Astronomy 401/Physics 903
Lecture 30
Reionization

Recombination and decoupling occurred at $z \sim 1100$, when the universe became cool enough for free electrons and free protons to combine, photons stopped scattering off of free electrons, and photons and baryons began to evolve independently. After recombination, most of the hydrogen in the universe was neutral.

When we look at the universe today, however, most of the hydrogen is ionized. We can see this in the spectra of quasars, when we look at the $\mathrm{Ly}\alpha$ forest. Recall that this is a series of absorption lines from clouds of neutral hydrogen between us and the quasar. Studies of the $\mathrm{Ly}\alpha$ forest show that this neutral hydrogen is rare; only one atom in $\sim 10^5$ is neutral, so most of the hydrogen is ionized.

This means that at some point after recombination but before the time at which we observe most quasars and galaxies, the universe went from neutral to ionized. This is called the **epoch of reionization**.

1 When did reionization happen and how do we know?

There are currently two observational results which constrain the time at which reionization occurred.

1.1 The Gunn-Peterson trough in QSO spectra

As previously discussed, high redshift quasar spectra show a dense forest of $\mathrm{Ly}\alpha$ absorption lines blueward of the $\mathrm{Ly}\alpha$ line in the quasar itself, from clouds of neutral hydrogen along the line of sight. However, if the light passes through very large areas of neutral hydrogen, the spectrum will be suppressed entirely, instead of showing a series of narrow absorption lines. This is known as the Gunn-Peterson trough, after the astronomers James Gunn and Bruce Peterson who predicted it in 1965.

The effect wasn't discovered until much later, in 2001, when quasars at $z \sim 6$ were discovered in the Sloan Digital Sky Survey (see Figure 1 and compare Figure 2). The spectra of the quasars showed increasingly complete suppression of the flux blueward of $\mathrm{Ly}\alpha$, from increasing amounts of neutral hydrogen in the intergalactic medium. This was clear evidence that reionization was not fully complete at $z \sim 6$.

1.2 Secondary anisotropies in the CMB

The effects of reionization can also be seen in the power spectrum of the cosmic microwave background radiation. After the universe became reionized but before it had expanded so much that the density of free electrons was too low, the CMB photons scattered off of the newly ionized electrons, producing anisotropies in the CMB. These are called secondary anisotropies, as opposed to the primary anisotropies which are due to the density fluctuations at the time of recombination. The overall effect of this is to erase anisotropies on smaller scales. Measurements of the CMB power spectrum allow the electron density at the time of recombination to be determined, and therefore the redshift at which it occurred. The WMAP results indicate that reionization began at $z \sim 11$ and was completed by $z \sim 7$. This is in rough agreement with the QSO results, though the quasar spectra indicated significant amounts of neutral hydrogen still existing at $z \sim 6$. Reionization is expected to be **patchy**, with different parts of the universe becoming ionized at different times and more dense regions taking longer.

