"The Intervening Universe:"

Addenda Notes for Serjeant Chapter 8

Dave 2/14/20- 3/2/20

Lyman alpha transitions (between orbital n=2 and n=1 in hydrogen atoms, λ_{alpha} = 121.6 nm UV, E= hν = 10.2 eV) are "one of the most important sources of information about the high redshift universe," but interpretation of its spectra has proven complicated (-- comprehending this chapter is challenging). For understanding the Lyman alpha forest, our **Figure 8.3** fails to make it clear that the quasar background light we care about here is UV with more than 10.2 eV of energy (a point of confusion). So rather than starting with Figure 8.1 for the Lyman Alpha Forest, first look at the unperturbed spectra of the nearby quasar QC273 in **Figure 8.8** (page 260). The plot to the left of the Ly α peak is relatively flat for UV > 10 eV (to the left because λ = c/ν = hc/hν energy).

As high energy UV photons from quasars redshift over cosmic distance, their effective energy decreases so they have a chance to match discrete absorption energies of intervening neutral hydrogen gas {primarily alpha n = 1 ground state to n = 2, i.e., "almost all the lines in the Lyman α forest correspond to the same atomic transition."}.

Given a photon with short wavelength λ_e from a quasar at redshift z_Q, there may be an intervening cloud at redshift z_c such that the photon can be absorbed.

$$\lambda_\alpha (1+ z_C) = \lambda_e(1+z_Q) = \lambda \text{ (un)-observed on Earth.}$$

This yields an absorption line in the final observed spectra. Of course the Lyman alpha activity near the quasar itself also produces its own strong Ly α emission line that may be seen from Earth as a big spectral peak. Two-thirds of all ionized hydrogen recombinations yield Lyman alpha photons.

Wikipedia says: "For wavelengths of light at the energies of one of the Lyman transitions of hydrogen, the scattering cross-section is large, meaning that even for low levels of neutral hydrogen in the intergalactic medium (IGM), absorption at those wavelengths is highly likely." [most clouds with z < 6 have (re)ionized hydrogen , but some neutral hydrogen still exists and is important]. The set of finally observed absorption lines is called the **Lyman α forest** (first discovered in 1970). The spectra of background high redshift quasars very far away from us show these similar patterns of absorption lines from intervening clouds of hydrogen. Prior to this discovery, astronomers believed that the intergalactic hydrogen was distributed uniformly throughout the universe—it most definitely is not! Variations in density can go up to a million to one.

Related to this is the **Gunn–Peterson trough:** Wikipedia says, "In astronomical spectroscopy, the Gunn–Peterson trough is a feature of the spectra of quasars due to the (strong) presence of neutral hydrogen in the (early) Intergalactic Medium (IGM). The trough is characterized by suppression of electromagnetic emission from the quasar at wavelengths less than that of the Lyman-alpha line at the redshift of the emitted light. This effect was originally predicted in 1965 by James E. Gunn and Bruce Peterson" but not actually seen until 2001. Transmitted flux becomes zero for λ <

$\lambda_{Ly\alpha}$ (1+z) = 121.6 nm (1+z) for z > ~6 – the forest near the peak but to its left turns into a flat trough (see **plots on page 272**). This is "strong evidence for the hydrogen in the universe having undergone a transition from neutral to ionized around z = 6."

Some of the concepts in chapter 8 seem difficult at first. But a few of the unstated background principles are simple. Here we care about the attenuation of photons {Ly α's} passing through clouds of hydrogen gas and a background concept of "growth and **exponential decay."**

For example, recall that in population growth, we have numbers of new offspring coming from numbers of parents with a rate dN/dt = kN with solution $N = N_o e^{kt}$ where k is "growth rate." {that is:
$\int dN/N = \int kdt$; ℓn(N) = kt+some constant; exp(ℓn(N)) = N = exp(kt+C) → $N_o e^{kt}$ }. In finance, interest is proportional to principal, and we have interest rates, r, for growth ∝ exp(r t). In the decay direction we have topics like radioactive decay rates with radiation ∝ number of atoms remaining. And, of more relevance, for light passing through a chemical solution or the atmosphere we have "Beer's Law" with absorbance "attenuation" A ∝ ℓ · c = optical light path times a concentration of scattering centers. **Optical depth tau τ** = natural log ℓn(incident flux/transmitted flux) ∝ A. Transmittance T = exp(-τ) {is used on the bottom of page 256 with photon flux being labeled as "$J_\nu/(h\nu)$ " – energy flux divided by energy.

