Concept Notes for Thesis

Owen Cox

September 11, 2023

Contents

1

Draine, Interstellar Medium

Things I do not yet understand: degeneracy, Maxwellian velocity distribution, and $\phi_\nu d\nu$, probability that emitted photon will have frequency within range $(\nu, \nu + d\nu)$ What is effective emission?

1.1 CHAPTER SIX: SPONTANEOUS EMISSION, STIMULATED EMISSION, AND ABSORPTION

1.1.1 absorption

If an absorber X is in a level l and there is radiation present with photons having an energy level equal to $E_u - E_l$, where E_l and E_u are the energies of levels l ("lower") and u ("upper"), the absorber can absort a photon and undergo a transition:

$$\text{absorption: } X_l + h\nu \rightarrow X_u, h\nu = E_u - E_l \tag{1}$$

This is proportion to the number density of absorbers in the level l. Rate per volume at which absorbers absorb photons is proportional to the density of photons with proper energy and the number density of absorbers.

Where u_v is the radiation energy density per unit frequency and the proportionality constant B_{lu} is the **Einstein** B **coefficient** for the transition $l \rightarrow u$

$$(\frac{dn_l}{dt})_{l\rightarrow u} = -(\frac{dn_l}{dt})_{l\rightarrow u} = n_l B_{lu} u_\nu, \quad v = \frac{E_{u-E_l}}{h} \tag{2}$$

1.1.2 emission

In absorber X in an excited level u can decay to a lower level l with emission of a photon. There are two ways this happens:

$$\text{spontaneous emission: } X_u \rightarrow X_l + h\nu \quad \nu = (E_u - E_l)/h \tag{3}$$

$$\text{stimulated emission: } X_u + h\nu \rightarrow X_l + 2h\nu \quad \nu = (E_u - E_l)/h \tag{4}$$

Spontaneous Emission is a random process independent of radiation with a probability per unit time A_{ul}, the **Einstein** A **coefficient**.

Stimulated Emission occurs when photons of identical frequency, polarization, and direction of propagation are already present. Proportional to density of these photons. Total depopulation rate of level u due to emission of photons can be written

$$(\frac{dn_u}{dt})_{u \to l} = -(\frac{dn_l}{dt})_{u \to l} = n_l B_{lu} u_\nu, \quad n_u(A_{ul} + B_{ul} u_\nu) \qquad (5)$$

Coefficient B_{ul} is the Einstein B coefficient for the downward transition. Three coefficients are now characterizing radiative transfer between these two levels. A from up to low, B from up to low, and B from low to up.

In thermal equilibrium thhe radiation field becomes the blackbody field, with intensity given by the blackbody spectrum.

$$B\nu = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} \qquad (6)$$

1.2 CHAPTER SEVEN

Radiative Transfer Theory decribes the propagation of radiation through absorbing and emitting media

1.2.1 Physical Quantities

Specific Intensity, $I_\nu(\nu)$ represents the electromagnetic power per unit area, with frequencies in $[\nu, \nu + d\nu]$ in direction $\hat{n}$ within solid angle $d\Omega$

$$I_\nu(\nu, \hat{n}, \vec{r}, t) d\nu d\Omega \qquad (7)$$

If radiation field is in local thermodynamic equilibrium (LTE), the intensity is equal to that of a blackbody.

Photon occupation number $n_\gamma(\nu)$ The photon occupation number is a dimensionless, and is simply the number of photons per mode per polarization. If field in LTE

Brightness temperature $T_B(\nu)$ The brightness Temperature is defined as the temperature such that a blackbody at that temperature would have specific intensity $B_\nu(T_B) = I_\nu$. In LTE this is equal to the actual thermodynamic temperature of the emitting and absorbing material.

Antenna Temperature $T_A(\nu)$ A nonlinear measure of intensities, because it is linear in the limit that $kT_A >> h\nu$, one sees $T_A \approx T_B$. This is commonly the case at radio frequencies.

Specific Energy Density $u_\nu(\nu)$

$$u_\nu(\nu, \vec{r}) = \frac{1}{c_m} \int I_\nu \Omega \qquad (8)$$

Where c_m is speed of light in a medium. u_ν has no direction.

All preceding definitions are essentially the same and can be obtained by each other. They all pertain to the strength of the radiation field. **Emission and absorption** are characterized by relative importance in the following:

Excitation temperature T_{exc} The excitation temperature of a level u relative to level l

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{-E_{ul}/kT_{\text{exc},ul}} \tag{9}$$

where n_u,n_l are the populations of the upper and lower levels: g_u, g_l are the degeneracies of the upper and lower levels, $E_{ul} \equiv E_u - E_l$.

WHAT IS A DEGENERACY?

1.2.2 Equations of Radiative Transfer

When considering a beam of radiation entering a slab of material, only considering absorption and emission, intensity evolves according to this equation of radiative transfer:

$$dI_\nu = -I_\nu \kappa_\nu ds + j_\nu ds \tag{10}$$

where s is the pathlength along the direction of propagation. The first term represents change in I_ν due to absorption and stimulated emission, and j_ν ds is the change in I_ν due to spontaneous emission by material in the path of the beam. κ_ν is the **attenuation coefficient** per frequency, dimensions of inverse length. j_ν is the **emissivity** at frequency ν, with dimensions of power per unit volume per unit frequency per unit solid angle

When the beam leaves the material, it will have intensity $I_\nu + dI_\nu$.

