Interstellar Medium 2020
Important concepts

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The exam for the 2020 Interstellar Medium (ISM) course will be $\sim$ 50% problems similar to those you have done in the tutorials, and $\sim$ 50% questions that can be answered in a qualitative fashion. This file lists, for the qualitative part, the concepts that you need to know, understand and/or be able to explain. Generally there will be no need for mathematical derivations, except where specifically requested (at the exam) or indicated (in this document). Of course, if you think a mathematical statement will clarify or strengthen your argument, you will be welcome to include it, and the formula sheet that will be provided at the exam may be helpful for this. However, unless specifically noted, you should be able to score full points (on the qualitative part) without any math, by giving a full and correct description or explanation (again, unless a calculation or mathematical derivation is specifically requested).

1 Introduction: Ecology of the Interstellar Medium

- What does the ISM consist of?
- Phases of the ISM and their global properties (including approximate densities, temperatures, volume filling factors)
- What are the sources of energy in the ISM, plus the fact that they all have similar energy densities.

2 Review of radiative processes

2.1 Radiation quantities and fundamental equilibrium conditions

- Radiation quantities: you should know the definitions, understand and be able to work with specific intensity (I_ν), flux density (F_ν), specific energy density (u_ν), photon occupation number (n_γ) and luminosity (L), all in the appropriate units. Equations will be provided on the formula sheet.
- You should of course be able to work with the Planck function. Equations will be provided.
- Rayleigh-Jeans (RJ) approximation and brightness temperature (T_b); you should be able to derive brightness temperature from the Planck function using the RJ approximation.
- Lack of thermodynamic equilibrium in the ISM (give arguments why this is the case). Instead we use statistical equilibrium. You should be able to explain what this is, and the difference with thermodynamic equilibrium.

- Kinetic temperature ($T_{\rm kin}$) and the Maxwell distribution (equation will be provided).
- Boltzmann distribution (equation will be provided)
- definition of excitation temperature ($T_{\rm ex}$)

2.2 Interaction of radiation with matter

- Einstein coefficients: you should know their definitions and be able to work with these. Equations relating these will be provided.
- Understand and explain absorption, spontaneous emission and stimulated emission.
- You should know when stimulated emission is (un)important, based on comparing $h\nu$ and kT.
- Line profile: definition and normalization
- Doppler broadening, Gaussian line profile and velocity dispersion (equations will be provided)

2.3 Radiative transfer

- You should of course be able to write down and work with the equation of transfer, in various units (specific intensity, flux density and brightness temperature).
- The concepts of source function and optical depth (τ_ν).
- you should be able to derive the specific limiting cases of the equation of transfer: very small or very large optical depth, or the case for a pure absorption line.
- All relevant equations will be provided.
- Masers: what are they, how does this happen, and what happens to $T_{\rm ex}$ and τ_ν and what is the result of this. There was a problem on masers in one of the problem sets. Take a good look at this.

3 The atomic medium

- The H I 21 cm line and the concept of spin temperature. All relevant equations will be provided.
- Combining H I emission and absorption observations to derive optical depth. You should be able to do this mathematically. Make sure you understand how to to derive or read off all relevant parameters from observed emission/absorption spectra.
- You should be able to explain when H I is observed in emission and when in absorption. This is not trivial, take a good look at this.
- Important: the 2-phase neutral ISM (CNM and WNM): describe what it is and what the observational evidence for it is.
- Absorption lines of other species than H I to determine abundances; all relevant equations will be provided.

4 Ionization and Recombination

- Photoionization of atomic hydrogen and the approximate shape of the photoionization cross section; you should know that the ionization edge is at 13.6 eV, which corresponds to 912 Å.
- Radiative recombination of hydrogen: you should know that the recombination process is independent of density (except at very high quantum numbers) and only weakly dependent on temperature (where does the temperature dependence come from?)
- What is case A and case B recombination (and which one applies in the ISM in practice)?
- The On-the-spot Approximation
- you should know what recombination lines are and how they arise.
- recombination lines spectrum: do not worry too much about details but focus on results; you should know that the recombination line spectrum (= ratios between recombination lines) is essentially fixed (there is a temperature dependence which is not very strong and anyway H II regions have only a small range of temperatures). Hence we can use the ratios of recombination lines to derive extinction (there was a problem on this in one of the problem sets; take a good look at this).
- All relevant equations will be provided.

