galaxies

Here is an overview picture of the Milky Way in different components From Radio to gamma-ray.

Textbook Plate 1, 2, 3, etc.
Maps of the entire Milky Way in various bands. Notice there is HI in all directions. Only at high galactic latitudes can you see much structure, since in the plane the gas is present over a wide velocity range and that has been integrated over to give a total HI map.

The Milky Way in the light of H-alpha recombination line, observed with the Wisconsin H-alpha Mapper telescope and other surveys is also shown. This is a low resolution imaging telescope which worked from the northern sky and provided a very sensitive image of the ionized gas distribution. Note that in optical (Halpha!) we cannot see all the way through the Milky Way so much of what you see in this picture if relatively nearby gas.

Here is what our Milky Way might look like from above. An HI image of the spiral M31, in a project I am working on with colleagues in Europe. This is among the highest resolution HI images we have of any external spiral. <u>M31 in HI with the Westerbork telescope</u>

Ionized or neutral?

The ISM is considered <u>neutral</u> if the dominant form of hydrogen gas (H) is neutral. The hydrogen gas can be in atomic form (HI) or molecular form (H_2). Whenever hydrogen is neutral in the ISM, the dominant number of atoms will be in the electronic ground-state (n=1) because at the prevailing temperatures, collisions cannot excite the gas to higher levels at significant rates. There is enough hydrogen around that the ISM is essentially opaque to radiation with wavelengths below 912 Å (photon energy equal to 13.6 eV). Hydrogen can be ionized of course, but there are not enough such photons around to keep all hydrogen ionized in the ISM. Photons with such energy are called Lyman continuum photons. A similar ionization limit exists for He. At what wavelength?

Many elements have ionization potentials less than H, so even if H is neutral there will be trace ions present, because there are plenty of photons at wavelengths that can ionize those elements (why, where from?). E.g. Sulphur has 10.36 eV ionization energy, Mg 7.65 eV, and Na 5.14 eV.

Discuss general view point:
What can happen to an atom or molecule or dust grain sitting in ISM?

need cross sections ↗

- can it absorb a photon? Energy levels $\Leftrightarrow h\nu$
- can it collide with other particles? → collisional rates
- is there a magnetic field? Is particle charged?
- are there cosmic rays?

Three possible sources of ionization (and excitation):
photons, collisions, cosmic rays.
What are typical collisional energies: kinetic energy.
Translate $\sim mv^2$ to $\sim kT$ to $\sim h\nu$ to $\sim eV$

Overall, in the solar neighborhood, $n(HI) \simeq 1$ at cm^{-3}
The effective thickness of the HI layer is ~ 250pc
↳ defined as $\frac{N_{\perp}(HI)}{n(HI, z=0)}$

where $N_{\perp}(HI) = \int_{-\infty}^{\infty} n(HI)\, dz$.

"He" will also be neutral in this medium, and makes up about 30% of the mass.

Spitzer discusses the existence of HI clouds with certain typical properties; it is not clear how realistic this description is. For one, "spherical clouds" appear not to exist, but filamentary structures dominate.
But his discussion does illustrate some of the basics of a clumpy medium embedded in a more diffuse substrate.

The typical temp. of HI gas is 50 – 150 K in "clouds", and up to ~ 6000 K in warm neutral medium.
The latter has low average density, in the range 0.05–0.2 at cm^{-3}.

<u>Molecular</u> gas in typically much cooler ($T < 40$ K), as low as 10 K. Perhaps there is even a colder component, with $T \sim 3$ K, the microwave backgrnd temp. This component would be very difficult to detect in emission (<u>why</u>?), but may have been seen, apparently, in absorption (need reference)
The molecular gas is warmer close to regions of starformation.
Typical densities of the molecular gas are in the range $10^3 - 10^6$ molecules cm^{-3}.