A key concept of this chapter is **Column number density**, σ [bottom of page 255 and also referred to as N_{HI}]. In astronomy, it is used to indicate the number of atoms or molecules per square cm along a line of sight in a particular direction (also on page 204 -- note the continual use of CGS units in astrophysics). If volume number density is ρ (e.g., 1 neutral H atom per cm^3) -- and a sample cubic volume V = $side^3 = \ell^3$, then count N = ρV (written in this book as a *"Kunstler"* script N, *see Google* – what do you do when you run out of symbols?). We view these atoms through a front face square area $A = \ell^2$, so $\sigma = N/A = \rho\, \ell^3/\ell^2 = \rho\ell$ atoms per cm^2 (cgs unit area). If σ is high enough, it can have an optical depth **τ** > 1 and, as a convention, call it "opaque" with "self-shielding." Giant clouds that are too opaque are called "Blobs" (e.g., page 146) and are very important in the early universe.

Wikipedia says that "Damped Lyman alpha absorption systems" is a term used by astronomers for concentrations of neutral hydrogen gas that are detected in the spectra of quasars – a class of distant Active Galactic Nuclei. They are defined to be systems where the column density (density projected along the line of sight to the quasar) of hydrogen is larger than 2×10^{20} atoms/cm^2.

A **Lyman-alpha blob (LAB)** "is a huge concentration of a gas emitting the Lyman-alpha emission line. LABs are some of the largest known individual objects in the Universe." Some of these gaseous structures are more than 400,000 light years across—3 x bigger than the Milky Way Galaxy. Page 146 (in Chapter 4) says that "the ionization causing the Lyman α line is from star formation." One blob from the year 2000 was 11.5 billion ℓy away with star formation rates 100 times greater than the MW. The UV light from star formation scatters off of surrounding hydrogen gas to give Ly α emission and LAB (extended Lyα glow). See:
http://www.sci-news.com/astronomy/lyman-alpha-blobs-04208.html

In this book, the degree of uncertainty about "the intervening universe" is often expressed by paragraphs posing a lot of question and known problems. Examples are the bottom of page 265 and middle of page 273.

Re-ionization of hydrogen in the universe after the Dark Ages (that began at z~ 1091):

Knowledge of the timing and sources producing re-ionization is still incomplete; but it may have begun as early as redshift z~11 and ended near z~6 with half-ionization at z~8. {A good reference is http://ned.ipac.caltech.edu/level5/March19/Wise/frames.html .}
Quasars and first generation stars are early sources of high-energy photons, but there weren't enough quasars. Now we can include dwarf galaxies as a primary source [see https://arxiv.org/pdf/1105.2038v4.pdf --after our book was written]. Hydrogen ionization requires $h\nu_{ion} > 13.6$ eV of photon energy.
There is a balance between photoionization of hydrogen and recombination with only neutral hydrogen absorbing Lyα photons. The ionization fraction x depends on the number of ionizing photons and free electrons expressed via an ionization parameter $U = n_\gamma/n_e$ (page 266).

The view from Wikipedia is that the hydrogen in the universe became ionized plasma "between 150 million and one billion years after the Big Bang (at a redshift $6 < z < 20$)." After the cosmic dark age, page 270 of our book refers to a time of **re-ionization** at redshift z ~ 11± 3.5 (a 2018 estimate was z = 7.7± 0.8).

