Quasar Absorbers and the InterGalactic Medium

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1 Introduction

When we measure the spectra of quasars, we see many absorption lines superimposed on the quasars' own emission spectra. These absorption features trace the intervening gas along our line of sight (LOS) to any quasar. There are many reasons why it is interesting to study this intergalactic medium (IGM): firstly, around 30% of all baryonic matter in the universe is contained in the IGM at the present day; the absorption lines we see span all the way out to the furthest quasars we can measure and so give us an unprecedented view into the early and distant universe; statistical analysis of the distribution of these absorption systems can give independent constraints on cosmological models; and absorption lines from the IGM actually outnumber all other detectable tracers of cosmic structure (Pettini, 2006).

In this seminar, I will try to give a feel for how we can get information about these cosmological systems that we only see by their absorption. I will start in Section 2 with a brief overview of the absorption features that we see and the systems that create them. I will then review some basic ideas from spectroscopy and go on to show how properties of the observed lines, such as the equivalent width and the line profiles, can tell us properties of the absorbing systems, such as their column density and temperature. I will finish in Section 4 with a summary of the different types of quasar absorbers that we see.

2 Quasar Absorption Spectrum Basics

When we study the absorption features in the spectrum of a quasar, we see a forest of absorption lines shortwards of the quasar's main emission feature. From the relative positions of the emission lines we can be sure that this peak is the Lyman-α (Lyα) transition of hydrogen redshifted to z_{QSO}. We deduce that the absorption features are also Lyα, but at lower redshifts between us and the quasar.

This Lyα absorption is a tracer of neutral hydrogen (since hydrogen ions have no electron to make the Lyα transition). We can be sure that the distribution of neutral hydrogen is not uniform throughout all of the intergalactic space as Gunn and Peterson (1965) predicted that this would produce a continuous absorption trough in quasar spectra. Instead we see a collection of individual lines known as the *Lyman-α forest*, which correspond to a population of clouds of primordial hydrogen (Sargent et al., 1980). Research in the last ten years has shown that these IGM clouds are not clearly-defined, discrete objects but

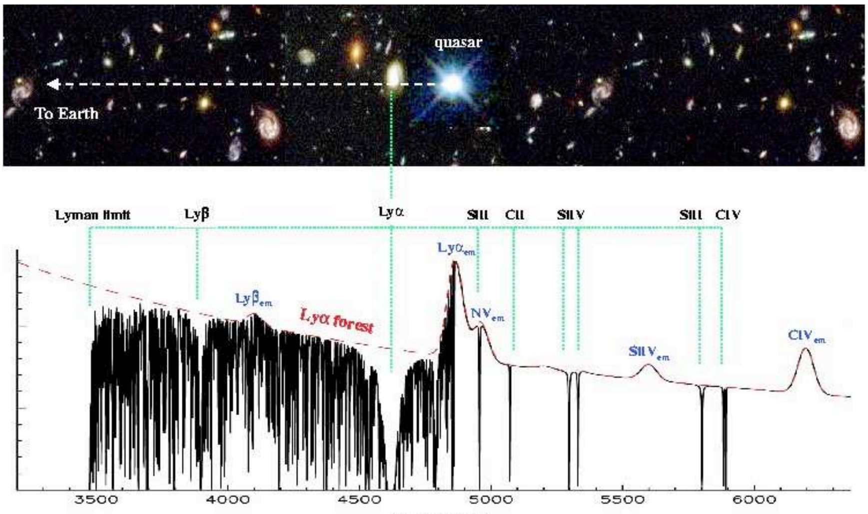

Figure 1: Illustration of a quasar spectrum showing many features of the IGM.

instead represent the strongest overdensities in a continuously varying density-field of primordial gas.

3 Absorption Line Characteristics

In this section I will go through some basic theory from spectroscopy so that we can understand what information we can gain from quasar absorption features. It is useful to consider that for any absorption line, we can observe its minimum intensity, the total intensity removed across the whole line, its shape and the characteristic width.

