1 Ecology of the Interstellar Medium

What does the ISM consist of?

- Hydrogen, helium and traces of 'metals' (all elements besides H and He)
- Ionized, neutral and molecular material
- Gas or solid (dust: heavy elements like C, O and Si; ice) state
- Magnetic fields
- Cosmic rays (relativistic particles)

Distinct objects in the ISM

- HII regions (including PNe)
- Reflection nebulae
- Dark (molecular) clouds
- Supernova remnants

Phases of the ISM and their global properties

Phase	T [K]	n [cm^{-3}]	f_V [%] (filling factor)	M [$10^9 M_\odot$] (excluding He)
Hot Ionized Medium	~10^6	~0.004	>50?	very low
Warm Ionized Medium	~8000	0.2	~10	~1.1
HII Regions	~8000	10^{2-6}	very low	~0.04
Warm Neutral Medium	~5000	0.6	~40	~1.6
Cold Neutral Medium	~50	30	~1	~1.3
Molecular Clouds	10-50	10^{3-6}	~0.01	~0.84

- CNM: atomic HI, the 'skins' of molecular gas clouds where the cloud transitions into the atomic phase
- WNM: atomic HI, there is no transition between the two NM
- WIM: photoionized by UV photons from stars; it's extended low density gas
    - HII regions: the densest pockets of the WIM that happen to be close to bright stars.
- HIM: gas created by supernova explosions

What are the sources of energy in the ISM, and why do they all have similar energy densities?

Sources:

- Radiation
- Thermal Energy

- Magnetic Fields
- Cosmic Rays
- Mechanical Energy (i.e. bulk motion of clouds)

The energy densities are similar because their sources are coupled: thermal, hydrodynamical and magnetic energies are coupled (magneto-)hydrodynamically, and the thermal energy is also somewhat coupled to the energy density of the starlight because the stars are heated by molecular clouds. The CMB energy density being in the same ballpark seems to be a coincidence, though.

2 Review of radiative processes

2.1 Radiation quantities and fundamental equilibrium conditions

What are the quantities specific intensity, flux density, specific energy density, photon occupation number and luminosity?

- Specific intensity (I_v) is the distance-independent measure of radiation energy of a certain frequency per frequency interval, solid angle, cross section and time interval.
  - In LTE, it's described as a blackbody
  - Sometimes called surface brightness
  - Units: erg s^{-1} cm^{-2} sr^{-1} Hz^{-1}
- Flux density (F_v) is the specific intensity integrated over solid angle, for describing a point source.
  - It's not an intrinsic property of the source, but proportional to D^{-2}, because of the inverse-square law
  - Units: erg s^{-1} cm^{-2} Hz^{-1} or Jansky, where 1 Jy = 10^{-23} erg s^{-1} cm^{-2} Hz^{-1}
- Specific energy density (u_v) is the flux density divided by a factor c, to give the time-independent energy density in a volume (element)
  - Units: erg cm^{-3} Hz^{-1}
- Photon occupation number (n_γ) is an alternative (equivalent) way to express specific intensity. It's defined as $(c^2/2hv^3)*I_v$.
  - Limiting cases in LTE
    - hv >> kT → n_γ << 1
    - hv <<kT → n_γ >> 1
  - Units: erg s^{-1} cm^{-2} sr^{-1} Hz^{-1}
- Luminosity is the total amount of energy radiated by an object. It's obtained by integrating the specific luminosity over (a selection of) all frequencies, which itself is the (specific) flux density times $4\pi D^2$. It's therefore an intrinsic quantity.
  - Units: erg s^{-1}

<u>'Be able to work with the Planck function'</u>

I'll interpret this as giving the definition and some ancillary information:

- The Planck curve/function/law gives the specific intensity of a blackbody in thermodynamic equilibrium.
- A blackbody is a physical body that absorbs all incident radiation. It then emits blackbody radiation, which is thermal radiation only arising from the body's temperature. A lot of spontaneous (non-reflective) emission can be described as blackbody radiation, which itself is more of an idealized, theoretical concept.
- A Planck distribution of radiation energies is generally not valid in the ISM.

<u>What are the Rayleigh-Jeans approximation and brightness temperature? Give the derivation of brightness temperature from the Planck function, using the RJ approximation.</u>

The RJ approximation is the low-frequency limit of the Planck function. It's derived from the Planck function using a Taylor expansion for small frequencies.
In the radio regime (hv << kT) this is a temperature of the Planck curve:

$$I_\nu = B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1}$$

$$h\nu \ll kT \;\Rightarrow I_\nu \approx \frac{2h\nu^3}{c^2}\frac{1}{\frac{h\nu}{kT}} = \frac{2k\nu^2}{c^2}T$$

This is called the brightness temperature. This is a characteristic temperature we can use to duplicate the temperature of a given observed specific intensity of a 'grey' body.

