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Lyman-α Forest

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Introduction

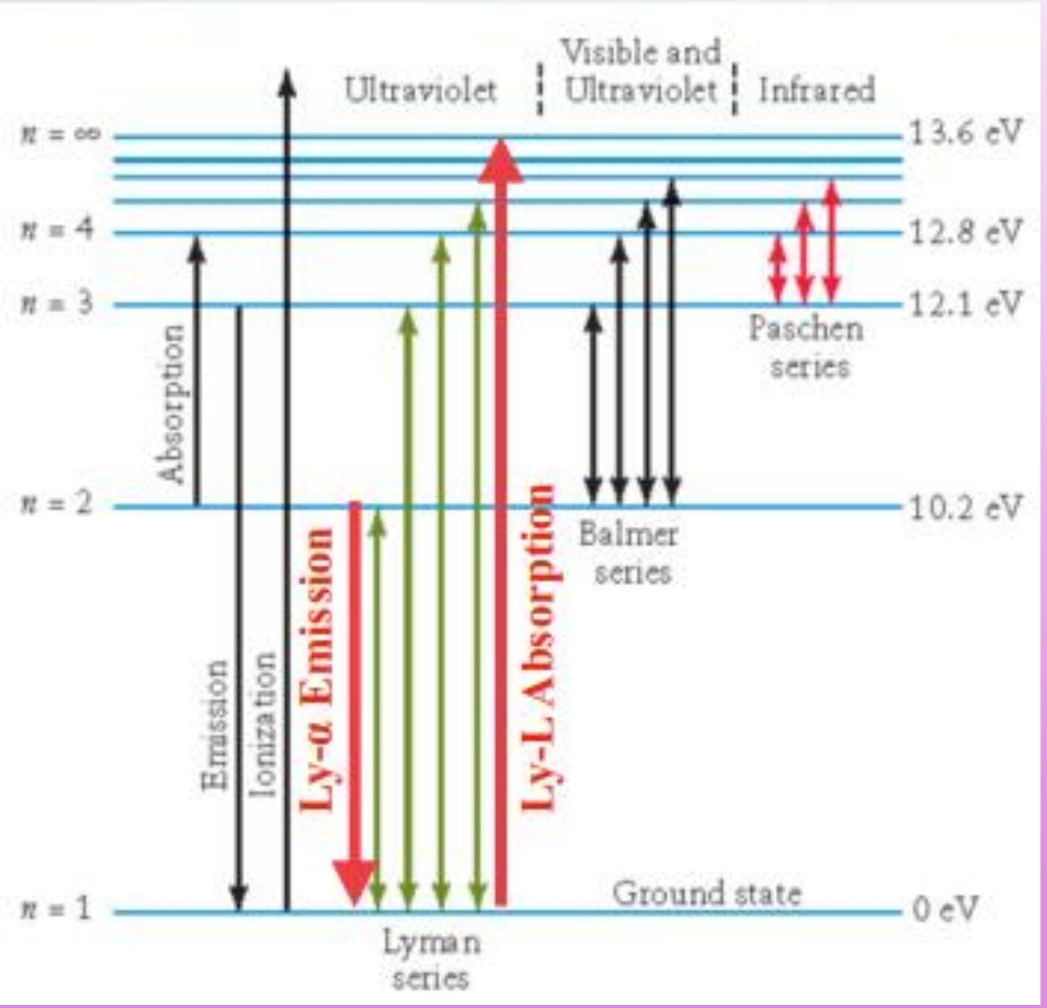
The Lyman alpha forest is an absorption phenomenon seen in the spectra of high redshift QSOs and galaxies.

For a neutral hydrogen atom, spectral lines are formed when an electron transitions between energy levels. The Lyman series of spectral lines are produced by electrons transitioning between the ground state and higher energy levels (excited states).

The **Lyman-alpha transition** corresponds to an electron transitioning between the ground state (n=1) and the first excited state (n=2).

The Lyman-alpha spectral line has a laboratory, or rest, wavelength of 1216 Å, which is in the ultraviolet portion of the electromagnetic spectrum.

The absorption or emission of photons with the correct wavelength can tell us something about the presence of hydrogen and free electrons in space.