Dust grains also occur in the neutral medium, and probably also in the (warm) ionized medium.
Dust grains play an important role in various processes:

- extinction of star light
- emission of absorbed energy in (far) infrared light
- formation of molecules often occurs on grain surfaces.
- absorption of ionizing UV radiation & Lyα photons (reducing amount of ionizing radiation)
- heating of HI gas by photoelectric emission

The composition of dust grains is still a matter of debate, although certainly carbon and silicates (i.e. "sand grains") are likely candidates. The typical sizes of grains are in the range 0.01 – 0.1 μm (how do we know?)

In recent years much smaller grains have been discovered, sometimes believed to be only ~ 60 Atoms across. The evidence for these comes from emission lines in the near-infrared and excess emission at 5 – 40 μm from dust in the ISM (excess over the emission expected from the larger dust grains). While the large dust grains have temperatures in the range 10 to 40K, the very small grains can be transiently heated to much higher temp., due to absorption of even a single UV photon. A promising candidate for the small grains are so-called polycyclic aromatic hydrocarbons (PAH's). A good, closely related, analog is car soot!

It is not clear how well dust grains survive in hot environments: the grains may be destroyed by sputtering, a process where collisions of grains with other atoms, electrons or molecules knock off molecules from grains.

Since atoms & molecules tend to stick on grains at low temperatures, grains can deplete the heavy elements of the ISM, producing apparently anomalously low abundances of these elements along certain lines of sight.

Dust contributes about 1% of the mass of the ISM in the solar neighborhood. Most of the mass is in the large grains.

- Ionized gas

Three processes can ionize gas in the ISM:

- absorption of photons → photo ionized gas
- collisions with other particles → collisionally ionized gas.
- cosmic rays

Photoionization is especially effective near hot stars, i.e. central stars in planetary nebulae, or white dwarfs in general, and massive OB stars in HII regions.

Shock ionization occurs due to expanding stellar winds, supernova explosions, and collisions among gas clouds.

Question: what collisional speeds are required to ionize hydrogen?
What temperatures does this correspond to?

Planetary nebulae are similar to HII regions, except that the central stars are typically hotter, resulting in emission lines from more highly ionized elements

The central stars, however, are usually much less luminous than OB stars, producing much smaller, less luminous nebulae.

Typical densities in HII regions are $10 - 10^4$ atoms (or ions) cm^{-3}. In compact HII regions, densities can be even higher.
The temperatures are in the range 5000 to 10,000K, as we will see.

In addition to planetary nebulae and HII regions we also recognize a much more diffuse warm ionized medium, which seems to fill a substantial portion of interstellar space. Most likely, this gas is also photo ionized, although shocks are likely important in certain locations.
Tracers/probes of this medium include pulsar dispersion measurements and Hα (and other Balmer) emission lines.

- cosmic ray ionization: can occur throughout most of ISM, so cosmic rays can also produce a small amount of ionization in denser gas (recombination happens quickly, so not much of gas is in ionized state at any given time.

Collisionally ionized gas

A typical example is the heating & resulting collisional ionization produced by supernova explosions.
The explosion creates a hot expanding bubble, initially some 10^7 K, which generally sweeps up a cooler shell of warm ionized gas ($\gtrsim 2*10^4$ K). The warm shell is largely ionized by shocks and shows a different optical spectrum than H II regions.

The hot gas shows up in different ways:

- it emits free-free & line X-ray radiation
- it is detected through absorption lines of highly ionized species towards UV bright sources.

Question Kirchhoff's laws tell us that absorption lines arise when we look through a cool gas towards a hotter source. The collisionally ionized gas showing up in O VI (λ 1031.9 + λ 1037.6 Å) is inferred to be several hundred thousand K, much hotter than the O star towards which these lines are seen in absorption. How can it be that we see this gas in *absorption*?

Typical densities of hot gas: 0.001 − 0.0001 cm^{-3}

The following table, summarizing our knowledge of the local ISM, is taken from Knapp (1989, Wyoming Conference).

