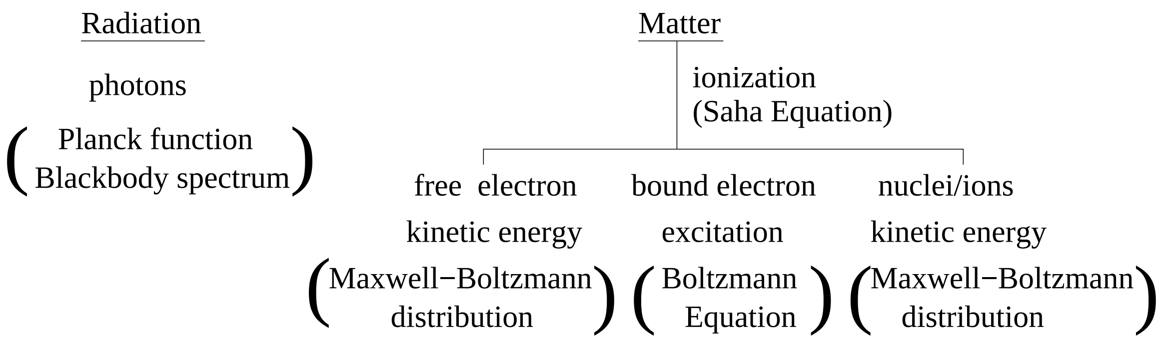
Interstellar Medium – What is Diffuse Matter?

The interstellar medium (ISM) is “diffuse matter,” which has much lower densities than “dense matter.” The densities of the diffuse matter, or the ISM, are so low that collisions among particles are infrequent and equilibrium cannot be achieved most of the time.

In a given volume, there exist radiation and matter. If they reach thermal equilibrium, they will be governed by the following equations:



If the matter is dense enough to establish thermodynamic equilibrium in the volume, the radiation should have a blackbody spectrum, the ionization of the matter should be described by the Saha equation, the free electrons should follow the Maxwell-Boltzmann distribution, the bound electrons at different energy levels should follow the Boltzmann equation, and the nuclei/ions should follow the Maxwell-Boltzmann distribution.

Saha Equation (Carroll & Ostlie, page 214)

$$\frac{N_{i+1}}{N_i} = \frac{2Z_{i+1}}{n_\mathrm{e}\, Z_i} \left(\frac{2\pi m_\mathrm{e} kT}{h^2}\right)^{3/2} e^{-\chi_i/kT}$$

where χ_i is the ionization energy of the ionization stage i, and Z is the partition function, the weighted sum of the number of ways the atom can arrange its electrons with the same energy.

$$Z = g_1 + \sum_{j=2}^{\infty} g_j\, e^{-(E_j - E_1)/kT}$$

where g_j is the degeneracy of energy level j and E_j is the energy of level j.

Planck Function, Blackbody Spectrum (Carroll & Ostlie, page 73)

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1} \qquad \text{or} \qquad B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$

Note: $B_\nu(T) \neq B_\lambda(T)$, but $B_\lambda(T)d\lambda = B_\nu(T)\ d\nu$, because:

$$B_\lambda(T)d\lambda = B_\lambda(T)\ \ d\left(\frac{c}{\nu}\right) = \frac{2h\nu^5/c^3}{e^{h\nu/kT}-1}\ \frac{c}{\nu^2}\ d\nu = \frac{2h\nu^3/c^2}{e^{h\nu/kT}-1}\ d\nu = B_\nu(T)\ d\nu$$

Maxwell-Boltzmann Distribution (Carroll & Ostlie, page 206)

$$n_v dv = n\left(\frac{m}{2\pi kT}\right)^{3/2} e^{-mv^2/2kT} 4\pi v^2 dv$$

Boltzmann Equation (Carroll & Ostlie, page 212)

$$\frac{N_b}{N_a} = \frac{g_b e^{-E_b/kT}}{g_a e^{-E_a/kT}} = \frac{g_b}{g_a} e^{-(E_b-E_a)/kT}$$

where E_a and E_b are energies of levels and g_a and g_b are the statistical weights of levels a and b, respectively.

In a diffuse medium with low density and low opacity, absorptions of photons and collisions among particles are not frequent enough to establish thermodynamic equilibrium. The only "equilibrium" that we can count on most of the time is a Maxwell-Boltzmann distribution of the free electrons.

Radiation field in the ISM in the Galaxy contains contributions from different components at different wavelengths.

Radio – thermal emission from ionized gas, nonthermal emission from SNRs and cosmic rays;
IR – far-IR has dust emission, near-IR has both dust emission and radiation from cool stars;
Optical – star light (OBAFGKM);
X-ray – emission from hot plasma $\geq 10^6$ K;
γ-ray – SNe, compact objects with accretion (binaries with NS or BH), etc.

Ionization of matter in a diffuse medium can be carried out in two ways:

photoionization – $A + h\nu \rightarrow A^+ + e^-$

collisional ionization – $A + P(v) \rightarrow A^+ + e^- + P(v')$.

The ionization state of a medium us determined by balancing the number of ionizations with the number of recombinations. Ionization equilibrium may not be achieved in a rapidly changing medium, such as SNRs.

Excitation of matter is determined by collisions among particles and absorption/emission of photons. Boltzmann equation is applicable only at high energy levels and with high densities. Most atoms/ions in the ISM are at the lowest energy levels.

Temperature of the ISM. Thermodynamic equilibrium if the ISM is out of the question. What is "temperature" then? The free electrons can achieve Maxwell-Boltzmann distribution easily because of their high velocities and frequent collisions. It takes longer for the heavier nuclei to achieve the Maxwell-Boltzmann distribution. The "temperature" of an ionized medium refers ro the "kinetic temperature" of electrons; therefore, it is frequently called "electron temperature".