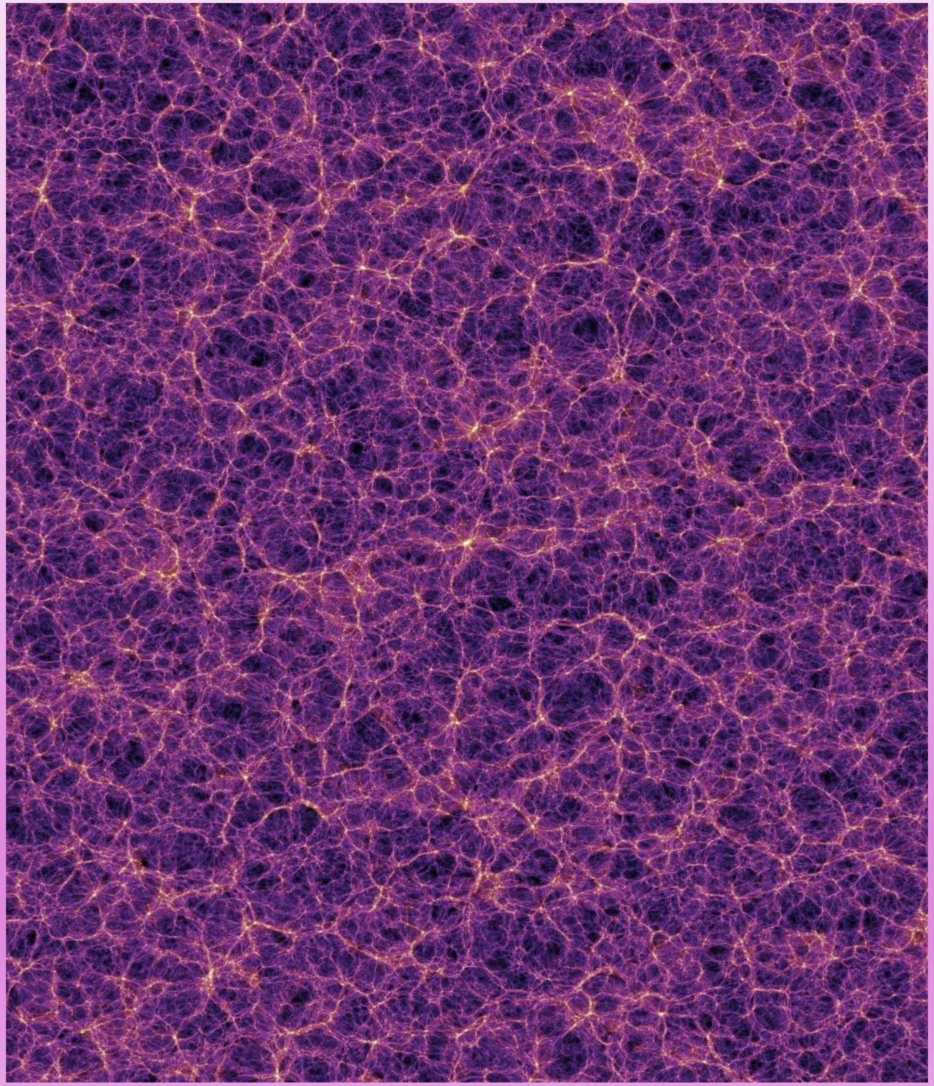
Intergalactic Medium

The intergalactic medium is the hot, X-ray emitting gas that permeates the space between galaxies.

With temperatures of millions of degrees Kelvin and containing less than one atom per cubic meter (a density less than 10^{-27} kg/m3), intergalactic space is one of the hottest and most rarefied environments in the Universe.

Originally it was assumed that the intergalactic medium was composed entirely of primordial Hydrogen and helium left over from the Big Bang. However, in the 1970s, X-ray observations revealed **large quantities of metals mixed in with the hydrogen and helium**.

These metals could only have been made by stars within the galaxies, and somehow later ejected into intergalactic space.