3.1 Absorption basics

We can derive these basic features by considering a beam of quasar light with an initial intensity I_0, travelling in the x direction along our line of sight and passing through an idealised slab of intergalactic gas of thickness L. We can deduce that the rate of change of the intensity $I(x)$ along x is negative and is proportional to both the *number density* $n(x)$ of absorbing atoms and the intensity itself:

$$\frac{dI_\lambda}{dx} = -a_\lambda n(x) I_\lambda(x). \tag{1}$$

The *line absorption coefficient* a_λ represents the cross-section of the absorbing atoms and has units of area. To solve for $I(x)$, we will integrate along x from 0 to L, and see that the intensity falls as an exponential. First, we will define the *optical depth* τ_λ as a concise form for the absorption factors:

$$-d\tau_\lambda \equiv -a_\lambda n(x) dx. \tag{2}$$

This gives the optical depth of the gas cloud along the line of sight as:

$$\begin{aligned}\tau_\lambda &= a_\lambda \int_0^L n(x)dx \\ &= a_\lambda N\end{aligned} \tag{3}$$

where we have defined the *column density* N as the integral of the number density along the LOS. Integrating Equation 1 shows that the intensity falls exponentially as:

$$I_\lambda(x) \;=\; I_{\lambda,0}e^{-a_\lambda N} \;=\; I_{\lambda,0}e^{-\tau_\lambda}. \tag{4}$$

3.2 Line profiles

For any line of wavelength λ_0, the absorption coefficient can be split into two factors:

$$a_\lambda = a_0\Phi_\lambda. \tag{5}$$

The quantum parameters of the atomic transition which causes this line are included in a_0, whilst the *broadening function* Φ_λ describes the shape of the line that is produced.

For an absorption line centred at a wavelength λ_0, the broadening function gives the likely distribution of wavelengths of the photons that were absorbed. It has a large value near λ_0 and falls off sharply on both sides. The probability that any photon absorbed in the line had a wavelength between λ and $\lambda + d\lambda$ is given by $\Phi_\lambda d\lambda$, so we see that the broadening function is normalised to give:

$$\int_{-\infty}^{\infty} \Phi_\lambda d\lambda = 1. \tag{6}$$

We find the form of Φ_λ for any line by considering the atomic processes involved. The most significant are *natural broadening* and *Doppler broadening* which we will consider now. Other processes such as atomic collisions could also contribute to the broadening. However, in an extremely rarified gas like the IGM their contribution is negligible and they do not change the shape of the lines.

Natural broadening (also known as natural damping) occurs because there is an uncertainty ΔE in the energy of the upper atomic level and this will give an intrinsic width to any absorption line. This is due to the fact that any energy state occupied for a finite time Δt must satisfy the relation $\Delta E \Delta t \sim \hbar$. The uncertainty in the energy of the transition gives the line a Lorentzian profile:

$$\phi_{nat} = \frac{1}{\pi}\frac{\delta_k}{{\delta_k}^2 + (\nu - \nu_0)^2}\,, \tag{7}$$

where

$$\delta_k = \frac{1}{4\pi}\sum_m A_{km}\,. \tag{8}$$

The Einstein coefficient A_{km} gives the probability per particle per second of a spontaneous transition to a lower state m.

If the absorbing atoms were in motion, then the resulting line will also have a width due to Doppler broadening. Clearly atoms in the IGM will have some thermal velocity along the line of sight. We can assume a Maxwell-Boltzmann distribution of velocities, therefore the atoms will have Gaussian distributed velocities along any component. This gives a Gaussian line profile for the Doppler broadening:

$$\phi_{Dopp} = \frac{1}{\Delta\nu_D \sqrt{\pi}} \exp\left\{-\tfrac{(\nu-\nu_0)^2}{(\Delta\nu_D)^2}\right\}. \tag{9}$$

The Doppler width $\Delta\nu_D$ is the frequency interval corresponding to the most likely thermal velocity along the LOS:

$$\Delta\nu_D = \frac{\nu_0}{c}\sqrt{\frac{2k_BT}{m_H}}. \tag{10}$$

It should be noted that the Doppler broadening of the lines is not due exclusively to thermal motions in the gas, but is also sensitive to any difference in velocities across the absorbing cloud as a whole. For example, a Lyα forest cloud that is following the Hubble expansion will have some differential Hubble flow along the length of the cloud which would contribute to the Doppler broadening.

The true line profile is the convolution of the Lorentzian and Gaussian profiles:

$$\Phi_\nu \quad = \quad \phi_{nat} * \phi_{Dopp}\,. \tag{11}$$

This produces a Voigt function which is the general form of the quasar absorption lines that we observe. Close to the line centre ν_0 the function has a Gaussian shape as atoms are more likely to absorb because of their motions. This probability falls off exponentially away from the line centre however, leaving Lorentzian wings which only fall off as the inverse square of $\Delta\lambda$. Therefore, absorptions away from the line centre tend to be occur because of natural damping.

The shape of an absorption line can therefore tell us the processes involved in the absorption, and gives us information about the conditions in the absorbing IGM gas. It can also tell us the relationship between the strength of the line and the column density of the absorbing cloud. However, things are rarely this simple, and we typically cannot resolve the shape of individual lines. Spectrographs record the convolution of the Voigt line profile with the instrument's own broadening function which is typically wider than the line itself. This means that we lose most of the information that could have been obtained from the line profile. Only the very best spectra taken with long observations on 8-10m class telescopes can resolve the shape of these lines, and this has only been possible since the mid-1990s.