Draine, 2012

Table 1.3 Phases of Interstellar Gas

Phase	T(K)	n_H(cm^{-3})	Comments
Coronal gas (HIM) $f_V \approx 0.5?$ $\langle n_H \rangle f_V \approx 0.002\,\mathrm{cm}^{-3}$ ($f_V \equiv$ volume filling factor)	$\gtrsim 10^{5.5}$	~ 0.004	Shock-heated Collisionally ionized Either expanding or in pressure equilibrium Cooling by: ◇ Adiabatic expansion ◇ X ray emission Observed by: • UV and x ray emission • Radio synchrotron emission
H II gas $f_V \approx 0.1$ $\langle n_H \rangle f_V \approx 0.02\,\mathrm{cm}^{-3}$	10^4	$0.2 - 10^4$	Heating by photoelectrons from H, He Photoionized Either expanding or in pressure equilibrium Cooling by: ◇ Optical line emission ◇ Free–free emission ◇ Fine-structure line emission Observed by: • Optical line emission • Thermal radio continuum
Warm H I (WNM) $f_V \approx 0.4$ $n_H f_V \approx 0.2\,\mathrm{cm}^{-3}$	~5000	0.6	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Pressure equilibrium Cooling by: ◇ Optical line emission ◇ Fine structure line emission Observed by: • H I 21 cm emission, absorption • Optical, UV absorption lines
Cool H I (CNM) $f_V \approx 0.01$ $n_H f_V \approx 0.3\,\mathrm{cm}^{-3}$	~ 100	30	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Cooling by: ◇ Fine structure line emission Observed by: • H I 21-cm emission, absorption • Optical, UV absorption lines
Diffuse H_2 $f_V \approx 0.001$ $n_H f_V \approx 0.1\,\mathrm{cm}^{-3}$	~ 50 K	~ 100	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Cooling by: ◇ Fine structure line emission Observed by: • H I 21-cm emission, absorption • CO 2.6-mm emission • optical, UV absorption lines
Dense H_2 $f_V \approx 10^{-4}$ $\langle n_H \rangle f_V \approx 0.2\,\mathrm{cm}^{-3}$	10 – 50	$10^3 - 10^6$	Heating by photoelectrons from dust Ionization and heating by cosmic rays Self-gravitating: $p > p$(ambient ISM) Cooling by: ◇ CO line emission ◇ C I fine structure line emission Observed by: • CO 2.6-mm emission • dust FIR emission
Cool stellar outflows	$50 - 10^3$	$1 - 10^6$	Observed by: • Optical, UV absorption lines • Dust IR emission • H I, CO, OH radio emission

Average ISM in local neighborhood

Note: $\langle n_H \rangle f_V$ is a measure of number density → mass density

- <u>Magnetic fields and cosmic rays</u>

Typically, in solar neighborhood, $B = 2-5 \underbrace{\times 10^{-6}\ \text{Gauss}}_{\mu G}$

This follows from measurements of Faraday rotation, giving $\langle n_e B_{\parallel} \rangle$ towards pulsars & radio sources. The random component of the B-fld is probably as large as the uniform component.
In clouds, the B-fld can be much higher, $\sim 70\ \mu G$ (from Zeeman effect splitting measurements).

The magnetic field is important for several reasons:
1. it aligns elongated grains, giving rise to polarization of star light
2. The B-fld causes relativistic electrons to emit synchrotron radiation. It almost certainly plays a dominant role in accelerating the electrons to relativistic velocities as well ("magnetic bottle"). (Fermi acceleration).
3. Magnetic fields provide pressure support against gravitational collapse of matter, since the B-fld is "frozen" into the matter (due to ionization of heavy elements). The B-fld also seems to play an important role in solving the angular momentum problem in star formation (Shu et al.)

The cosmic rays that reach the Earth are mainly protons. At 1 GeV the numberdensity ratio of protons to electrons is about 100. However, the electrons are more affected by energy loss mechanisms and it is not clear that this ratio holds in the ISM.
The total energy density (or pressure) of cosmic rays in solar neighborhood is $U_R \sim 1.3 * 10^{-12}\ \text{erg cm}^{-3}$

Why are cosmic rays important?