<u>Why is the ISM out of thermodynamic equilibrium? What is statistical equilibrium (which we use instead of TE), and what are its differences with TE?</u>

The ISM is out of TE because of a lack of detailed balance: not every process is balanced exactly by its counterprocess, and there are many foreign processes like

- Starlight photons
- Stellar ejecta kinetic energy
- Extragalactic background photons

Instead, we use statistical equilibrium. This states that the sum of rates of all processes populating level i = sum of rates of all processes depopulating level i. This is different from detailed balance because individual processes can be out of equilibrium with their counterprocesses, but the sum of rates of all populating and depopulating processes for all levels *are* in equilibrium.

What is the kinetic temperature, and what is the Maxwell distribution?

The Maxwell distribution is valid in the ISM, and it gives the thermal velocity of particles. In thermal equilibrium, the temperature is higher for higher particle velocities. This defines the kinetic temperature, which is dependent on the thermal velocity given by the Maxwell distribution.

What is the Boltzmann distribution? And what is the excitation temperature?

- The Boltzmann distribution gives the energy level populations, taking into account level generacies and the partition function.
- The Boltzmann distribution is generally not valid in the ISM. We can therefore not just plug in the (kinetic) temperature to arrive at level populations. However, if we take the ratio between level populations of some upper and some lower level, we can use a (fictitious) excitation temperature, defined per upper-lower level transition, to describe the level population ratio.
    - In general, T_{ex} != T_{kin}. Level populations are 'thermalized' if $T_{ex} = T_{kin}$ and 'subthermal' if $T_{ex} < T_{kin}$.

2.2 Interaction of radiation with matter

'Be able to work with the Einstein coefficients'

- The Einstein coefficients give the rates (per unit volume and time) at which radiative level transitions occur. There are three transition types, and therefore three coefficients:
    - Spontaneous emission: $X_u \rightarrow X_l + h\nu_{ul}$, given by A_{ul}
    - Absorption: $X_l + h\nu_{ul} \rightarrow X_u$, given by B_{lu}
    - Stimulated emission: $X_u + h\nu_{ul} \rightarrow X_l + 2h\nu_{ul}$, given by B_{ul}
- These coefficients are interrelated:

$$B_{lu} = \frac{g_u}{g_l} B_{ul}$$
$$B_{ul} = \frac{c^3}{8\pi h\nu^3} A_{ul}$$

When is stimulated emission (un)important, based on comparing hv to kT?

Stimulated emission becomes important if the average photon occupation number is important, because . As previously stated, in LTE the photon occupation is significant (larger than 1) when hv << kT (and it isn't when hv >> kT).

How is the line profile defined, and how is it normalised?

The line profile gives the shape of a spectral absorption or emission line. A line can be broadened by several processes:

- Natural linewidth: coming from quantum uncertainty, is described by a Lorentz profile, with wings falling off as v^{-2}.
- Doppler motions: coming from thermal and bulk motion, is described by a Gaussian profile with wings falling off as $\exp(-v^{-2})$. Furthermore, the Gaussian line profile is broadened too by particles having a velocity dispersion in accordance with the Maxwell distribution.
- The convolution of these profiles is a Voigt profile, but since the natural linewidth is always much smaller than the thermal linewidth, the line profile is Gaussian in practice, with the exception of extremely strong lines like the damped Lyman alpha absorbers.

The line profile is normalized to one by integrating over all frequencies.

2.3 Radiative transfer

'Be able to write down and work with the equation of transfer, in various units'

- Specific intensity: $I_v = I_v(0)\exp(-tau_v) + B_v(T_{ex})(1 - \exp(-tau_v)$
- Brightness temperature: $T_b = T_c\exp(-tau_v) + T_{ex}(1 - \exp(-tau_v))$
- Flux density: ???

Limiting cases:

- Optically thick ($tau_v >> 1$) → $I_v = B_v(T_{ex})$
- Optically thin ($tau_v << 1$) → $I_v = tau_v B_v(T_{ex})$
- Bright background object (in the optical and UV means that the upper level is almost unpopulated) → T_{ex} is very low → so $I_v = I_v(0)\exp(-tau_v)$

What are the source function and optical depth (tau_v)?

The source function, S_v, is defined as the ratio between the coefficients of emission and absorption (both at a certain frequency) of a medium. This therefore gives information on how photons in a light beam are removed and replaced by new photons from the medium.

The optical depth, tau_v, is defined as the integral of the absorption coefficient over a path length through a medium. Therefore it gives information on the transparency of the medium.

What are masers, how do they occur, and what happens to T_{ex} and tau_v and what is the result of this?

The excitation process may cause an *inverted population*, where $n_u/g_u > n_l/g_l$. Through the equations of the excitation temperature and the optical depth, we get $T_{ex} < 0$ and $tau_v < 0$. This means that, since $I_v = I_v(0)\exp(-tau_v)$, the incoming radiation is amplified. This is called maser emission.