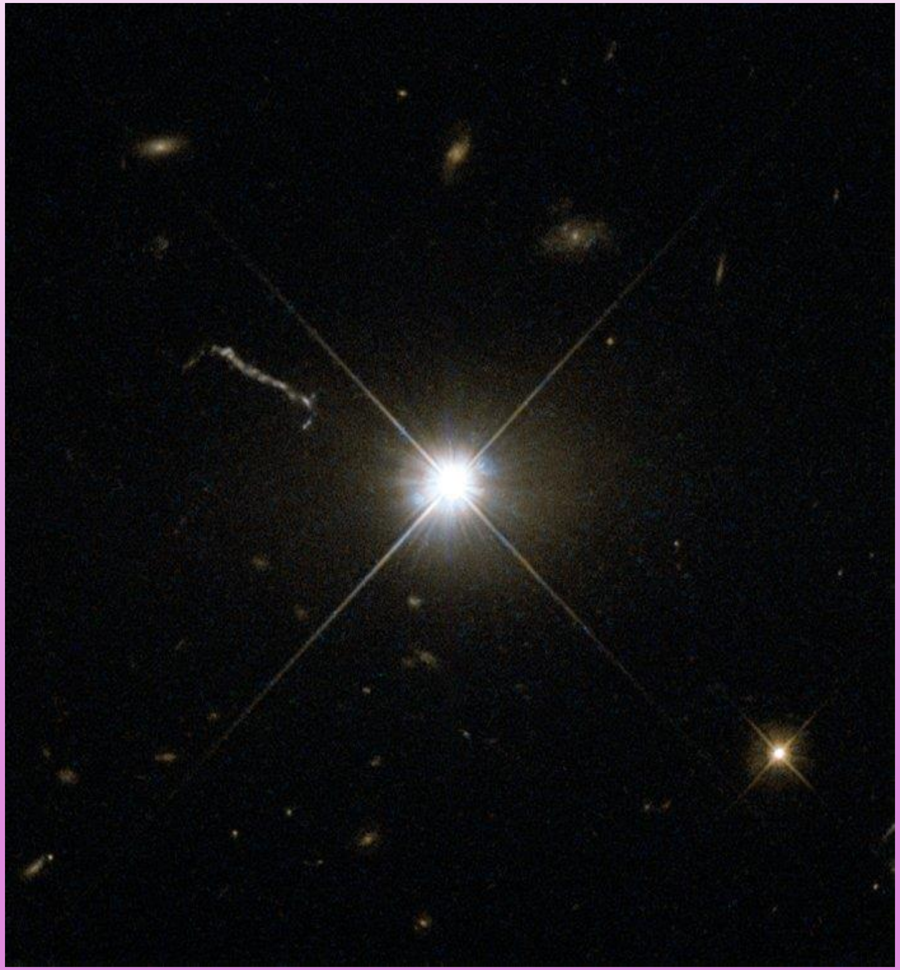


Quasi-Stellar Object

The term quasar is an abbreviation of the phrase "quasi-stellar radio source", as they appear to be star-like on the sky. In fact, **quasars are the intensely powerful centers of distant, active galaxies, powered by a huge disc of particles surrounding a supermassive black hole.**

In the late 1950s, astronomers found the radio sources coincided with faint, **very blue, stellar-like objects**. Unaware of the true nature of these objects, astronomers called them "radio stars."

Astronomers were greatly puzzled by the results. Rather than displaying the expected absorption lines that are characteristic of blue stellar objects, **the spectra showed only a single pair of emission lines,** that did not seem to correspond to the lines of any known substances.