In **Figure 8.8** (p 260) again recall that **3C273** is the famous radio quasar that was found to have unusually 'high' optical redshift z = 0.158 by Maarten Schmidt in 1963. It was 1.9 Gℓy away from us and yet very energetic -- suggesting a powerful source. That quickly led to the name QSO or "**quasar**" and much later to Its central black hole having nearly a billion solar masses. It is too close to us to allow for many big gas clouds between it and us, so there is no Ly α forest for this quasar.

The first page of Chapter 8 has the Initial statement: **Cosmological surface dimming goes as $(1+z)^4$** (page 253, Why?).

Recall names: Luminosity L is a power P; Flux is S= P/area = dP/dA = dL/dA. Page 224 uses the symbol "I" = "Surface **Brightness** = "Radiance" = luminosity flux ("S") per unit area of sky (Ω) = $(L/r^2)/(\Delta\theta = D/r)^2 = L/D^2 = S/(\Delta\theta)^2$.

And, on page 32, the book introduced "angular diameter distance" $d_A = D/\Delta\theta$ (the greater the distance d_A, the smaller the subtended angle $\Delta\theta = D/d_A$). And Luminosity distance $d_L = (L/4\pi S)^{1/2}$. Now consider expansion where cosmic scale factor $a_{now}=1$ and $a= a_{then}= 1/(1+z) <1$.

"Cosmological time dilation is a fundamental phenomenon in an expanding universe, which stresses that both the duration and wavelength of the emitted light from a distant object at the redshift z will be dilated by a factor of 1 + z at the observer."

This redshifting expands wavelengths so that energy per photon seen now has $dE \rightarrow a\, dE$. So, $P=\Delta E/\Delta t \rightarrow [\Delta E/(1+z)]/[\Delta t(1+z)] = P_{old}/(1+z)^2 = P_{old}(a^2)$. So $S \rightarrow (L/4\pi d_L^2)\, a^2$. Then use equation 1.50 p 33 to yield Brightness $\propto a^2(d_A^2/d_L^2)=a^4$; and $a^4 = (1+z)^{-4}$, a reduced Brightness.

Page 262 mentions the usefulness of the **Lorentzian profile** for spectral line shapes. Physics students first encounter this shape in mechanics classes for the problem of "damped forced harmonic oscillation." That is, if a mechanical weight with spring system also has a damping term (like friction proportional to velocity), and D is d/dx then it obeys a differential equation $D^2x+\gamma Dx + \omega_o^2x$ = (Force F_o/m)cosωt.

Its solution for the case $\omega_o \gg \gamma$ (high "Q") is: $|x(\omega)| = (F_o/2m\omega_o)[(\omega_o-\omega)^2 + (\gamma/2)^2]^{-½}$ -- which matches the profile form on page 262. Electrical oscillators (LRC circuits) also have this shape. I didn't know that H.A. Lorentz used it for atomic oscillators with radiation damping (and hence its name!).

Page 267 refers again to rather complex units (like we had in Chapter 5). In this case the units are ionizing background of 10^{-21} ergs of energy per cm^2 **per** second **per** Hertz **per** steradian of solid angle {called J_{-21}}. This ionized universe background is fairly constant near $n_\gamma \sim 63/m^3$ for $4 > z > 1.6$ but then drops after cosmic quasar activity and star formation essentially end.

Figure 8.14 on page 268 shows the contribution of neutral hydrogen to the critical density of the universe – only about **Ω_{HI} ~ 0.1%.** But the total baryon density of the universe is $\Omega_b = \rho_b/\rho_{critical}$ = 4.8%. This difference is due to the present universe being strongly ionized rather than neutral as it was in the dark age.

A dark web ties the universe together. Now, we can see it. **Dark Matter Filaments** have few galaxies and can only be deduced by shearing background galaxy images. Begin with Luminous Red Galaxies (LRG's) because they sit in the center of blobs of dark matter (big BOSS Baryon Oscillation Spectroscopic survey) and then look between them at shear distortions. See **picture** at:

https://www.livescience.com/dark-matter-filaments-mapped.html,