3 The atomic medium

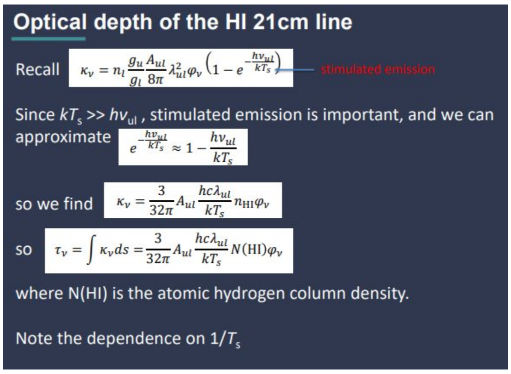
<u>What is the HI 21 cm line, and what is spin temperature?</u>

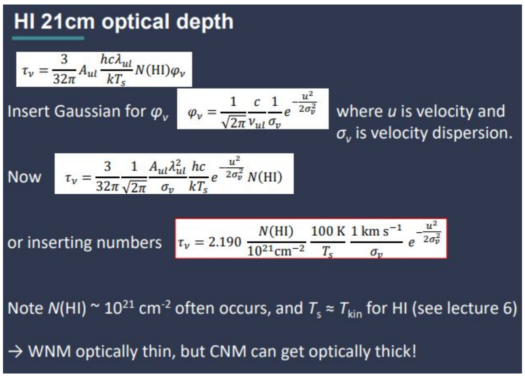
Due to hyperfine splitting (coupling of electron and nuclear spins) of the ground electronic state of HI, there is an emission line from the F = 1 hyperfine level and F = 0 hyperfine level. This emission has a wavelength of 21.1 cm and a frequency of 1420 MHz.

Spin temperature, T_s, is the excitation temperature of the 21 cm line.

<u>How is optical depth derived from HI emission and absorption observations?</u>

The derivation is seen in these screencaps, leading up to the optically thin, WNM, case.





For the optically thick case, in the CNM, we need another derivation, with a trick. The trick is to observe on and off a strong radio source. If we assume that T_s and tau_v do not change between the on-source and off-source position, we can solve for T_s and tau_v separately.

<u>When is HI observed in emission and when in absorption?</u>

When $T_s > T_c$ (continuum), there is a weak background and/or warm gas: emission
When $T_s < T_c$, there is a strong background and/or cold gas: absorption

<u>What is the 2-phase neutral ISM? Also describe the observational evidence for it.</u>

There is the distinction between warm and cold neutral material. The observational evidence for this lies in the observation that the emission spectrum of neutral material is very complex, with many lines, while the absorption spectrum is very broad and 'simple'. This tells us that we're not looking at the same gas in those spectra. There is a warm and a cold medium. "There is gas that is seen in emission that is not seen in absorption".

The CNM consists of cool clouds with T_{kin} ~ 80 K which cause the narrow emission peaks and the absorptions.
The WNM is an extended (meaning: not clouds) warm medium which causes the broad emission features without detectable absorption.

How do absorption lines of other species than HI determine abundances?

Through Lyman alpha absorption. ???

4 Ionization and recombination

What is the photoionization of atomic hydrogen and what is the approximate shape of the photoionization cross section?

Photoionization happens in the WIM and HII regions. Photoionization itself is the process in which a photon ionizes an atom or molecule. So the photoionization of atomic hydrogen means that a photon liberates a bound electron, ionizing the atom.
As for the photoionization cross section, its approximate shape is frequency^{-3} for $h\nu > Z^2 I_H$ (I_H is the hydrogen ionization potential.

Need to know: The ionization potential/edge is at 13.6 eV, which corresponds to 912 Angstrom.

What is radiative recombination of hydrogen?

The reverse process of ionization, where an ionized particle captures an electron, emitting a photon. This process is weakly dependent on temperature, because electrons have a Maxwell velocity distribution that does influence their recombination. Also, the recombination process is not dependent on density, except only at high quantum numbers.

What is case A and case B recombination? Which one applies in the ISM in practice?

Case A is where all recombination lines (since a photon is emitted in the recombination process) are optically thin, case B where all Lyman lines are optically thick, while all other recombination lines are optically thin. In practice, case B is the one that applies in the ISM.

What is the 'on-the-spot'-approximation?

Under case B conditions, photons emitted in the Lyman lines (or the Lyman continuum) during the recombination process and subsequent decay are reabsorbed. The on-the-spot approximation is that this reabsorption happens at the place where the photons were emitted. This has the net effect as if those photons had not been there at all.

What is the recombination lines spectrum?

Recombination lines arise from the downward cascade following recombination in ionized gas. The recombination lines spectrum is all the ratios between recombination lines. It's essentially fixed: there is a slight temperature dependence, but it's not very strong (and anyway HII regions have only a small range of temperatures). We can use that these ratios are fixed to get information on extinction, because extinction causes this ratio to change. The degree of change is then proportional to the degree of extinction.

5 HII regions

Derive the radius of a homogeneous spherical HII region (Stromgren sphere).

This region is where all stellar Lyman continuum photons have been absorbed. So for R_s the radius of this sphere, the medium is fully ionized for $r < R_s$ and fully neutral for $r > R_s$. We assume a pure H nebula, with constant density n_H. So for $r < R_s$, $n_e = n_p = n_H$.
Within the Stromgren radius, the total number of ionizations is equal to the total number of recombinations. We have expressions for both, and so equating them, we get

Ionizations: $Q_0 = \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu$ Lyman continuum photon production rate by central star or star cluster

Recombinations: $\frac{4}{3}\pi R_s^3 \alpha_B n_e n_p = \frac{4}{3}\pi R_s^3 \alpha_B n_H^2$ case B, note $\alpha_B(T)$

So: $\boxed{R_s = \left(\frac{3Q_0}{4\pi\alpha_B n_H^2}\right)^{\frac{1}{3}} = 3.2\ \mathrm{pc}\left(\frac{Q_0}{10^{49}\ \mathrm{s}^{-1}}\right)^{\frac{1}{3}}\left(\frac{n_H}{100\ \mathrm{cm}^{-3}}\right)^{-\frac{2}{3}}}$ (at $T = 10^4$ K)

What is the emission measure (EM)?