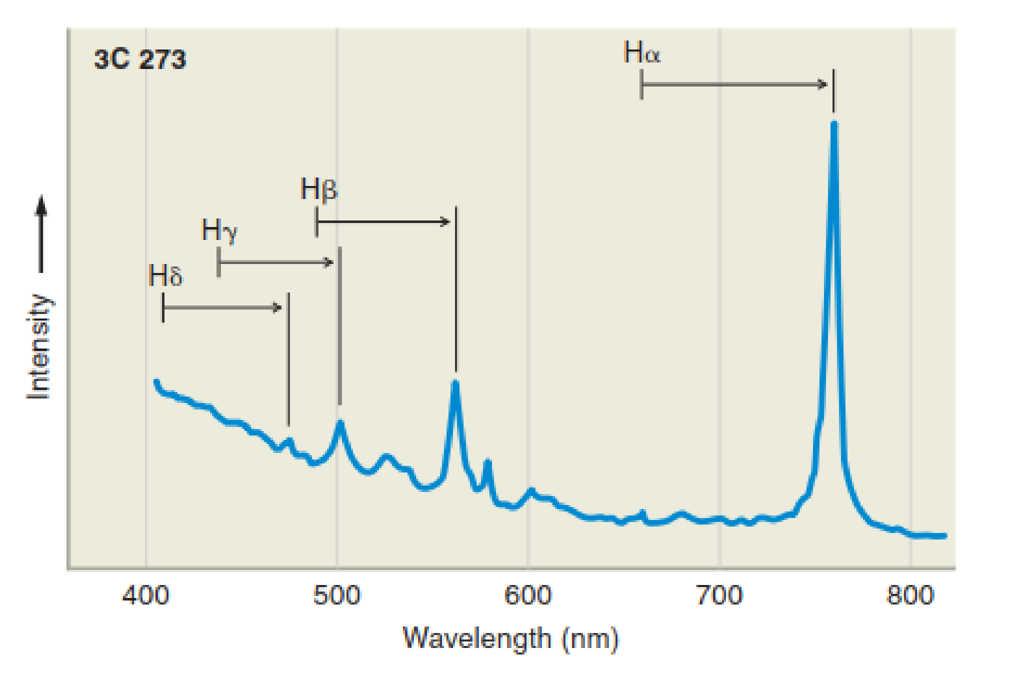
Quasar 3C 273

Quasi-Stellar Object

For several years astronomers believed they had discovered a new type of star, until one astronomer, Maarten Schmidt, realized that these were the highly redshifted lines of ordinary hydrogen. The implications were surprising: these “stars” were not stars.

They were **extraordinarily luminous objects at enormous distances**. Other “quasars,” were soon found by the same techniques. Many were relatively easy to identify because of their unusual blue color.

This image from Hubble’s Wide Field and Planetary Camera 2 (WFPC2) is likely the best of ancient and brilliant **quasar 3C 273,** which resides in a giant elliptical galaxy in the constellation of Virgo. **Its light has taken some 2.5 billion years to reach us. Despite this great distance, it is still one of the closest quasars to our home**. It was the first quasar ever to be identified, and was discovered in the early 1960s by astronomer Allan Sandage.



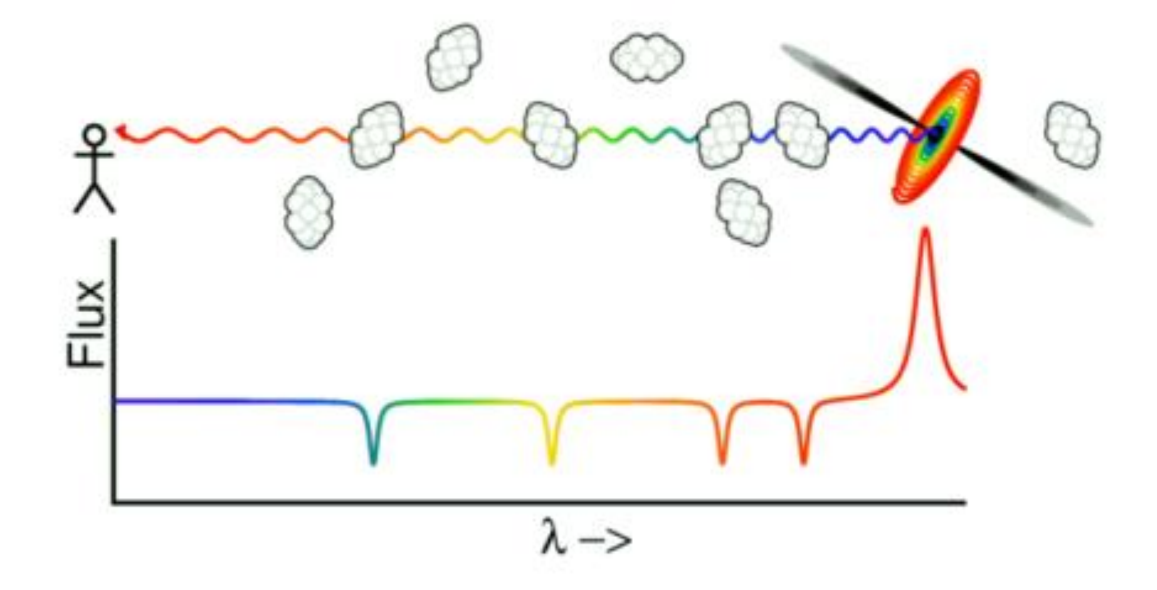
Lyman-Alpha Systems

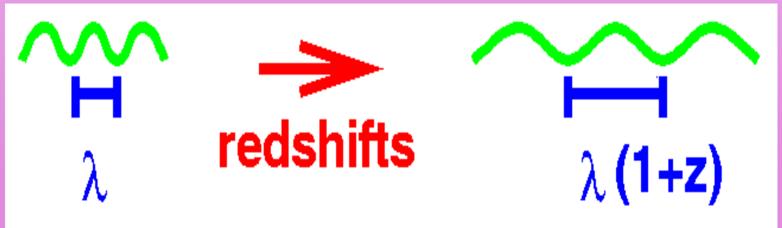
On its way to us the light of a bright, distant QSO passes through intervening intergalactic gas and through gas clouds associated with foreground galaxies.