Absorption and emission are caused by a variety of things. Atoms, ions and molecules with discrete energy level contribute in the following.

$$j_\nu = \frac{1}{4\pi} n_u A_{ul} h\nu \phi_{nu} \tag{11}$$

Where $\phi_\nu d\nu$ is the probability that the emitted photon will have frequency in the range $(\nu, \nu + d\nu)$ (see Draine 6.5).

The attenuation coefficient is proportional to **net absorption**, true absorption minus stimulated emission.

$$\begin{aligned}
\kappa_\nu &= n_l \sigma_{l\to u}(\nu) - n_u \sigma_{u\to l}(\nu) \\
&= n_l \sigma_{l\to u}(\nu)[1 - \frac{n_u/n_l}{g_u/g_l}] \\
&= n_l \sigma_{l\to u}(\nu)\left[1 - e^{-h\nu/kT_{\text{exc}}}\right]
\end{aligned} \tag{12}$$

Absorption cross section $\sigma_{l\to u}(\nu)$ is given by Eq. (6.37 Draine) for absorbers with a Maxwellian velocity distribution.

1.2.3 Integration of Equation of Radiative Transfer

It is convenient to write pathlength s in terms of optical depth, defined

$$d\tau_\nu \equiv \kappa_{\nu ds} \tag{13}$$

According to this definition, radiate propagates in direction of increasing τ_ν as long as $\kappa_\nu > 0$, in which case

$$dI_\nu = -I_\nu d\tau_\nu + S_\nu d\tau_\nu \tag{14}$$

where

$$S_\nu \equiv \frac{j_\nu}{\kappa_\nu} \tag{15}$$

This is known as the **source function**.

Integration of Eq. 14 is outlined in pg. 67 of Drain. Results in

$$I_\nu(\tau_\nu) = I_\nu(0)e^{-\tau_\nu} \; + \; \int_0^{\tau_\nu} e^{-(\tau_\nu - \tau')} S_\nu d\tau' \tag{16}$$

This is a fully general solution to the equation of radiative transfer if scattering is ignored. Intensity as a function of optical depth is the initial intensity attenuated by a factor of $e^{-\tau_\nu}$, plus the integral over the emission $S_\nu d\tau'$ attenuated by the factor of $e^{-(\tau_\nu - \tau')}$ due to effective absorption over the path from the point of emission.

When considering propagation of **optical or higher frequency radiation** through cold interstellar clouds, upper levels of the atoms and ions usually have negligible populations, and stimulated emission can be neglected.

$$\kappa_\nu \approx n_l \sigma_{l\to u}.$$

1.3 CHAPTER THIRTEEN, PHOTOIONIZATION

In an HII region around an early O star, the hydrogen may bemostly ionized, the helium may be mostly singly ionized, and elements like oxygen or neon mainly doubly ionized (OIII and NeIII). In a Lyman α cloud, hydrogen and helium may be mostly ionized, with C triply ionized.

The nonrelativistic quantum mechanics of hydrogen and one-electron ions is simple that ground-state photoelectric cross sections for photons with energy $h\nu > Z^2 I_H$ is given by an analytic expression

$$\sigma_{\rm pe} = \sigma_0 \Big(\frac{Z^2 I_H}{h\nu}\Big)^4 \frac{e^{4-4\arctan(x)/x}}{1 - e^{-2\pi/x}}, x \equiv \sqrt{\frac{h\nu}{Z^2 I_H} - 1} \tag{17}$$

Where Z is the atomic number of the nucleus, and σ_0 is the cross section at threshold

$$\sigma_0 \equiv \frac{2^9 \pi}{3e^4} Z^{-2} \alpha \pi a_0^2 = 6.304 \times 10^{-18} Z^{-2} cm^2 \tag{18}$$

Where e is the mathematical constant.

Other energy levels can be found at page 128 of Draine. At $h\nu \approx_2 .5keV$ photoionization of H is dominated by Compton Scattering

It gets pretty complicated after this talking about atoms and ions with higher electron counts. Go back if necessary.

1.4 CHAPTER FIFTEEN.1, HII REGIONS AS STROMGREN SPHERES

1.5 CHAPTER 18, NUCLEAR DIAGNOSTICS

To probe an emission nebula the following are required

1. sufficiently abundant
2. energy levels at suitable energies
3. radiative transitions that allow observation of these levels

1.5.1 18.7, BPT Diagram

Active Galactic Nuclei will usually dominate the emissions of a galaxy. They are characterized by high-ionization species like C IV and Ne V, which are ionized from x-rays originating from the AGN. Also known as Serfert galaxies. Extremely luminous, point-like nuclei.

Low Ionization Nuclear Emission Regions strong emission lines but from low-ionization species.

Baldwin, Philips and Terlevich (1981) asserted that star-forming galaxies can be distinguished from AGN by plotting [O III]$\lambda 5008/\text{H}\beta$ vs [N II]$\lambda 6586/\text{H}\alpha$. This is the **BPT Diagram**. These emission lines are the strongest optical emissions from H II regions, and they use pairs of similar wavelengths so that the ratios are **nearly unaffected by dust extinction.**

LINERs are defined by [N II]$\lambda 6586/\text{H}\alpha > 0.6$ and [O III]$\lambda 5008/\text{H}\beta > 3$. They have temperature exceeding 10^4 K, which is required to satisfy first condition while maintaining relatively low ionization.

Veilleux Osterbrock 1987 have suggested that LINERs are systems where an AGN is emitting hard x rays that only partially ionize nearby gas...... look into for sure

LINERs oxygen is mostly in [O I] and [O II], with O Iλ6302/Hα > 0.16. This is very different than an H II regions. H II regions and LINERs are easily seperated by plotting [O III] to [O I] (Ho 2008)