- they produce γ-rays through collisions with atoms and molecules in ISM. In fact, the observed γ-ray intensity from the ISM forms an excellent independent measure of the total amount of matter present between the stars; γ-ray data, for example, have been used to calibrate the conversion factor of CO line intensity to H_2 mass.

- cosmic rays also provide pressure against gravitational collapse.

So we have five pressures that play an important role in supporting the ISM against gravitational collapse:

1. the thermal pressure $P = nkT$, where n = number density
2. The magnetic pressure $\frac{B^2}{8\pi}$
3. Turbulent pressure*
4. cosmic ray pressure
5. Radiation pressure

*There is a pressure associated with turbulent velocities in the ISM. The cloud to cloud velocity dispersion, due to turbulence, on various scales: increases line widths over thermal widths. If you look at the table describing the local ISM, you will note rough pressure equilibrium, between the components. thermal

This is not a coincidence; in fact some of this information was inferred by assuming pressure equilibrium. The argument is that if there were no equilibrium, the resulting perturbations would be wiped out on sound-crossing time scales, which are short compared to the time scales we would consider the ISM to evolve over.

However, the actual evidence for equilibrium in the thermal pressure is scarce, and there are claims that it is not true in the very local ISM (see e.g. the article from 1995 Nature, by Bowyer et al).

There seems to be a "cosmic conspiracy":
The estimates for the thermal, magnetic, and cosmic ray pressure for the solar neighborhood give roughly equal numbers for all three. Thus it may be totally inappropriate to only consider the thermal pressure (which is the only one that can be measured with much certainty). Interestingly, the magic pressure number is also very similar to the energy density of the microwave background! Draine discusses possible reasons in section 1.3. Note that pressure and energy density have same units, if you convert them!

Now look at Ch1 in Draine for supplemental info.

Next section is sort of a shortened condensation of Draine's Ch 2&3
We may come back to specific topics discussed there in more detail.

IV. Validity of laws of statistical physics in ISM conditions

To what extent are the four major laws of statistical physics valid in the ISM?
What are the "big 4"?

- Maxwellian velocity distribution
- Boltzmann distrib. of energy levels in atoms & molecules
- Saha equation for ionization equilibrium
- Planck function for radiation

- Maxwell's velocity distribution ($\vec{w}$ = velocity = $\vec{v}$ in Draine)

$f(\vec{w})\,d\vec{w}$ = fractional number of particles whose velocity lies within the three-dimensional volume element, $d\vec{w} = dw_x\, dw_y\, dw_z$, centered at velocity $\vec{w}$.

In thermodynamic equilibrium:

$f(\vec{w})$ is isotropic, so w can replace $\vec{w}$ as the argument.

$$f(w) = \frac{l^{3/2}}{\pi^{3/2}} e^{-l^2 w^2} \qquad \text{where } l^2 = \frac{m}{2kT} = \frac{3}{2\langle w^2\rangle}$$

$$= \left(\frac{m}{2\pi kT}\right)^{3/2} e^{-\frac{mw^2}{2kT}} \qquad \text{or } \langle w^2\rangle = \frac{3kT}{m}$$

For two groups of particles with different masses, we replace w by u, the relative velocity between the two groups, and m by the reduced mass m_r.
(what is the reduced mass?)