EM is defined as the integral of the density of electrons times the density of protons over a certain line of sight [cm^{-6} pc]. You can interpret it as analogous to column density from the HII 21 cm line, since recombination line intensity and radio continuum intensity (through Bremsstrahlung) are proportional to EM, not column density.
EM can also be understood by its integral over an area: that integral is equal to the ratio of the number of ionizations and recombination coefficient.

How is the recombination line luminosity a measure of star formation rate? What are the assumptions in this conversion?

We can calculate the luminosity from its equation with the recombination coefficients and Q_0.
When looking at the luminosity of recombination lines of an entire galaxy, we are looking at the luminosity of the sum of all HII regions of that galaxy. In other words, then we are measuring the total number of O stars. This is also seen in the equation of luminosity and Q_0, because Q_0 is exclusively produced by O stars.
Since O stars are very short lived, to observe them is to know there is a constant formation of them → what we are measuring then is a formation rate of O stars. For this we have to

assume a certain star formation history. A constant one, for instance. However, we can also assume a burst of star formation, after which no formation occurs. Then, the formation rate of O stars is time-dependent. To get to a star formation rate we also need an initial mass function (distribution of star formation per unit mass), which is the second assumption.

What is the ionization structure of an HII region with helium and heavy elements?

A sort of 'onion shell' structure where the fractional ionization of the different elements fall off sooner when they are heavier. ???

What are the spectra of HII regions and planetary nebulae?

???

What is the ionization front?

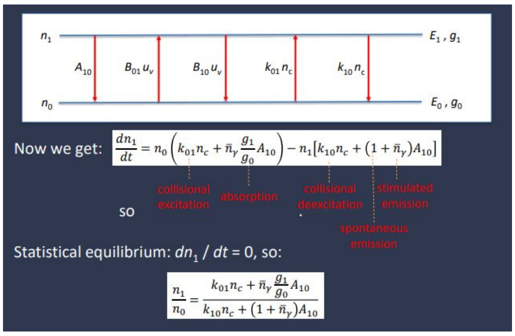
The ionization front is a dense layer at the Stromgren radius.

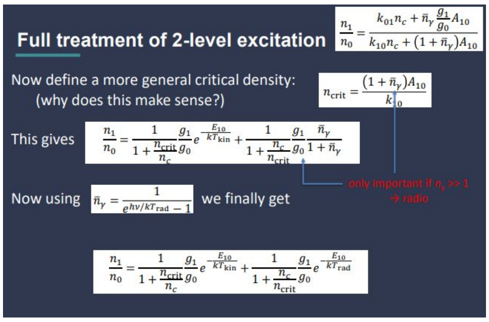
What does it mean for an HII region to be 'ionization', 'density' or 'dust'-bounded?

- A Stromgren sphere is ionization bounded if the nebula absorbs all ionizing photons from the star, so when there is no more gas to be ionized.
- Some HII regions, including planetary nebulae, are density bounded which means that some UB photons escape the nebula so that there are ionizing photons left when you are out of gas.
- Some UV photons are absorbed by dust. This partially suppresses emission lines, radio continuum, radius, etc. Dust may even be dominant in dust-bounded HII regions.

6 Collisional excitation

You should be able to write down the excitation for a 2-level system, considering collisional excitation and de-excitation, absorption and spontaneous and stimulated emission. Make sure you can derive the needed equations.





What is the critical density?

Critical density is defined as the ratio between A_{10}, the Einstein coefficient of the 1 → 0 spontaneous emission and k_{10}, the collisional de-excitation coefficient.
It expresses to what extent the collisional de-excitation and the spontaneous emission are equally important.

Describe the behaviour of the population ratio of a 2-level system (ignoring the radiation field) and of the excitation temperature in the limiting cases for the density n >> n_{crit} and n << n_{crit} (thermal and subthermal excitation)

- At high densities, the population ratio is a thermalized (Boltzmann) distribution.
    - The excitation temperature is then equal to the kinetic temperature.
- At low densities, the population ratio *is* density-dependent, with a n_c/n_{crit} (<1)prefactor in front of the Boltzmann distribution. This is subthermal excitation.
    - The excitation temperature is then smaller than the kinetic temperature.

What is the application of this last point to the HI 21 cm line?

We can use the equation for population ratio to prove that under all practical conditions, $T_s = T_{kin}$.

When is a line ratio a temperature diagnostic, and when a density diagnostic?

