The cosmic history of the intergalactic medium

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Chapter 1

Resonant scattering

Let us consider the propagation of photons with energy which closely matches the energy difference between the ground state and the lowest (first) excited state of an atom. Suppose that one of these photons is absorbed by an atom. When the atom de-excites, another photon with (almost) exactly the same energy is emitted but in a new direction. At the low densities of the intergalactic medium, the time between absorption and emission is very short compared with the collision time. Therefore absorption and emission together can be regarded as a single scattering process. This process goes under the name of *resonant scattering* because the photons are in resonance with the atomic transition. A classic example of this is the propagation of hydrogen Lyman-α photons.

Consider a photon emitted in the center of a cloud of atoms with which is in resonance through a bound-bound transition of central frequency ν_0. If the cloud is optically thick to absorption, the photon cannot travel very far before it is absorbed and instantly re-emitted in another direction. Thus, it may take a very long time to escape the cloud. However, atoms have thermal velocities that need to be accounted for. Let us consider a single scattering event and indicate by ν and ξ the photon frequency as measured in the laboratory frame and in the scattering atom rest frame, respectively. Note that

$$\nu = \xi \left(1 + \frac{\mathbf{v} \cdot \hat{n}}{c} \right) , \tag{1.1}$$

where $\mathbf{v}$ is the velocity of the atom in the lab frame due to thermal motions and $\hat{n}$ is the direction of propagation of the photon (in the same frame). Absorption happens when the incoming photon has the resonant energy in the rest-frame of the atom, i.e with a cross section proportional to the natural line shape

$$\phi(\xi) = \frac{\Gamma}{4\pi^2} \left[(\xi - \nu_0)^2 + \left(\frac{\Gamma}{4\pi} \right)^2 \right]^{-1} . \tag{1.2}$$

Since no collision happens between absorption and emission, when the atom de-excites it will still move with the same velocity $\mathbf{v}$. Moreover, in the rest frame of the atom, a new photon will be emitted with frequency ξ (for energy conservation). However, since the photon is re-emitted in a different direction, $\hat{n}'$, it will have a different frequency from the initial one in the reference system of the laboratory. In fact:

$$\nu' = \xi \left(1 + \frac{\mathbf{v} \cdot \hat{n}'}{c} \right) . \tag{1.3}$$

What is the relation between the incoming and outcoming directions of the photon? This is quantified by the redistribution (or phase) function, $P(\cos\theta)\, d\cos\theta$ which gives the probability distribution of $\cos\theta = \hat{n}' \cdot \hat{n}$ and depends on quantum physics. It can be shown that resonant scattering in the core of the line is isotropic ($P(\cos\theta) = 1$), while wing scattering is coherent and characterized by the Rayleigh phase function $P = 3(1 + \cos^2\theta)/4$.

Therefore, during the propagation of resonant lines, photons execute a random walk both in frequency and in physical space. This makes the calculation of the transfer for resonant lines notoriously difficult. The typical shift in frequency per scattering event is of order the thermal (or microturbulent) Doppler width $\Delta = \sqrt{2}\nu_0\sigma_{\rm th}/c$ because a photon might be scattered by an atom either moving towards or away from it with a velocity of magnitude typically equal to the velocity dispersion. It is thus convenient to measure the photon frequency in terms of

$$x = \frac{\nu - \nu_0}{\Delta} . \tag{1.4}$$

The average shift in position per scattering event is simply the mean free path $[k\phi(x)]^{-1}$ with $\phi(x)$ the line profile (the Hjerting-Voigt function at the temperature of the medium). The total number of scatterings before the photon leaves the cloud depends on the geometry and the optical depth of the cloud and on the line profile of the transition. A general result is that a resonance-line photon will escape the medium in a single long excursion in frequency away from the line center (Zanstra 1949, Adams 1972). In fact, the scattering of resonant-line photons is mostly local (i.e. little diffusion in space) as long as the re-emitted photons are in the core of the line (say within 4 Doppler widths of the line center). The photons thus escape the cloud by frequency diffusion in the line wings where scattering is coherent and a small number of scatterings (often even a single one) carry the photon a large distance in space. Consider for instance a single catastrophic scatter that suddenly moves the dimensionless Doppler shift x to the extreme tail of the distribution (say $|x| > 4$). The photon then faces a very low optical depth $\tau \simeq \tau_0 \exp(-x^2/2)$, where τ_0 is the optical depth at the line center. It therefore escapes directly from high τ. This process is commonly referred to by saying that "resonance photons escape from the wings of the line".

THE FLUORESCENT EMISSION OF THE IGM WON'T BE PART OF THE EXAMINATION MATERIAL AND WON'T BE DISCUSSED HERE.