For H atoms colliding with particles of mass Am_H, Spitzer derives:

$$\langle u \rangle = \left[\frac{8kT}{\pi m_r}\right]^{1/2} = 1.46 \times 10^4 \sqrt{T} \left(1 + \frac{1}{A}\right)^{1/2} \ \mathrm{cm\,s^{-1}}$$

Exercise:

- verify the above calculation, esp. the numerical constant

Note that there is a difference between the <u>speed</u> and the <u>velocity</u> distribution.
Verify that $\langle w \rangle = 0$.
But, evidently, the mean <u>speed</u> is not 0.
The speed distribution is given by:

$$f'(w')\,dw' = \left(\frac{m}{2\pi kT}\right)^{3/2} e^{-mw'^2/2kT} \underbrace{4\pi w'^2\,dw'}_{\text{volume in phase space}}$$

where $f'(w')\,dw'$ = fractional number of particles with speeds between w' and $w' + dw'$ and $w' = |w|$

The Maxwell velocity distribution is characterised by several characteristic speeds:

most probable speed $w_0 = \sqrt{\frac{2kT}{m}}$

root-mean-square speed $\langle w^2 \rangle^{1/2} = \sqrt{\frac{3kT}{m}}$

root-mean-square velocity in one direction: $\langle w_x^2 \rangle^{1/2} = \sqrt{\frac{kT}{m}}$

- The population of energy states or levels in an atom or molecule is given by the Boltzmann distribution:

$$\frac{n_u}{n_l} = \frac{g_u}{g_l}\, e^{-(E_u - E_l)/kT}$$

where $n_{u,l}$ are the number densities,
$g_{u,l}$ the statistical weights,
and $E_{u,l}$ the energies of the levels

- Ionisation equilibrium is described by the Saha equation:

$$\frac{n_{i+1}}{n_i}\, n_e = \frac{g_{i+1}\, g_e}{g_i} \left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{-I/kT}$$

where I = ionization potential for ion in groundstate and initial ionization state i
(so energy required to ionize from $i \rightarrow i+1$)
g's are the statistical weights
n's are number densities
$g_e = 2$ (two spin conditions)

- The radiation field is specified by the Planck function:

$$B(\nu) = \frac{2h\nu^3}{c^2}\, \frac{1}{e^{h\nu/kT} - 1}$$

$$\rightarrow\ \cong \frac{2\nu^2}{c^2} kT \text{ for } h\nu << kT$$
(Rayleigh-Jeans)

$$\rightarrow\ \simeq 2\frac{h\nu^3}{c^2} e^{-h\nu/kT} \text{ for } h\nu >> kT$$
(Wien)

These four laws hold under conditions of <u>thermodynamic equilibrium</u>. Unfortunately, this is not often the case for the Interstellar Medium.

<u>Thermodynamic equilibrium</u> requires <u>detailed balancing</u>,

i.e. each process is equally likely to occur as its inverse.
<u>An example:</u>

Consider the 3727 Å emission from O$^+$. This is a forbidden transition (actually a doublet). The excitation of the (electron) level occurs through <u>collisions</u> with electrons, in most conditions in the ISM.
If detailed balancing were to hold, deexcitation should also occur by collisions. However, as we will see, under the low density conditions found in the ISM, collisions are rare, and deexcitation is more likely to proceed through emission of a photon, in spite of the fact that we are dealing with a forbidden transition.
Thus [OII] emission can be quite strong, and by converting collisional (kinetic) energy into radiation, we actually have created a cooling mechanism for the gas.

Another reason why TE does not hold is the strong <u>dilution</u> of the radiation field:

The concept of a dilute radiation field is quite familiar. For example, the Sun's photosphere is ~6000K, and at the surface the flux leaving the Sun is approx. that of a blackbody of this temp. However, the Earth is not 6000 K because by the time the radiation reaches us it is diluted. So what we mean with a diluted radiation field is that its energy density does not match its color temp.

For the solar neighborhood, the total energy density of the radiation field due to all stars in that volume is about ~ 1 eV cm^{-3} (so close to cosmic ray energy density, as mentioned before).

When interpreted as an average temp., using the Stefann-Boltzmann law (energy density of a black body, $u = aT^4$), this energy density implies an equivalent temp. of ~ 3 K. Yet the color temp. implied by the shape of the spectrum of this Instellar Radiation Field (ISRF) is that of A & B stars ~ 10^4 K. So the dilution factor

$$W \simeq \left(\frac{3}{10^4}\right)^4 \simeq .25 \times 10^{-14}$$

We conclude that using the Planck law to describe intensities is not correct.