Absorbing clouds absorb ultraviolet light at the wavelength of the Lyman alpha line of hydrogen at a wavelength of 1216 angstroms and because they have smaller redshifts than the quasar the absorption lines are all on the blue or shorter wavelength side of the quasar emission line.

While photons travel to us, the universe expanding and stretching out all the light waves. Neutral hydrogen atoms in their lowest state will interact with whatever light has been redshifted to a wavelength of 1216 angstroms when it reaches them. The rest of the light will keep travelling to us.

Absorption by the gas modifies the spectra of the background objects and imprints a record of the gas clouds' physical and chemical states on the observed background QSO and galaxy spectra.





Lyman-Alpha Systems

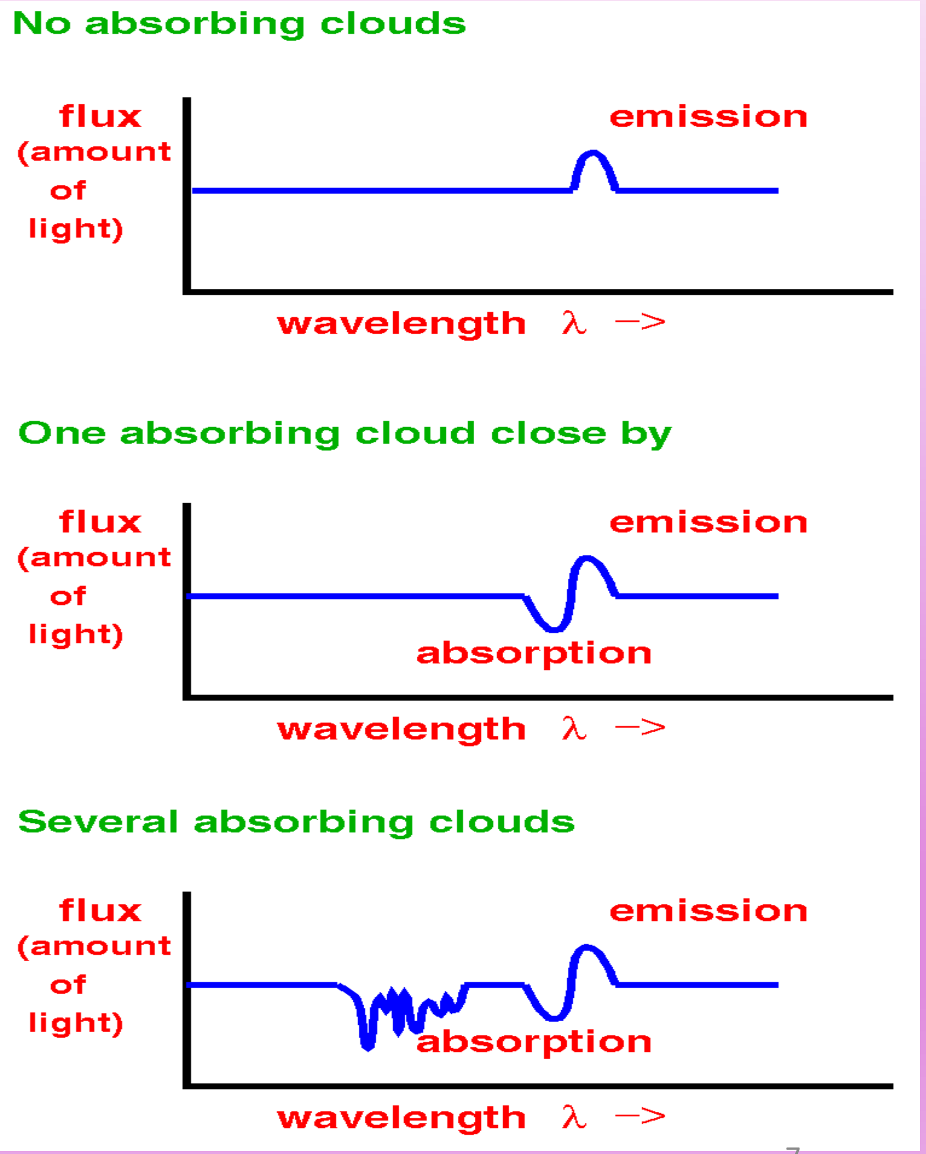
The quasar shines with a certain spectrum or distribution of energies, with a certain amount of power in each wavelength.

As the 1216 wavelength is preferably absorbed, we know that at the location the photon is absorbed, its wavelength is probably 1216 angstroms.

