Gas between galaxies - 
quasar absorption lines (contd)

Longair chap. 17, 18

Friday 28th February

Baryon budget

Local Universe

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galaxies</td>
<td>66%</td>
</tr>
<tr>
<td>Stars</td>
<td>6.0%</td>
</tr>
<tr>
<td>Atomic neut. gas</td>
<td>3.2%</td>
</tr>
<tr>
<td>Molecular gas</td>
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<tr>
<td>ICM</td>
<td>3.8%</td>
</tr>
<tr>
<td>Total structures</td>
<td>~12%</td>
</tr>
<tr>
<td>IGM</td>
<td>~29%</td>
</tr>
<tr>
<td>Lyα forest</td>
<td>~17%</td>
</tr>
<tr>
<td>Missing</td>
<td>~60%</td>
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Early Universe (z=3)

<table>
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<tr>
<th>Component</th>
<th>Percentage</th>
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</thead>
<tbody>
<tr>
<td>Galaxies</td>
<td>~60%</td>
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<tr>
<td>Stars</td>
<td>&lt;0.5%</td>
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<tr>
<td>Atomic neut. gas</td>
<td>~1.7%</td>
</tr>
<tr>
<td>Molecular gas</td>
<td>~1%</td>
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<tr>
<td>IGM</td>
<td>~3%</td>
</tr>
<tr>
<td>Total structures</td>
<td>~3%</td>
</tr>
<tr>
<td>IGM</td>
<td>~65%</td>
</tr>
<tr>
<td>Lyα forest</td>
<td>~95%</td>
</tr>
<tr>
<td>Missing</td>
<td>&lt;20%</td>
</tr>
</tbody>
</table>

Evolution of the Cosmic Web of Matter

- The intergalactic gas evolves with time under the influence of gravity.
- Large-scale gaseous structures collapse into sheets and filaments.
- Shocks in the collapsing structures heat the intergalactic gas to high temperatures.
Intergalactic Medium (IGM)

Baryons between galaxies

density evolution follows LSS formation, and the potential wells defined by the DM, forming a web of filaments, the "Cosmic Web".

- Much of this gas unassociated with galaxies
- Samples the low-density regions, which are still in a linear regime
- Gas will eventually fall into galaxies, where it replenishes star formation fuel
- Enriched gas is driven from galaxies through primarily through SN powered galactic winds, which chemically enriches the IGM
- Chemical evolution of galaxies and IGM thus track each other
- Star formation and AGN provide ionizing flux for the IGM

Types of Absorption line systems

- Lyman alpha forest: $10^{14} \leq N(\text{HI}) \leq 10^{16}$ cm$^{-2}$
  - Numerous, weak lines from low-density hydrogen clouds
  - Lyman alpha clouds are proto-galactic clouds, with low density, they are not galaxies (but some may be proto-dwarfs)
- Lyman Limit Systems (LLS) and “Damped” Lyman alpha (DLA) absorption lines: $N(\text{HI}) \geq 10^{17}$ cm$^{-2}$
  - Rare, strong hydrogen absorption, high column densities
  - Coming from intervening galaxies
  - An intervening galaxies often produce both metal and damped Lyman alpha absorptions
- Helium equivalents are seen in the far UV part of the spectrum
- “Metal” absorption lines
  - Absorption lines from heavy elements, e.g., C, Si, Mg, Al, Fe
  - Most are from intervening galaxies

Very different selection effects from emission line surveys not by luminosity or surface brightness, but by the cross section (size) and column density

Lyman-α forest

The most common type of system. The column density, log $N(\text{HI}) \leq 17.00$, highly ionized, very low density and low metallicities. They are believed to trace the low density intergalactic medium, and possibly (proto-)galaxies. Too many for galaxies. Chemical abundances similar to the Galactic halo.

Lyα forest

Lyα forest is highly ionised, so that the HI we see directly is only a small fraction ($\sim 10^{-3}$ to $\sim 10^{-6}$) of the total amount of hydrogen present.

With this large ionisation correction the forest can be made to account for majority of the baryons at high, and perhaps also low, redshift, $\Omega_{\text{Ly}α} = 0.02 \, h^{-2}$

the physics of the absorbing gas is relatively simple and the run of optical depth $\tau(\text{Lyα})$ with redshift can be thought of as a “map” of the density structure of the IGM along a given line of sight.