3.3 The equivalent width

The way that we deal with low resolution spectra is to define the *equivalent width* W_λ which is invariant to convolution and so is conserved even when the

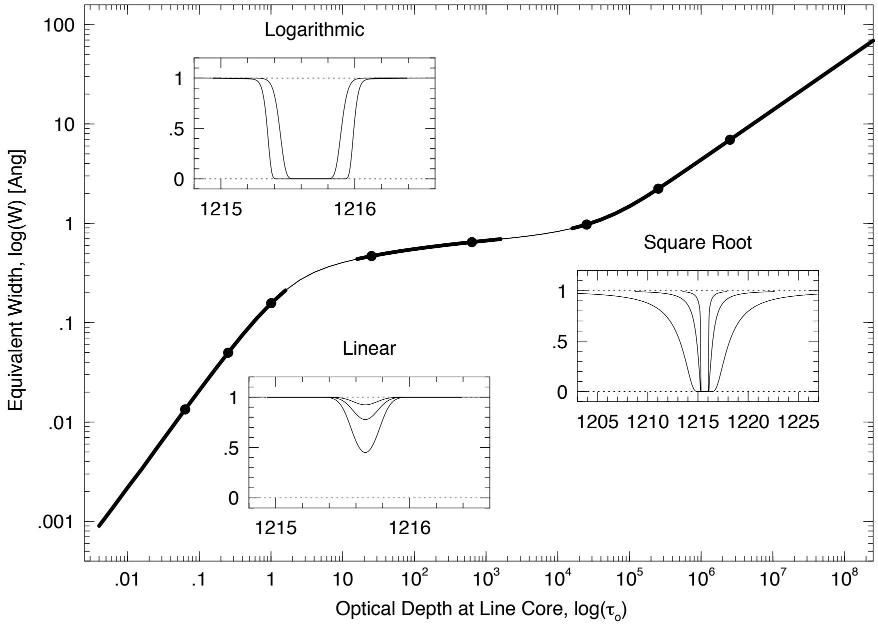

Figure 2: The Curve of Growth, plotting W_λ against $\tau(\lambda_0)$

shape of the line profile is lost. It is a measure of the line intensity and should not be confused with the velocity width. The equivalent width of some line is defined as the width in wavelength units of a line of the same total energy but with zero intensity throughout (i.e. the width of a rectangular strip of the spectrum with the same area as the line in question):

$$W_\lambda = \int_{-\infty}^{\infty} \frac{I_{\lambda,0} - I_\lambda}{I_{\lambda,0}} d\lambda \,. \tag{12}$$

If this formula for the equivalent width is not obvious, consider the area of the absorption line as the difference between the integrals of I and I_0 wrt λ, and divide this area by the (constant) background intensity I_0 to get the width of a line with zero intensity.

From the definition of I_λ in Equation 4 we can see that the equivalent width is also a function of the optical depth:

$$W_\lambda = \int_{-\infty}^{\infty} (1 - e^{-\tau_\lambda}) d\lambda \,. \tag{13}$$

Under the right conditions we can therefore recover the optical depth and the column density from the equivalent width, which is conserved even for unresolved spectral lines. However, as we shall see, the dependence of the optical depth on the broadening function means that the relationship between W_λ and N is not trivial.

Integrating Equation 13 and plotting the equivalent width W_λ against the optical depth at the line centre $\tau(\lambda_0)$ shows the three different regimes in which an absorption line can be. This *Curve of Growth* shows how the equivalent width grows for Lyα lines of increasing optical depth. The position of any absorption line as a point on this curve dictates the relationship between W_λ which we can measure, and N which we want to recover:

Linear regime For optically thin gas clouds with $\tau(\lambda_0) \ll 1$, thermal motions dominate and give a Gaussian shape to the line profile. For clouds with increasingly large N and τ, the lines stay Gaussian and the equivalent width increases linearly: $W_\lambda \propto N$.

Logarithmic regime For sufficiently dense clouds with $\tau(\lambda_0) \gtrsim 10$, the absorption line becomes saturated and the cloud is optically thick, absorbing all photons in the line core. If we increase the density and optical depth further, very little additional light is removed and the equivalent width changes only a small amount. Note that in this regime, the equivalent width is sensitive to the Doppler width $\Delta\nu_D$ and so is not a good measure of N:
$W_\lambda \propto \Delta\nu_D \sqrt{\ln(N/\Delta\nu_D)}$.