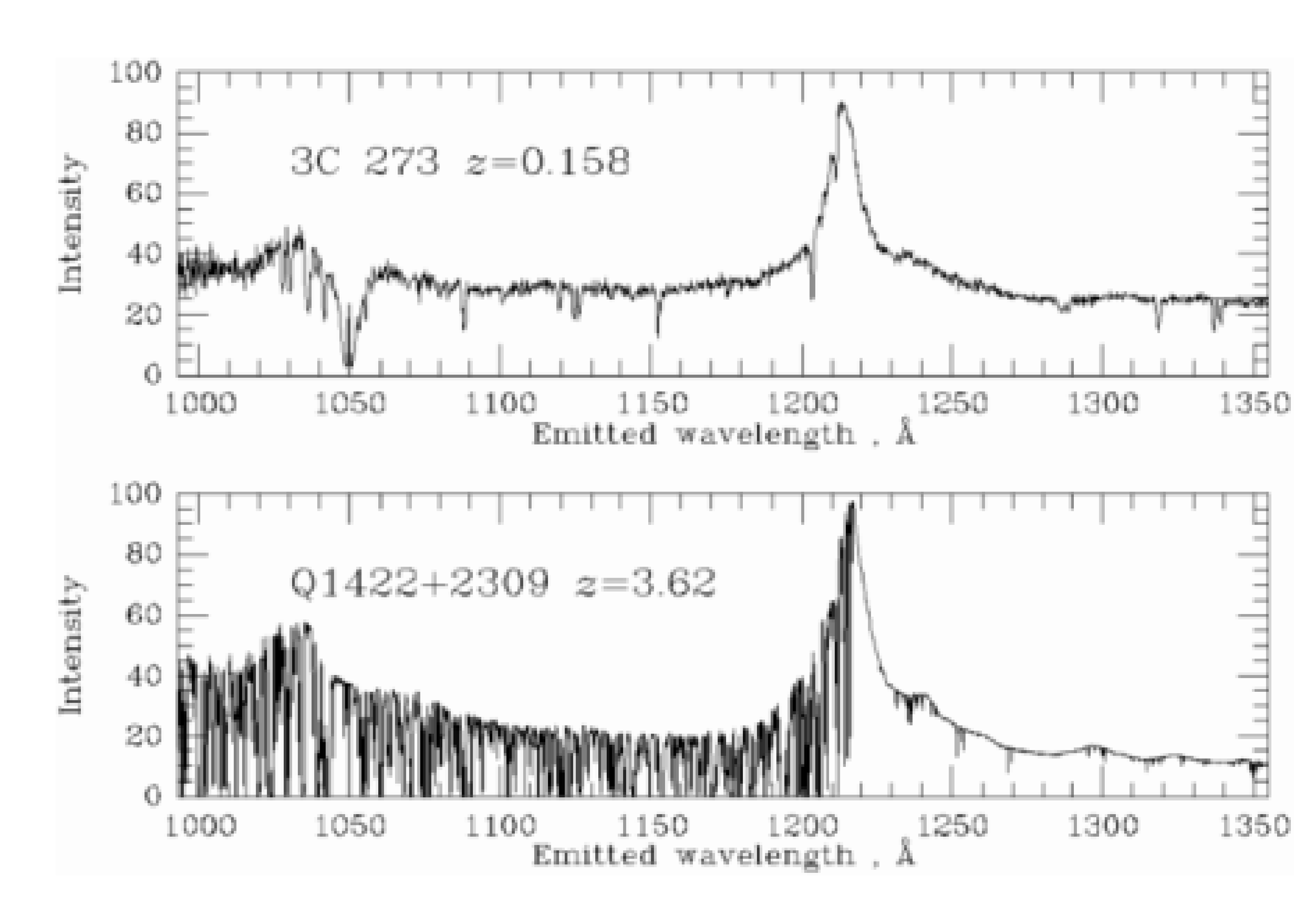
Thus we see the dip in flux at the wavelength corresponding to that which the 1216 angstrom (when it was absorbed) photon would have had if it had reached us.

As we can calculate how the universe is expanding, we can tell where the photons were absorbed in relation to us. Thus one can use the absorption map to plot the positions of region of intervening hydrogen between us and the quasar.