At low densities, the temperature of the gas is determined by the balance between photoionisation (produced by the intergalactic ionising background) and adiabatic cooling (due to the expansion of the universe), $\tau(\text{Lyα}) \propto (1 + \delta)^{1.5}$, where $\delta$ is the over-density of baryons $\delta = (\rho_b/\langle \rho_b \rangle - 1)$. At $z = 3$, $\tau(\text{Lyα}) = 1$ corresponds to a region of the IGM which is just above the average density of the universe at that time ($\delta = 0.2$).
Fitting the Forest

Lyman Limit Systems

LLS, $N(\text{HI}) > 10^{17} \text{ cm}^{-2}$. This is sufficient column density to absorb all ionising photons shortward of the 
lyman limit (912 Å) in the rest frame (like UV-dropout for Lyman break galaxies). They are associated with 
strong metal absorption lines and are believed to arise in the halos of galaxies.

10% of LLS are heavily saturated and show damping wings in the Lyman-α lines, so $\log(\text{HI}) \geq 20$.

Hydrogen is neutral and therefore detailed study of metallicities is possible. These systems are 
believed to trace proto-galactic disks and therefore are unique probes of galaxy formation history.

Damped Lyman Alpha Absorbers

Most of the mass density neutral gas in the 

Voigt profile, consistent with natural broadening 
of an absorption line in the limit $\tau \gg 1$.

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Hydrogen is neutral and therefore detailed study of metallicities is possible. These systems are 
believed to trace proto-galactic disks and therefore are unique probes of galaxy formation history.

courtesy John Webb
Identification of Absorbing systems

Absorber Cross Sections

Extracting Information

- Information about the gas from the spectral lines

<table>
<thead>
<tr>
<th>Question</th>
<th>Information</th>
<th>Observable quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>What is it?</td>
<td>Chemical composition</td>
<td>Pattern of lines</td>
</tr>
<tr>
<td>What state?</td>
<td>Molecular/atomic/ionic</td>
<td>Pattern of lines</td>
</tr>
<tr>
<td>How hot?</td>
<td>Temperature</td>
<td>Widths of lines</td>
</tr>
<tr>
<td>How much?</td>
<td>Quantity</td>
<td>Strengths of lines</td>
</tr>
<tr>
<td>How fast?</td>
<td>Velocity</td>
<td>Wavelengths of lines</td>
</tr>
<tr>
<td>Where is it?</td>
<td>Location (redshift)</td>
<td>Wavelengths of lines</td>
</tr>
</tbody>
</table>
Absorption-line techniques

The principal observable of an absorption line is its equivalent width $EW$, the fraction of light over a spectral interval that is absorbed by the gas. The principal physical parameter is the column density $N$, the number of atoms per unit area along the sightline. Multiplying the number of absorbing atoms per unit area by the f-value (oscillator strength) gives the number of atoms in an absorbing layer.

$$\tau_0 = 1.497 \times 10^{-15} N (\text{cm}^{-2}) f \lambda_0 (\text{Å}) / \delta (\text{km s}^{-1})$$

$$b = v_{\text{rms}} \sqrt{2} = \text{FWHM} / 2 \sqrt{\ln 2}$$

When the column density is small ($\tau_0 < 0.1$), the absorption line is optically thin and the equivalent width does not depend on $b$. This is the linear part of the curve of growth, where the determination of $N$ from $w$ is easy and reliable. For any transition,

$$N (\text{cm}^{-2}) = 1.13 \times 10^{20} \frac{w_0 (\text{Å})}{N (\text{Å}) f} \tag{8}$$

A few strong atomic transitions

<table>
<thead>
<tr>
<th>Ion</th>
<th>$\lambda_0$ (Å)</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>O VI</td>
<td>1031.927</td>
<td>0.130</td>
</tr>
<tr>
<td>O VI</td>
<td>1037.616</td>
<td>0.0648</td>
</tr>
<tr>
<td>H I</td>
<td>1215.670</td>
<td>0.4162</td>
</tr>
<tr>
<td>O I</td>
<td>1302.169</td>
<td>0.0486</td>
</tr>
<tr>
<td>C II</td>
<td>1334.532</td>
<td>0.118</td>
</tr>
<tr>
<td>Si IV</td>
<td>1393.755</td>
<td>0.528</td>
</tr>
<tr>
<td>Si IV</td>
<td>1402.770</td>
<td>0.262</td>
</tr>
<tr>
<td>C IV</td>
<td>1548.202</td>
<td>0.194</td>
</tr>
<tr>
<td>C IV</td>
<td>1550.774</td>
<td>0.097</td>
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<tr>
<td>Mg II</td>
<td>2796.352</td>
<td>0.592</td>
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<tr>
<td>Mg II</td>
<td>2803.531</td>
<td>0.295</td>
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</table>