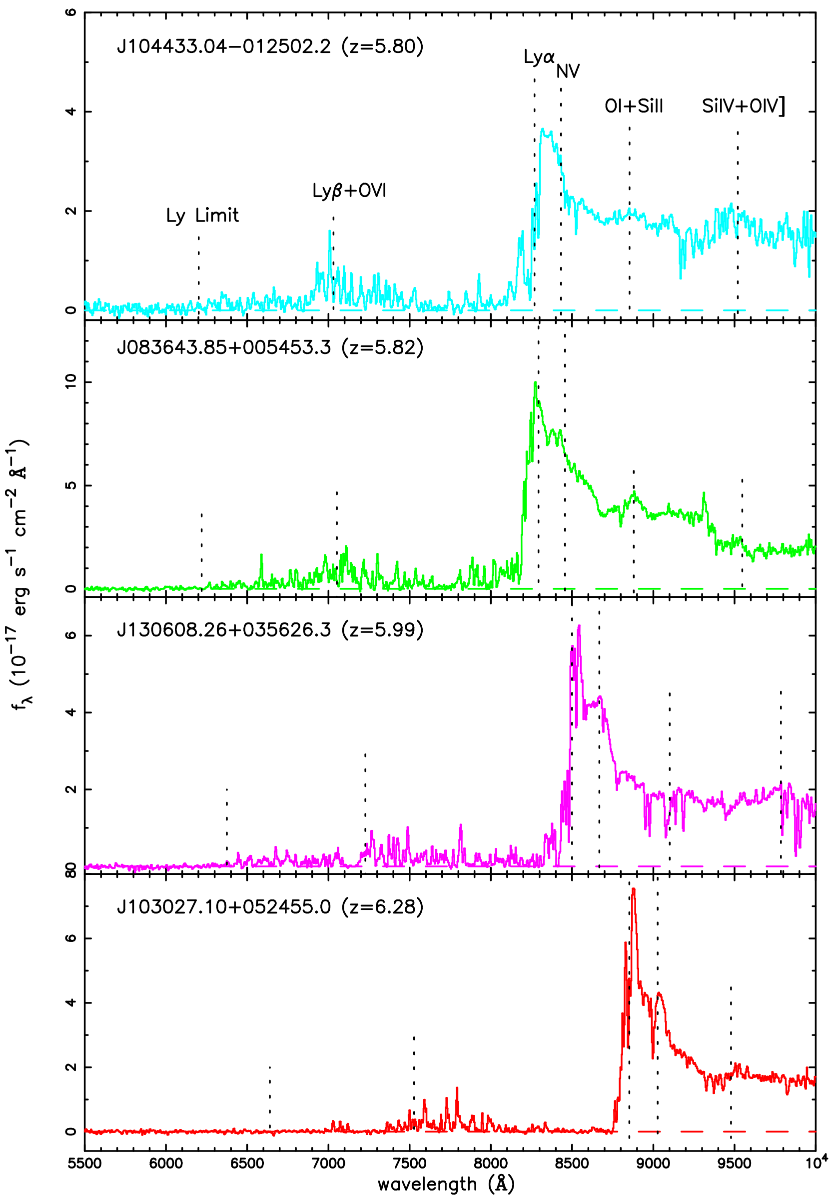

Figure 1: The Gunn-Peterson trough in the spectra of $z \sim 6$ quasars.

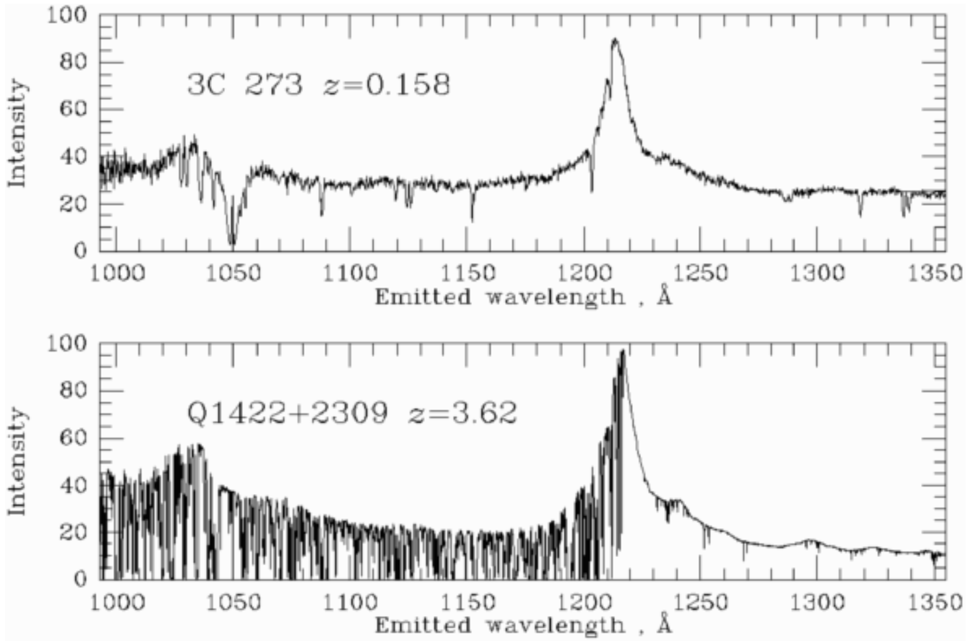

Figure 2: The Lyα forest in the spectrum of a QSO at $z = 3.6$, when the universe was reionized, and the absence of the forest in a low redshift QSO.