5 H II regions

- You should be able to derive the radius of a homogenous spherical H II region (Strömgren sphere).
- the concept of Emission Measure (EM)
- You should know that the emission (in UV/optical/infrared recombination lines and thermal radio continuum) from an H II region is proportional to EM and therefore to the square of density.
- You should know that recombination line luminosity (how do you calculate luminosity?) is a measure of star formation rate and should be able to explain this and what the assumptions in the conversion are.
- Ionization structure of an H II region with helium and heavy elements
- Spectra of H II regions and planetary nebulae
- Ionization front
- Ionization bounded, density bounded, dust bounded

6 Collisional excitation

- Important: you should be able write down (mathematically) the excitation for a 2-level system, considering collisional excitation and deexcitation, absorption, and spontaneous and stimulated emission, and you should be able to work with this (I am not going to provide the equations, make sure you can derive them).
- The concept of critical density ($n_{\rm crit}$)
- Important: behaviour of the population ratio (for a 2-level system, and ignoring the radiation field) and of the excitation temperature in the limiting cases for density $n \gg n_{\rm crit}$ and $n \ll n_{\rm crit}$; thermal and subthermal excitation
- Application to the H I 21 cm line: the fact that under all practical conditions $T_{\rm s} = T_{\rm kin}$.
- Nebular diagnostics: when is a line ratio a temperature diagnostic (different upper levels, bracketing $T_{\rm kin}$) and when a density diagnostic (similar upper levels, different $n_{\rm crit}$). You should be able to sketch and explain the behaviour of line ratios (this is not trivial, make sure you understand this; see Draine Fig. 18.4 for an example).

7 Molecules and molecular excitation

- energy levels of (simple) molecules: electronic, vibrational and rotational levels, and where these types of transitions lie (approximately) in the electromagnetic spectrum.
- Rotational spectrum of simple (heteronuclear) molecules such as CO, CS, HCN, HCO^+.
- Special properties of the H_2 spectrum.
- You should be able to explain fully why we cannot use H_2 lines to measure molecular gas masses.
- explain why CO (ignoring for the moment optical depth effects) is in principle a good tracer of molecular gas.
- You should know that most other molecules probe higher densities than CO and be able to explain why this is.
- you should know that higher rotational levels (of the same molecule) probe higher temperature and higher densities and be able to explain why.
- How is H_2 formed?
- Photodissociation of H_2: how does this work, and what is self-shielding and what role does this play?
- All relevant equations will be provided.

8 Thermal balance

- Write down (in general form) the equation of thermal balance by equating the heating rate and the cooling rate.
- heating of H II regions by UV photons (who does this work exactly?)
- cooling of H II regions by collisionally excited lines
- resulting temperatures of H II regions and why are they always of the order of 10^4 K; and why planetary nebulae and low-metallicity H II regions have higher temperatures
- heating of the neutral atomic medium by the photoelectric effect (how exectly does that work?)
- cooling of the neutral atomic medium by collisionally excited lines (which are the most important lines?)
- Important: you should be able to explain the existence of a stable 2-phase neutral ISM (CNM and WNM in pressure equilibrium) using diagrams such as Fig. 30.2 in Draine.
- Heating of molecular clouds: photoelectric effects at the cloud edge, cosmic rays in the interior
- cooling of molecular clouds: collisionally excited lines (fine structure lines at the edge, molecular rotational lines in the interior).
- All relevant equations will be provided.

9 Interstellar dust

- Behaviour of extinction for $\lambda \ll a$ and $\lambda \gg a$ (where a is the radius of the dust grain)
- Rayleigh scattering for $\lambda \gg a$
- The extinction curve; general shape and features on the curve
- extinction and reddening
- composition of dust grains
- thermal balance of dust grains (don't worry over details too much but you should know the principle, heating and cooling mechanisms and general results)
- emission by dust grains
- spectral energy distribution of dust emission
- size distribution of dust grains
- emission by very small grains
- thermal spiking of very small grains
- PAHs: what are they and what kind of spectrum do they produce (and in what wavelength region approximately).

- ice mantles
- dust formation and destruction
- All equations that you may need will be provided.

10 Molecular clouds

- The most common molecular lines are optically thick
- How to deal with optically thick lines: escape probability (β)
- For optically thick lines, replace $A_{\rm ul}$ with $\beta A_{\rm ul}$
- radiation trapping
- effect of high optical depth on critical density
- Molecular clouds are (mostly) in virial equilibrium
- Using CO(1−0) to determine molecular cloud masses (why does this work?)
- Larson's relations
- All relevant equations will be provided.

11 Shocks, supernova remnants and the 3-phase ISM

- What is a shock
- Physics of shocks only qualitatively
- Shocks in molecular gas: C-type shocks and J-type shocks; what are these, what are their properties, and under what conditions do they occur?
- sketch the structure of shocks (of various types)
- Supernova shocks and evolution of supernova remnants
- The 3-phase ISM: describe why it is needed and what its key features are