Key Baryon Diagnostic Lines & Features

<table>
<thead>
<tr>
<th>Line</th>
<th>Phase</th>
<th>$T$ (K)</th>
<th>$\lambda_{\text{Ly}}$ (Å)</th>
<th>$\lambda_{\text{HeI}}$ (Å)</th>
<th>$\lambda_{\text{CIV}}$ (Å)</th>
<th>$\lambda_{\text{OVII}}$ (Å)</th>
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</thead>
<tbody>
<tr>
<td>Lyman-Werner</td>
<td>Molecular gas</td>
<td>10–100</td>
<td>~1000</td>
<td>2000</td>
<td>4000</td>
<td>1</td>
</tr>
<tr>
<td>21cm</td>
<td>Atomic gas</td>
<td>100–1000</td>
<td>21cm 0.7 GHz 0.4 GHz 140 MHz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lyα</td>
<td>Atomic+Ionized gas</td>
<td>100–4000</td>
<td>216</td>
<td>2400</td>
<td>4800</td>
<td>1.2</td>
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<td>HeI</td>
<td>Ionized gas</td>
<td>10000–4000</td>
<td>6560</td>
<td>13000</td>
<td>26000</td>
<td>65000</td>
</tr>
<tr>
<td>Lyman limit</td>
<td>Ionized gas</td>
<td>10000–4000</td>
<td>912</td>
<td>1800</td>
<td>3600</td>
<td>0.9</td>
</tr>
<tr>
<td>HeII</td>
<td>Ionized gas</td>
<td>10000–4000</td>
<td>304</td>
<td>450</td>
<td>912</td>
<td>0.2</td>
</tr>
<tr>
<td>CIV</td>
<td>Ionized Gas</td>
<td>20000–4000</td>
<td>1550</td>
<td>3000</td>
<td>6000</td>
<td>1.5</td>
</tr>
<tr>
<td>OVI,OVIII</td>
<td>Warm/Hot Gas</td>
<td>2000–10^5</td>
<td>10^3</td>
<td>2000</td>
<td>4000</td>
<td>1</td>
</tr>
<tr>
<td>NeVIII</td>
<td>Hot Gas</td>
<td>10^7</td>
<td>775</td>
<td>1550</td>
<td>3100</td>
<td>7750</td>
</tr>
</tbody>
</table>

Prochaska & Tumlinson 2008, review arXiv:0805.4635
Absorption system column densities

\[ f(N_{HI}) = B \times N_{HI}^{-\beta} \]
\[ \beta \approx 1.5 \]

\( f(\text{Ly} \alpha \text{Forest}) \rightarrow \text{Ly} \alpha \text{Systems} \)

Storrie-Lombardi & Wolfe 2000

DLAs

\[ N(\text{HI}) \geq 2 \times 10^{20} \text{ cm}^{-2} \]

integral of the column density distribution

\[ \rho(\text{HI}) = \frac{H_0}{c} \frac{\mu m_{\text{HI}}}{\rho_{\text{crit}}} \int_{N_{\text{min}}}^{N_{\text{max}}} N f(N) dN = \frac{H_0}{c} \frac{\mu m_{\text{HI}}}{\rho_{\text{crit}}} \frac{B}{2-\beta} \left( N_{\text{HI}}^{2-\beta} - N_{\text{min}}^{2-\beta} \right) \]

\[ \rho_{\text{crit}} = \frac{3 H_0^2}{8 \pi G} = 1.96 \times 10^{-29} \text{ g cm}^{-3} \]

\( \mu \) is the mean atomic weight per baryon

\( \mu = 1.4 \) for solar abundances; Grevesse & Sauval 1998

Pettini 2003 astro-ph/0303272

DLAs

\[ N(\text{HI}) \geq 2 \times 10^{20} \text{ cm}^{-2} \]

What are DLAs?

Wolfe et al. (1986), proposed that DLAs are the progenitors of present-day spiral galaxies, observed at a time when most of their baryonic mass was still in gaseous form.

The evidence supporting this scenario, however, is mostly indirect.

Prochaska & Wolfe (1998) showed that the profiles of the metal absorption lines in DLAs are consistent with the kinematics expected from large, rotating, thick disks, but others have claimed that this interpretation is not unique (Haehnelt, Steinmetz, & Rauch 1998; Ledoux et al. 1998).

Typically very metal poor

Large range in values at same redshift

Little evidence for redshift evolution

the mean metallicity of DLAs is the closest measure we have of the global degree of metal enrichment of neutral gas in the universe at a given epoch

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Pettini 2003 astro-ph/0303272
Comparing DLAs to MW

Comparing MDFs of DLAs at $z \sim 2 - 3$ with those of stars belonging to the disk (Wyse & Gilmore 1995) and halo (Laird et al. 1988) in the Milky Way.

Evolution of Ly-α forest


Why is there a break at $z \sim 1.5$? How much is due to the number density evolution and how much to a possible cross-section evolution?