We can 'diagnose' (figure out characteristics of) nebulas with line ratios in three ways (this works for neutral and molecular clouds too, besides the discussed case study of HII regions):

1. Temperature probes: for this we need upper level temperatures with respect to the expected temperatures
2. Density probes: for this we need critical densities with respect to expected densities
3. Abundance probes

A line ratio is a temperature diagnostic when the lines have different upper levels and bracketing T_{kin}, and a line ratio is a density diagnostic when the lines have similar upper levels and different n_{crit}.

The line ratio curves (like Draine 18.4) behave as follows: they all behave the same, namely that they drop off steeply between two density-independent (constant) regimes. This behaviour is explained as follows: in the low density regime (below the critical density), both lines have population ratios proportional to density (so when taking the ratio, this dependence cancels out). At the high density side (above the critical density), both lines have population ratios independent of density so their ratio is, too. In the middle (transition) regime, one of the two lines can be above or below the critical density while the other is *at* the critical density.

7 Molecules and molecular excitation

Be sure to understand the energy levels of simple molecules: what causes vibrational and rotational levels. and where do these types of transitions lie in the EM spectrum?

- Electronic transitions are caused by reconfigurations of the electron cloud.
    - High excitation energies, around 50000 K, so not collisionally excited
    - UV absorption lines
- Vibrational energy levels are caused by a process best understood by analogy with a spring, with spring constant determined by the mode of vibration and the nature of the chemical bond.
    - Excitation energies around 1000 K, so usually not collisionally excited
    - IR absorption bands
- Rotational energy levels are caused by the end-over-end rotation of the molecule itself.
    - Lines in mm/submm/far-IR
    - Typical molecular cloud temperatures, so we can expect collisional excitation

N.B. All the electronic energy levels are split into vibrational energy levels and all the vibrational levels are split into rotational energy levels. The rotational ones are by far the most important!

What does the rotational spectrum of simple (heteronuclear (= multiple element species)) molecules such as CO, CS, HCN and HCO^+ look like?

Because of the 'large' size of the molecules, the transitions have low A coefficients, meaning the transitions are slow. WHAT DOES THIS MEAN FOR THE SPECTRUM?

What are the special properties of the H_2 spectrum?

The 'H_2 problem' is unique for that molecule: the lowest H_2 transition is the J = 2-0 transition at 28 microns, this line is therefore only observed in warm H_2, and it is only observable from space and is a very weak line. Conclusion: H_2 emission is very hard to observe directly and is not a tracer of bulk molecular gas.

What are and what aren't good probes of molecular gas (masses)?

H_2 emission is *not*, as mentioned in the point directly above. CO *is* a good probe, because the transition J = 1-0 with wavelength at 2.6 mm is accessible from the ground, and the J = 1 level is 5.5 K above the ground state. Therefore it's a good probe of cold gas.

Molecules with a low electric dipole moments have low critical density. Therefore CO (with a low electric dipole moment) probes to lower densities, and most molecules (with higher electric dipole moments) probe to higher densities. This comes from the equation for the Einstein A coefficient for rotational electric dipole transitions.

Higher rotational levels (of the same molecule) probe higher temperature and higher densities, because ???

How is H_2 formed?

Firstly, simply, H + H → H_2 + hv (4.5 eV). This hv radiation is impossible for the H_2 molecule because H_2 is a very poor radiator: because it's a homonuclear molecule, it only has quadrupole transitions. Therefore this reaction is super slow. Alternatively, electrons are used as catalysts for this reaction:
H + e^- → H^- + hv (0.77 hv) and subsequently H^- + H → H_2 + e^-
This applies only for the first H_2 molecules (the production rate for this is way too low to be in accordance with present observations). At this point in time, H_2 is formed differently, namely on dust grains: hydrogen atoms can tunnel through the barriers of a potential well on the dust grains (this is called thermal hopping), and once they meet, the reaction H + H → H_2 + hv (4.5 eV) *can* take place, because the dust grain can absorb the radiated photon. Water can also be formed this way.

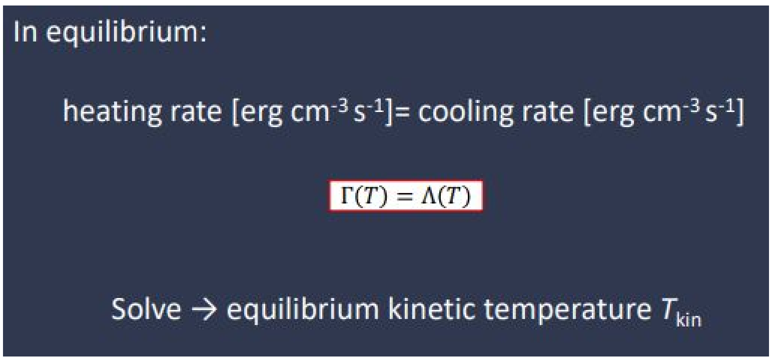
How does photodissociation of H_2 work? What is self-shielding and what role does it play?

The reaction H_2 + hv → H + H is a forbidden transition. Nature solve this by making H_2 dissociation a two-step process which works as follows:

1. Absorption in Lyman or Werner bands gives an electronically excited molecule
2. Cascading down, there is a 13% chance of ending up with the forbidden transition, but the remaining 87% falls back to the ground state emitting IR photons (vibrational fluorescence)

8 Thermal balance

Give the equations of thermal balance by equating the heating rate and the cooling rate.