What about the other laws?

1. Maxwell velocity distribution: good news! It is generally valid. Detailed balancing is possible for the elastic collisions that are generally occurring. See Draine section 2.3.3 for an analysis of "deflection times": they tend to be short. (In dynamics we speak of a "relaxation time").

Because the Maxw. distribution is a good description of the motions of the particles, we can define a <u>kinetic temp.</u> which describes the physical condition of the gas. Often, for a plasma, the kinetic temp. equals the electron temperature: $T_{ions} \simeq T_{electrons}$

$T_{ions} \neq T_{el}$ may occur behind shocks.

2. The Boltzmann distribution is rarely correct:
   - if excitation <u>and</u> deexcitation occurs by photons, we may still not have a Boltzmann distribution, because the photon distribution is not given by the Planck function.
   - often we do not even have detailed balancing

However, as we will see, sometimes the distribution of excited levels is not too different from Boltzmann distribution. This happens when collisions dominate excitation and deexcitation, while radiation is relatively unimportant.
To describe situations close to TE, Spitzer introduced the so-called <u>b-factors</u>. Draine calls them "departure coefficients" (section 3.8)

$$b_j \equiv \frac{n_j\ (\text{true distribution})}{n_j\ (\text{LTE distribution})}$$

In an HII region, the highest excited levels of HI have $b_j \sim 1$. Some radiation does escape (producing radio recombination lines) but collisions dominate the level populations. Since motions of particles <u>are</u> described by a Maxwellian velocity distrib., whenever collisions dominate the level pop. they will closely follow a Boltzmann law.

In general, a Maxwellian velocity distribution tends to set up a Boltzmann population for energy levels in the atoms/particles <u>if</u> transitions resulting from emission and absorption of photons are relatively unimportant, and collisional (de-) excitation is dominant.
In the case of the highly excited levels in H mentioned before, collisions with electrons are dominant.

3. The Saha equation is generally not valid; there is no detailed balancing. Eventhough the ionization and recombination process are each other's inverse ($h\nu + A \rightarrow A^+ + e^- \rightarrow h\nu + A$), the ionization process is determined by the <u>photon</u> field in most cases, while the recombination process is determined by collisions between A^+ and e^-. The collision rate depends on $\left\{\begin{matrix} n_e \\ n_{A^+} \end{matrix}\right.$ and T_e, the electron temp, but the ionization is dependent on $T_{radiation}$ ($\neq T_e$).

So, what do we do in general? We assume <u>statistical equilibrium</u>, where there is a balance between transitions one way and the other way:
In level i, we have n_i atoms cm^{-3}. Let R_{ij} = rate coeff of # transitions from level $i \rightarrow$ level j (for <u>all</u> possible process)
then $n_i R_{ij}$ = # transitions for level $i \rightarrow j$ per sec
$R_{ji} n_j$ = # " " " $j \rightarrow i$ " "

$$\frac{dn_i}{dt} = \sum_j \left(-R_{ij} n_i + R_{ji} n_j \right), \quad i = 1, 2, \ldots$$

In statistical equilibrium $\frac{dn_i}{dt} = 0$.

The rate factor R_{ij} includes all possible processes that would take the atom or molecule from level i to j.
E.g. if you consider excitation of an electron in an atom, R_{ij} could include absorption of photons, collisional excitation, etc.

In worst case, you will have to include many processes to calculate the n_i values.
This requires knowledge of a lot of physical input parameters, e.g. cross sections for particular processes, collisional rate coefficients (Draine section 2.1), etc.

In other cases, where only one or two processes matter, the situation can be very simple.
We will encounter cases of each.

Before going more into Ch 2 & 3 in Draine, we will first discuss some basic radiative transfer.
(RL Ch 1, Draine Ch 6, 7