Square root regime The most dense gas clouds with $\tau(\lambda_0) \gtrsim 10^4$ have wide Lorentzian wings as the optical depth has started to become significant far from the line centre. Increasing the optical depth further will cause the line's equivalent width to grow again as more light is absorbed in the damping wings because of natural broadening: $W_\lambda \propto \sqrt{N}$.

In order to recover the column density from any line, we need to know where it sits on the Curve of Growth. This is straightforward for well resolved lines, but for an unresolved line with an equivalent width W_λ, the column density is degenerate with the Doppler width $\Delta\nu_D$. It is sometimes still possible to identify the regime of an unresolved line and thus find the column density N if we can see other lines with a transition to the same energy level.

4 Types of quasar absorbers

Now that we have seen how the column density of intervening absorbers affects the spectral lines, I will finish with a summary of the sorts of systems that we actually detect in quasar spectra. Almost all of the absorption lines that we see in quasar spectra are due to hydrogen Lyα absorption, so we are detecting clouds of hydrogen gas with different densities in the IGM.

Lyα forest clouds The majority of the lines that we see make up the Lyα forest and represent overdensities in the IGM with $10^{12} cm^{-2} \lesssim N(HI) \lesssim 1.6 \times 10^{17} cm^{-2}$. These low density clouds produce absorption lines whose Voigt profiles are basically Gaussian.

Lyman-limit systems Gas clouds with $N(HI) \gtrsim 1.6 \times 10^{17} cm^{-2}$ produce a stronger line in the Lyα forest (at $\lambda_{rest} = 1216$Å) but also introduce a new absorption feature. At these column densities, the clouds have enough neutral hydrogen atoms to absorb all photons with $E_\gamma \geq 13.6eV$. Lyman-limit systems are therefore optically thick to this ionising radiation, which causes a cutoff in the quasar spectrum at the Lyman limit, $\lambda_{rest} = 912$Å. All denser hydrogen clouds will also show this cutoff.

sub-Damped Lyα systems From around $N(HI) \gtrsim 10^{19} cm^{-2}$, selfshielding means that a high percentage of the hydrogen in sub-DLAs remains neutral. The Lyα line will begin to show the Lorentzian damping wings as radiation is absorbed at wavelengths away from the line centre. Sub-Damped Lyα systems are a new classification from the last five years, for systems detected at $z \gtrsim 3.5$ which fall below the traditional column density threshold for DLAs but contain a significant fraction of the *neutral* gas at high redshift.

Damped Lyα systems DLAs have very little ionised hydrogen, and their neutral hydrogen column densities $N(HI)$ are higher than $2 \times 10^{20} cm^{-2}$. This puts them on the 'square root' part of the Curve of Growth and so they produce absorption lines that are dominated by very wide damping wings. Between redshifts of 2 and 3.5, DLAs contain $\sim 90\%$ of neutral gas in the universe, and $\sim 55\%$ at $z \gtrsim 3.5$. There is an idea that DLAs could be the progenitors of today's galaxies before the gas had collapsed to stars.

Metals in the IGM Finally, I will briefly discuss detections of other elements in the intergalactic medium. Metal lines are greatly outnumbered in any quasar spectrum by lines from hydrogen, and we only see the strongest lines from the most abundant metals (e.g. OI, CII, CIV, MgII, SiII and FeII). We can identify absorption lines at longer wavelengths that the main Lyα emission peak since there is no hydrogen absorption there, but it is not trivial to identify metal lines that are hidden in the Lyα forest. We can identify lines if they show a doublet (e.g. the first metal lines detected were CIV $\lambda\lambda 1548, 1550$) at the correct rest wavelength away from a strong Lyα absorption line. If we refer back to Equation 10, we can also tell that metal lines will have a lower Doppler width than hydrogen lines. Atoms of other elements will have a mass greater than m_H, so will have a lower thermal velocity, producing narrower absorption lines.

The origin of the metals in the IGM is still an unresolved question. Until the first detection of CIV in 1995, the IGM was expected to consist only of the light primordial elements produced during bigbang nucleosynthesis. Since element heavier than Li can only be produced in stars or supernovae, it was expected that any metals in the IGM would only be found in very dense regions near to galaxies that could form them. Observations have continued to detect metals in ever less dense systems leaving us with a picture of the entire IGM as being contaminated by heavy elements. Explaining this is now an active field of research, lead by simulations of different distribution mechanisms. One idea is based on large scale winds being driven out from galaxies over long periods of time, with the winds being both powered by and polluted by supernovae. This looks like the most promising model for explaining the distribution of metals in the intergalactic medium.

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