How does the heating of HII regions by UV photons work?

The UV photons cause the following reaction: H + hv → H^+ + e^- (similarly for He etc.). The heating occurs because the e^- now carries a kinetic energy expressed as E_{kin} = h(v - v_0) (these are frequencies), where the first term is from the absorbed photon and the second from its own intrinsic ionization edge. In short: the energy is converted from stellar radiation into kinetic energy of particles, resulting in heating.

<u>How does the cooling of HII regions by collisionally excited lines work?</u>

Cooling occurs when collisional excitation is followed by emission of a photon, where the photon can escape: $A + B \rightarrow A^* + B$, followed by $A^* \rightarrow A + h\nu$

<u>Why are HII regions always of the order 10^4? Why do planetary nebulae and low-metallicity HII regions have higher temperatures?</u>

Collisionally excited line cooling is the dominant cooling mechanism, this reduces the temperature of 20000 - 50000 K from the central star to $T_e \sim 6000 - 10000$ K.
PNe?
Low-metallicity HII regions are warmer because the higher metallicity causes the collisionally excited line cooling to be less dominant.

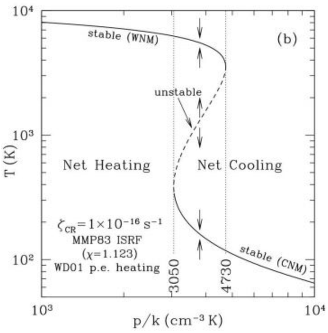
<u>How does the heating of the neutral atomic medium by the photoelectric effect work?</u>

Interstellar irradiation on dust grains liberates electrons, which then carry kinetic energy, which heats the gas.
N.B. Although this is an inefficient process, it's more effective than cosmic ray heating (which is the only other NM heating process)

<u>How does the cooling of the neutral atomic medium by collisionally excited lines work? Which are the most important lines?</u>

Cooling occurs when collisional excitation is followed by emission of a photon, where the photon can escape: $A + B \rightarrow A^* + B$, followed by $A^* \rightarrow A + h\nu$ (same as for HII regions). The most important lines are the CII and OI lines by far, only to be followed by SiII and, at high temperatures (10^4 K) we get Ly alpha lines to be the most important.

<u>Why is there such a clear division between the warm and the cold neutral medium?</u>



The left figure shows this clearly: the intermediate temperature regime is unstable. The reason for this is that there is no equilibrium state (between heating and cooling). You can see this in the graph if you take a pressure (x-axis) point on the graph, and look at what unstable temperature corresponds to this. If you then increase the pressure a little bit, you enter the net cooling part, but that makes you move away and downwards from your graph, towards the cold neutral medium solution. The same happens for when you decrease the pressure, that makes you end up in the warm neutral medium.

<u>How does heating of molecular clouds work?</u>

At the cloud edge, photoelectric effects dominate, in the interior cosmic rays do.

<u>How does cooling of molecular clouds work?</u>

Collisionally excited lines (fine structure lines at the edge, molecular rotational lines in the interior).

9 Interstellar dust

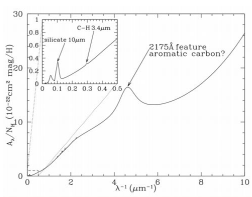
What is the behaviour of extinction for wavelengths much shorter and much longer than a, the radius of the dust grain?

For the ‘smaller than’ wavelengths, absorption dominates (because the dust grain is so much larger than the wavelength, there are no more quantum effects like tunneling). For the ‘larger than’ wavelengths, scattering dominates.

How does Rayleigh scattering behave for wavelengths much larger than a?

Dust becomes transparent, resulting in reddening (due to the absorption cross section being reversely proportional to the wavelength to the power 2).

What is the extinction curve? What is its general shape and what are features on the curve?



Features on this curve require a combination of silicate grains and carbonaceous grains.
The slope of this curve gives us information on the grain size distribution.
The features give information on the dust composition.

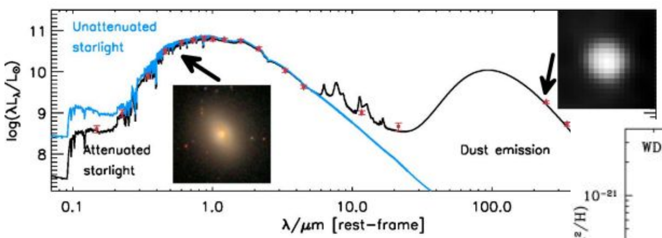
What is the composition of dust grains?

There are silicate and graphite species.

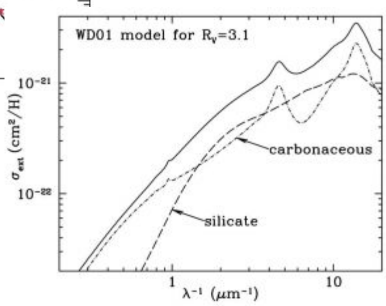
What are the heating and cooling mechanisms for dust grains? What are the general results?