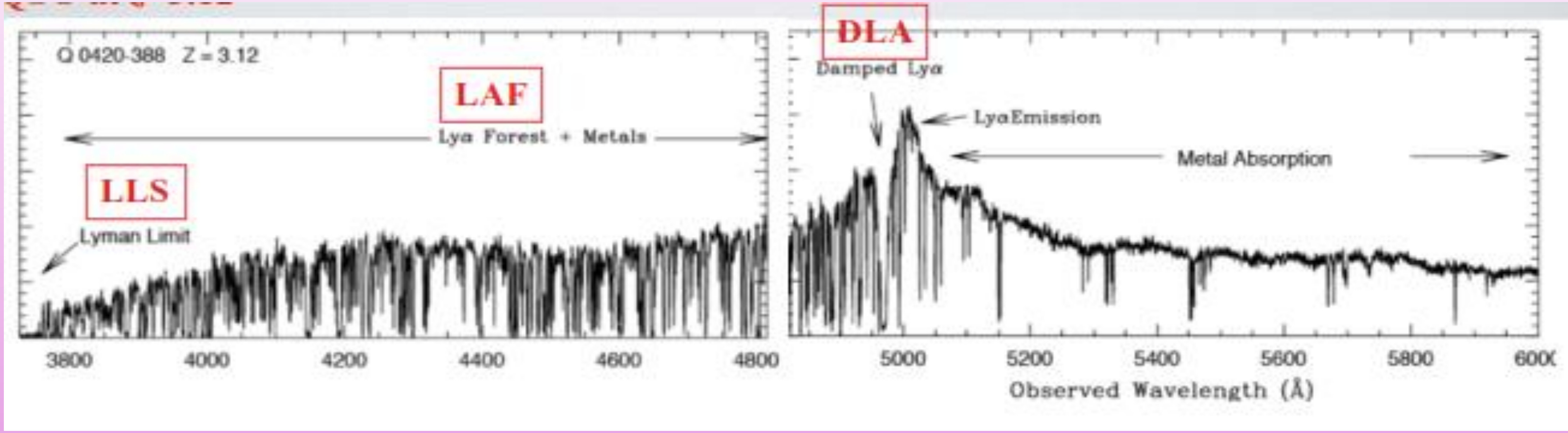
The middle picture at right shows the flux for one nearby region while the bottom picture shows the case for several intervening regions.



Lyman-Alpha Forest



Lyman-Alpha Forest



A series of absorption lines, called the **Lyman alpha forest**. Systems which are slightly more dense, **Lyman limit systems**, are thick enough that radiation doesn't get into their interior. If the regions are very thick, there is instead a wide trough in the absorption, and one has a **damped Lyman alpha system.**

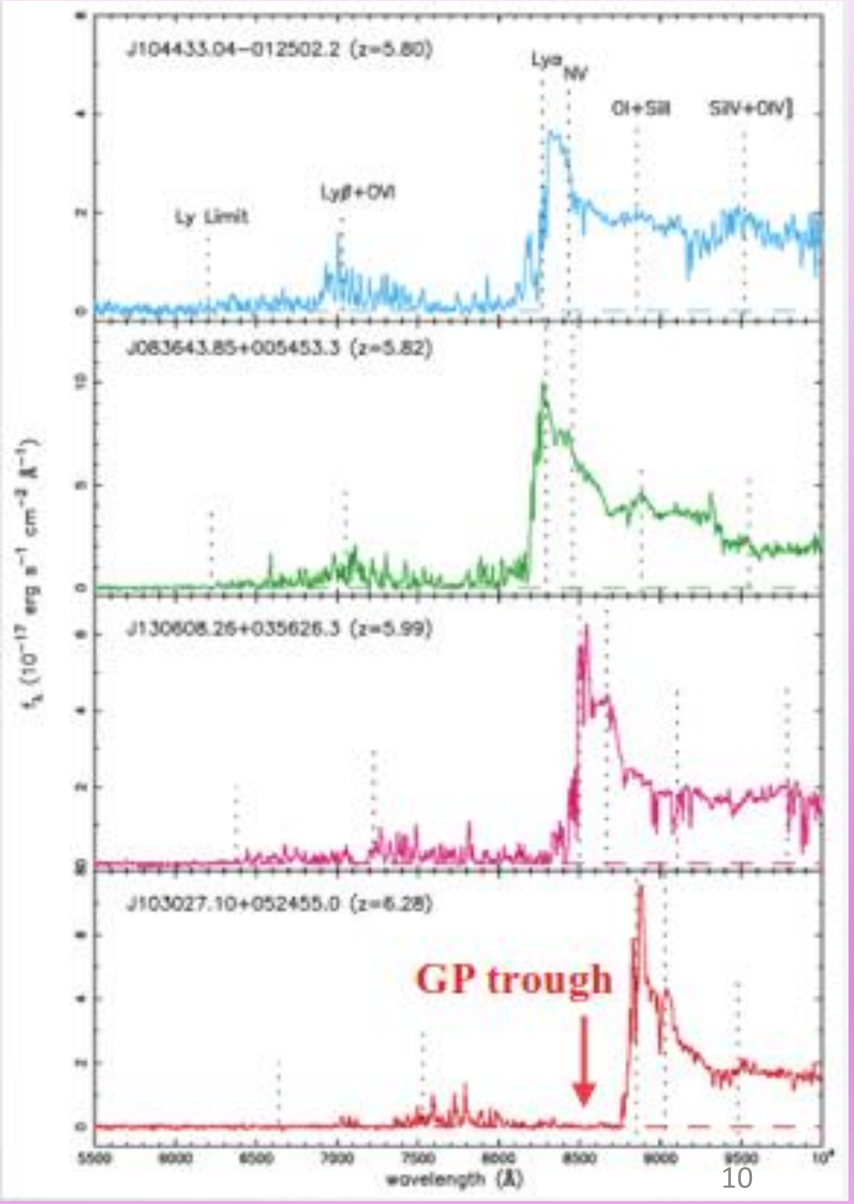
Absorption lines generally aren't just at one fixed wavelength, but over a range of wavelengths, with a width and intensity (line shape) determined in part by the lifetime of the excited n=2 hydrogen atom state. These damped Lyman alpha systems have enough absorption to show details of the line shape such as that determined by the lifetime of the excited state. These dense clumps are thought to have something to do with galaxies that are forming.