Evolution of Ly-α forest

Modelling

The evolution of $N(z)$ is governed by two main factors: the Hubble expansion and the cosmic UV background. Coming to lower $z$ the background starts to decrease as the number of ionising sources falls off (quasars & star forming galaxies), counteracting the Hubble expansion.

Bianchi, Cristiani & Kim 2001
Metals in the Lyα forest

IGM metallicity provides information on:

- History of star/galaxy formation.
- Formation of unobservably early stars/galaxies.
- UV ionizing background.
- Feedback in galaxy formation processes.

The lack of associated metal lines was originally one of the defining characteristics of the Lyα forest and was interpreted as evidence for a primordial origin of the clouds (Sargent et al. 1980).

However, this picture was shown to be an oversimplification by observations with sufficient sensitivity to detect the weak CIV λλ 1548, 1550 doublet associated with Lyα clouds with column densities log N(H I) ≥ 14.5 (Cowie et al. 1995; Tytler et al. 1995).

Typical column density ratios in these clouds are N(C IV)/N(H I) ≃ 10^{-2} - 10^{-3}, indicative of a carbon abundance of about 1/300 of the solar value, or [C/H] ≃ −2.5 with a scatter of ∼ 3 (Davé et al. 1998).

Aracil et al. 2004

Where do these metals come from?

STARS! Of course

but are these stars located in the vicinity of the Lyα clouds observed? or are we seeing a more widespread level of metal enrichment, perhaps associated with the formation of the first stars which re-ionised the universe at z > 6 ?

A level of metal enrichment of 10^{-3} to 10^{-2} of solar in regions of the IGM with N(H I) ≥ 10^{14} cm^{-2} may be understood in terms of supernova driven winds from galaxies. Such outflows are observed directly in Lyman break galaxies at z = 3, and may propagate out to radii of several hundred kpc before they stall. However, if O VI is also present in Lyα forest clouds of lower column density, as claimed by Schaye et al. (2000), an origin in pregalactic stars at much earlier epochs is probably required (Madau, Ferrara, & Rees 2001).

How Does Matter Get Out of Galaxies?

Galaxies power strong winds that blow dust, gas, and heavy elements into the intergalactic medium.
Outflows in line profiles

1406 galaxy spectra at $z \sim 1.4$ from the DEEP2 redshift survey

The outflows have column densities of order $N_{\text{H}} \sim 10^{20}$ cm$^{-2}$ and characteristic velocities of $\sim 300$-500 km/s, with absorption seen out to 1000 km/s in the most massive, highest SFR galaxies. These velocities suggest that the outflowing gas can escape into the IGM and that massive galaxies can produce cosmologically and chemically significant outflows. Both the MgII EW and the outflow velocity are larger for galaxies of higher stellar mass and SFR, with $V_{\text{wind}} \propto \text{SFR}^{0.3}$, similar to the scaling in low redshift IR-luminous galaxies. The high frequency of outflows in the star-forming galaxy population at $z \sim 1$ indicates that galactic winds occur in the progenitors of massive spirals as well as those of ellipticals.


Sizes & Metallicities

Estimates of the baryonic mass density relative to $\Omega_b$ for various phases of baryons in the $z=0$ universe.
Estimates of the baryonic mass density

relative to $\Omega_b$ for various phases of baryons in the $z=3$ universe.

HI in galaxies throughout the Hubble time

HI column density distribution function

Missing Baryons...

missing baryons are likely to be hidden in a warm/hot ($T = 10^5$ to $10^7$K) diffuse medium that precludes easy detection.

The evolution of the WHIM is primarily driven by shock heating from gravitational perturbations breaking on mildly non-linear, non-equilibrium structures such as filaments. Supernova feedback energy and radiative cooling play lesser roles in its evolution.
Theoretical Expectations

Einstein-de Sitter Universe

- HI column densities
- Co-moving density of HI as a function of redshift
- Co-moving star formation rate

Distribution function of column density at z=2.4

Metallicity in solar units

assuming initial HI density, $\Omega_{HI} = 4 \times 10^{-3} \, h^{-1}$

Summary

- Intergalactic medium (IGM) is the gas associated with the large scale structure, rather than galaxies themselves; e.g., along the still collapsing filaments, thus the "cosmic web"
  - However, large column density hydrogen systems, and strong metallic absorbers are always associated with galaxies
- It is condensed into clouds, the smallest of which form the "Ly \alpha forest"
- It is ionized by the UV radiation from star forming galaxies and quasars
- It is metal-enriched by the galactic winds, which expel the gas already processed through stars; thus, it tracks the chemical evolution of galaxies
- Studied through absorption spectra against background continuum sources, e.g., quasars or GRB afterglows