Heating: photon absorption, with attenuation coefficient $\kappa_\nu = n_{\mathrm{gr}} C_{\mathrm{abs}} = n_{\mathrm{gr}} Q_{\mathrm{abs}} \pi a^2$
Cooling: Infrared radiation, with emissivity $j_\nu = n_{\mathrm{gr}} Q_{\mathrm{abs}} \pi a^2 B_\nu(T_d)$

What is the spectral energy distribution of dust emission?



What is the size distribution of dust grains?



Different models:
- MRN (1977): power law ($dn/da \sim a^{-3.5}$) with most mass in large particles, but most area in small particles.
- Typical Milky Way dust models (see figure)

What is the emission by very small dust grains like?

In the entire emission spectrum from interstellar dust there is a plateau in intermediate wavelengths. This is proof of very small grains: the idea is that these very small grains are not in equilibrium. Their heat capacity is very small, so when it is hit by a photon, the energy dumped into the grain by absorption gives rise to a very large temperature spike (and it cools back down after emission). This transient heating called thermal spiking causes that plateau.

PAHs: what are they, and what kind of spectrum do they produce (and in what wavelength regime, approximately)?

PAHs (polycyclic aromatic hydrocarbons) are the smallest graphite particles. Their characteristic emission features are in the low IR (~10 microns) and highly erratic.

What are ice mantles?

Grains may acquire molecular ice mantles consisting of a mix of water, CO, CO_2, CH_3OH etc. This produces absorption bands due to solid-state features in dense clouds towards embedded and background IR sources. These are simply formed from atoms that move around the dust grain surface.

How is dust formed, and how is it destroyed?

Formation (very poorly understood)
- Envelopes of AGB stars
  - These envelopes are so extended that they are cold enough for molecules to form, forming dust
  - We observe dust emission in high redshift galaxies, so it cannot be the only mechanism
- Supernova explosions
  - As the ejecta cool, dust has been observed to form
- Growth in the ISM
  - Simply the gradual growth in the ISM

Destruction
- Sputtering (abrasion (= making surfaces rough)) and shattering in shocks
- Consumption by star formation

10 Molecular clouds

What can be said about the opacity of the most common molecular lines?

They are optically thick.

How do you deal with optically thick lines through escape probability?

In the optically thin case, the equation of transfer reduces to a simple form that allows us to directly calculate the intensity.
The problem is that we need the photon occupation number and the optical depth, but these are circularly dependent on each other in a non-local way. It requires nasty Monte Carlo codes to solve this. The solution is with the formalism of escape velocity. This uses $beta_v$, the escape velocity, the probability that a photon of frequency v escapes from the cloud, then averaging over direction. If we then also average over the line profile this gives the probability that a photon emitted in a particular spectral line will escape.
Next, this uses two approximations to turn the non-local problem into a local problem:

1. Excitation is uniform → single T_{ex}
2. If a photon does not escape, it is absorbed on the spot

Approximation 1 gives us a new form of the equation of transfer, in which we use approximation 2 to replace the exp($-tau_v$) with the direction-averaged escape probability, and average over the line profile to arrive at an expression for the radiation field. The net effect is that we replace A_{ul} with (escape probability)*A_{ul}.

What is radiation trapping?

In dn/dt, all Einstein coefficients are reduced by a factor direction and line profile averaged escape probability. Only this fraction of the photons escapes, the rest is "trapped" in excited states of the particles. This is called photon trapping.
There are two other effects: there is no internally generated radiation field due to the on-the-spot approximation and the cloud is transparent to the external radiation field.

What is escape probability?

A very good fit for the direction and line profile averaged escape probability is given by 1/(1 + 0.5*tau_0)

What is the effect of high optical depth on critical density?

If a transition becomes optically thick, its critical density goes down, due to photon trapping, because we go from

$$n_{\text{crit}} = \frac{A_{10}}{k_{10}} \quad \text{to} \quad n_{\text{crit}} = \frac{\langle\bar{\beta}\rangle A_{10}}{k_{10}}$$

What can be said about the equilibrium conditions of molecular clouds?

That there is virial equilibrium (mostly), meaning that there is a balance between gravity and internal random motions, such that for a spherical cloud with radius R and mass M the velocity dispersion is given by

$$\sigma_v = \sqrt{\frac{GM}{5R}}$$

Why are CO(1-0) transitions used to determine molecular cloud masses?

Because it's a bright line, accessible from the ground, and the upper line gets excited at typical molecular cloud conditions. We can then calculate the hydrogen column density using the X-factor conversion.

What are Larson's relations?

They are three empirical relations:

1. Molecular clouds are virialized
2. Column density of molecular clouds is approximately constant
3. The size-linewidth relation (on the right)

$$\sigma_v \approx 1.10 \left(\frac{L}{\mathrm{pc}}\right)^{\gamma} \mathrm{km\,s^{-1}}$$

11 Shocks, supernova remnants and the 3-phase ISM

What is a shock?