The Gunn-Peterson Effect

The Gunn–Peterson trough is a feature of the spectra of quasars due to the presence of neutral hydrogen in the 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 Gunn and Bruce Peterson.

For over three decades after the prediction, no objects had been found distant enough to show the Gunn–Peterson trough. It was not until 2001, with the discovery of a quasar with a redshift z = 6.28 by Robert Becker and a Gunn–Peterson trough was finally observed.

The discovery of the trough in a z = 6.28 quasar, and the absence of the trough in quasars detected at redshifts just below z = 6 presented strong evidence for the hydrogen in the universe having undergone a transition from neutral to ionized around z = 6.



Uses:

The Lyman-alpha forest is an important probe of the intergalactic medium and can be used to determine the frequency and density of clouds containing neutral hydrogen, as well as their temperature. Searching for lines from other elements like helium, carbon and silicon (matching in redshift), the abundance of heavier elements in the clouds can also be studied.

Neutral hydrogen: because we see any light at all, we can limit how much neutral hydrogen is out there between us and the quasar and what its distribution is. It used to be thought that there was a smooth intergalactic medium (IGM) with regions embedded in it, and the smooth background would provide an absorption at all positions between us and the quasar (Gunn-Peterson effect). But observers only see evidence of lumpy regions. There isn't evidence for a spatially smooth component of neutral hydrogen between us and the quasar sources. It is a question of active research what is making the amount of neutral hydrogen so small (that is, what is ionizing the rest of the hydrogen).

Structure formation: the regions in the Lyman alpha systems are not very massive compared to objects like galaxies. As a result, reliable computer simulations of their gravitational collapse (formation) from primordial fluctuations are possible. Until the 90's, it was thought that gravity alone could not form all the structure. However, the Lyman alpha simulations did produce this structure by starting with small fluctuations in matter density and then letting gravity and other known forces act. It was not necessary to add other mechanisms to get the observed structure in these systems.

Uses:

Distribution of matter: The Lyman alpha regions are formed by gas falling into gravitational potential wells of all the matter, not just the luminous matter. So they provide another tracer of dark matter.

Nucleosynthesis: deuterium is produced in 'the first three minutes' in the early universe, and afterwards is believed to only be destroyed. The Lyman alpha systems have deuterium in them too, and as these systems also have low amounts of metals (heavier elements), one might hope that they are measuring unprocessed or primordial deuterium. The deuterium also absorbs light from quasars, and thus its abundance can be measured in a similar way. Searches in many of these systems have provided the current strongest constraint on the amount of primordial deuterium and thus the baryon density in the universe.

Cosmological constant: the path back to a given redshift depends on how the universe has expanded since that time. The angular extent of an object at any redshift also depends on the expansion of the universe since the light was emitted, but in a different way. Thus one can compare angular and radial (more precisely redshift) lengths for objects. If one knows the expected ratio of these lengths for an object for other reasons, one can constrain the expansion history of the universe, in particular the cosmological constant.

Thank You