2 The epoch of reionization

Reionization should be thought of as a process rather than an event. It is expected to proceed as follows:

- An initial phase in which the universe is largely neutral except for isolated HII regions produced by individual ionizing sources;
- A second phase in which individual HII regions start to overlap, but about half of the IGM is still neutral;
- A third phase in which the universe is largely ionized, except for some pockets of neutral gas associated with high density regions;
- A final phase in which the universe is completely ionized, with a very small neutral fraction, as inferred from the Gunn-Peterson test at $z \sim 6$.

An illustration of the process from a numerical simulation is shown in Figure 3.

The details of this reionization process depend on several factors. First, it depends on the physical properties of the individual ionizing sources, such as luminosity, spectrum, and the fraction of ionizing photons that can escape from the source. Second, it depends on the properties of the source population, such as number density, time evolution, and spatial distribution (clustering) in the cosmic density field. Third, it depends on the properties of the gas density field. Since recombination is a two-body process, accurate predictions for the ionized fraction require accurate modeling of the high-density regions, even if these only cover a small fraction of the total volume. Finally, the first generation of ionizing sources can affect the IGM not only through ionization, but also through photoheating, shock heating, and chemical enrichment, which can affect the subsequent formation of ionizing sources.

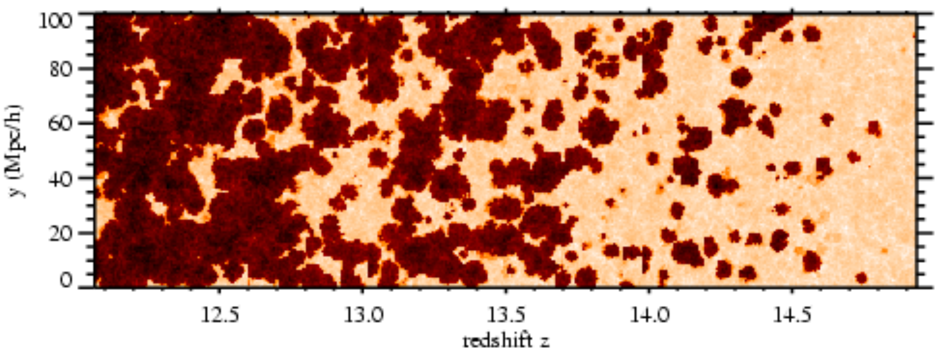

Figure 3: A slice from an N-body simulation showing the progress of reionization with redshift. Light regions represent neutral gas, and dark regions show ionized gas. Reionization is expected to be an extended process, as HII regions produced by individual ionizing sources begin to overlap. Simulation by Garrelt Mellema; see `http://astrohydro3d.strw.leidenuniv.nl/garrelt_wiki/doku.php?id=reionization_simulations` for details.

All of these factors make modeling the reionization history of the universe a difficult problem, even with modern computer simulations. One needs very high resolution to properly model star formation, feedback effects (the injection of material and energy from stars back into the IGM, through stellar winds and supernovae), and small-scale clumpiness of the IGM. One also needs a large volume to properly represent the cosmic density field, and one also needs to keep track of the radiation field through radiative transfer and to calculate the ionization states of different species. Reionization has been investigated both numerically and analytically in recent years. The details are still far from clear, but we will mention some results that illustrate the complexities involved.

During the early phase, reionization proceeds slowly because of the small number density of ionizing sources and because of the small sizes of HII regions due to the high density of the IGM. The process accelerates as more ionizing sources form and the average density of the IGM decreases. As the HII regions start to spread, reionization then proceeds very fast as the ionizing photons can propagate to large distance to ionize the neutral medium. Since the medium is inhomogeneous and the sources are clustered in space, reionization can be extremely patchy, with complicated morphologies.

Naively, we might expect that the HII regions will grow and spread first in regions of high source density. However, if ionizing sources form preferentially in high density regions, then it is not obvious that this is true. The ionization fraction of the gas depends not only on the local flux of ionizing photons, but also on the recombination rate, which is higher in regions of higher gas densities. It may be possible that the enhancement of the recombination rate in high density regions overcomes the high UV flux associated with the high source density, so that reionization proceeds in an "inside-out" fashion, i.e. from low density to high density. The results depend on the details of the assumptions about source distribution and the radiative transfer around sources, with the result that this issue is not yet resolved.