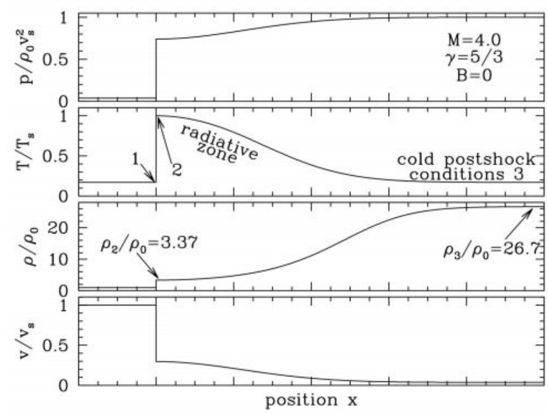
A shock *wave* is a pressure-driven compressive disturbance propagating faster than "signal speed" (the speed of sound): a hydrodynamic surprise. They produce an irreversible change in the state of the gas (or fluid).
When speaking of a 'strong' shock, this refers to the velocity of the disturbance: a strong shock is a fast shock.
In the absence of magnetic fields, information travels with sound speed, when M < 1 it's subsonic, and when M > 1 it's supersonic, resulting in a shock. (M is the Mach number, ratio of velocity and the speed of sound.
Shock waves occur in:

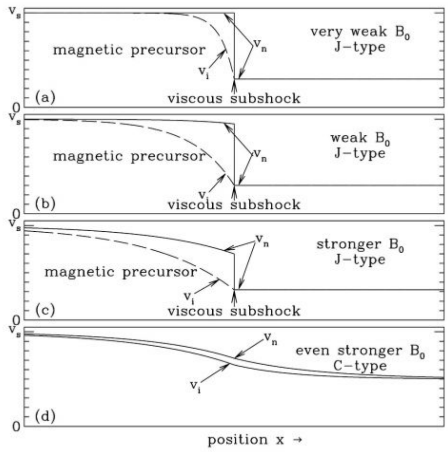
- Cloud-cloud collisions
- Expansion of HII regions
- Fast stellar winds
- Supernova blast waves
- Accretion and outflows during star formation
- Spiral shocks in galactic disks
- Supersonic turbulence

What are C-type and J-type shocks? What are their properties, and under what conditions do they occur?

A C-type shock is a continuous one, whereas a J-type shock is a 'jump' shock. This is explained as follows:
In many cases, the speed of sound is smaller than the velocity of the shock wave, which itself is smaller than the Alfven speed (the speed at which disturbances travel, along B). In those cases, the ion-electron fluid if a *real* gas cloud is not actually shocked, but subject to a submagnetosonic disturbance (as opposed to the neutral particles, which don't react to a magnetic field), which sends information ahead of the shock front to 'inform' pre-shock gas that compression is coming: a magnetic precursor. The resulting transition can be smooth (without jump discontinuities) → C-type.
In the case of a jump we call the shock a J-type shock.

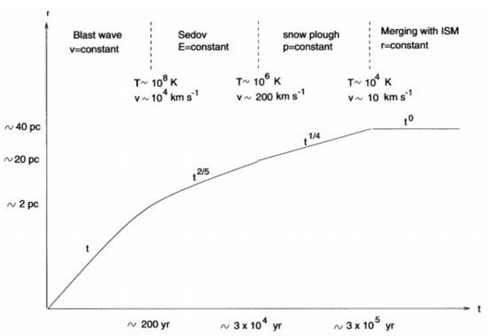
What is the structure of a shock?

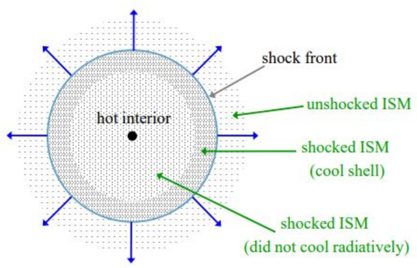




What is the evolution of supernova remnants?

When a supernova explodes, it leaves a supernova remnant, which propagates through the ISM as a shockwave. This shockwave has an evolution, characterized by the figures below:





Why is the 3-phase ISM needed, and what are its key features?

There are three reasons we need a 3-phase ISM:

1. The WNM and CNM can (partly) become ionized or molecular, so how, in a 2-phase model, do we account for the HIM?
2. With Milky Way supernova rate, lifetimes and sizes, the neutral medium will be destroyed on timescales < million years.
3. Vertical scale height of CNM/WNM can only be explained if the medium is turbulent, so something must be stirring up the ISM continuously.

These three reasons point to a role of supernova remnants as the 'third phase'. The principle is that SNRs create a "tunnel" system of hot ionized gas threading the HI clouds, much like the 'holes' in a swiss cheese: the HIM. An SNR evolves in isolation until it intersects a tunnel and connects to the HIM, then pressure drops suddenly as the SNR 'vents' into the tunnel system and contributes to the pressure of the HIM.

Physical features of the 3-phase model

1. Pressure balance: pressure is from supersonic tubulence, maintained by SNRs, can be used to determine P_{ISM} giving the correct result within a factor of 2.
2. Mass balance: balanced mass exchange between phases
3. Energy balance: most SN energy leaves the system as radiation. This is satisfied if SNRs enter the radiative phase before they overlap (which they do). A small fraction of SN energy remains as kinetic energy of shells at time of SNR overlap. This energy maintains random motion of clouds.