Lecture Twelve:

Counting Baryons

Baryon Census

How much "raw material" is there in the Universe available for star (and galaxy) formation & evolution?

We most often study baryons by observing the radiation that they emit, absorb or reflect: stars, HII regions, cluster gas, planets, debris disks, etc.

The problems making a complete census and analysis of baryons in the present and past universe:

1. there is the simple fact that more distant objects are fainter, no reason why the baryon budget should be dominated by bright objects.

2. it is generally difficult to estimate precisely the mass of an emitting object. With stars and galaxies, for example, mass estimates generally rely on stellar evolution modelling which is subject to many uncertainties (e.g., IMF) that are difficult to resolve even in the local universe.

3. only a small fraction of the universe’s baryons are in the collapsed, luminous objects that are most easily detected especially in the young universe.

4. although diffuse gas emits line and continuum radiation, it is very difficult to detect this radiation even from gas in the nearby universe.

<table>
<thead>
<tr>
<th>Component</th>
<th>Central</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stars in spheroids</td>
<td>0.0026 $h_0^2$</td>
<td>0.0043 $h_0^2$</td>
<td>0.0014 $h_0^2$</td>
<td>A</td>
</tr>
<tr>
<td>Stars in disks</td>
<td>0.00006 $h_0^2$</td>
<td>0.00129 $h_0^2$</td>
<td>0.00051 $h_0^2$</td>
<td>B</td>
</tr>
<tr>
<td>Stars in irregulars</td>
<td>0.000049 $h_0^2$</td>
<td>0.00016 $h_0^2$</td>
<td>0.000033 $h_0^2$</td>
<td>C</td>
</tr>
<tr>
<td>Neutral atomic gas</td>
<td>0.000015 $h_0^2$</td>
<td>0.000041 $h_0^2$</td>
<td>0.000025 $h_0^2$</td>
<td>A</td>
</tr>
<tr>
<td>Molecular gas</td>
<td>0.00030 $h_0^2$</td>
<td>0.000073 $h_0^2$</td>
<td>0.000023 $h_0^2$</td>
<td>A</td>
</tr>
<tr>
<td>Plasma in clusters</td>
<td>0.0026 $h_0^2$</td>
<td>0.0044 $h_0^2$</td>
<td>0.0014 $h_0^2$</td>
<td>A</td>
</tr>
<tr>
<td>7a. Warm plasma in groups</td>
<td>0.0056 $h_0^2$</td>
<td>0.0113 $h_0^2$</td>
<td>0.0029 $h_0^2$</td>
<td>B</td>
</tr>
<tr>
<td>7b. Cool plasma</td>
<td>0.002 $h_0^2$</td>
<td>0.0033 $h_0^2$</td>
<td>0.0007 $h_0^2$</td>
<td>C</td>
</tr>
<tr>
<td>7c. Peculiar in groups</td>
<td>0.0014 $h_0^2$</td>
<td>0.0030 $h_0^2$</td>
<td>0.0007 $h_0^2$</td>
<td>B</td>
</tr>
<tr>
<td>8. Sum (at $k = 70$ and $z &gt; 0$)</td>
<td>0.021</td>
<td>0.041</td>
<td>0.007</td>
<td>...</td>
</tr>
</tbody>
</table>

Gas components at $z = 3$

<table>
<thead>
<tr>
<th>Component</th>
<th>Central</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damped absorbers</td>
<td>0.0015 $h_0^2$</td>
<td>0.0027 $h_0^2$</td>
<td>0.0006 $h_0^2$</td>
<td>A</td>
</tr>
<tr>
<td>Lyman forest clouds</td>
<td>0.04 $h_0^2$</td>
<td>0.05 $h_0^2$</td>
<td>0.01 $h_0^2$</td>
<td>B</td>
</tr>
<tr>
<td>Intergalactic (HI)</td>
<td>0.001 $h_0^2$</td>
<td>0.001 $h_0^2$</td>
<td>0.001 $h_0^2$</td>
<td>B</td>
</tr>
</tbody>
</table>

Table 1. Summary of the cosmic baryon budget.

~30-50% missing

Even though ordinary matter accounts for only a small fraction of the mass of the Universe, it is the only form of matter that is directly observable.

About 50% of ordinary matter has yet to be accounted for in the present-day Universe. It is “hidden” (or “missing”) in the form of tenuous intergalactic material.

Where is the Material that Forms Stars and Galaxies?

- Interstellar medium
  - Gas and dust between stars inside galaxies
  - ~10%

- Circumgalactic medium
  - Gas and dust outside but near galaxies
  - ~40%

- Intercluster medium
  - Diffuse gas between galaxies
  - ~50%

the majority of baryons at z ~ 0 lie in diffuse gas outside of virialized structures

Where is the Ordinary Matter?

- Most of the ordinary matter in the Universe is in the intergalactic medium.
  - Galaxies contain less than 10% of the ordinary matter.
  - Gas near galaxies (in clusters and groups) accounts for about 30%.
  - Another 10-20% has been identified in the intergalactic medium.
  - The remaining 50% is believed to be in the form of hot, ionized intergalactic gas.

- The intergalactic medium provides the raw materials needed to build galaxies, stars, planets, and life.

- The intergalactic gas is hard to detect because it is so tenuous.
  - It has such a low density that it is not yet possible to image it.

What is the Density of the IGM?

- Air has a density of ~ 3x10^{19} molecules per cubic centimeter.
  - This is about 30 billion billion molecules.
  - 1 cubic centimeter is about the size of a sugar cube.

- The Sun’s photosphere has a density of about 10^9 atoms per cc.
  - This is a much better vacuum than can be produced in any laboratory.

- The interstellar medium has a density of about 1 atom per cc.
  - Take the air particles in a box the size of a sugar cube and stretch the cube in one dimension 33 light years to get the same density!

- The intergalactic medium has a density of about 1/100,000 atom per cc.
  - Take the box and stretch it 3 million light years, or about 4 times further than the Andromeda galaxy!
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 unaffiliated 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

Quasar Absorption Lines

Most absorption lines seen in the spectra of high redshift quasars are unrelated to the quasars and simply produced by intervening gas. Sometimes associated with galaxies and sometimes by the gas located in the desolate regions of space (intergalactic medium) where no star can be found.

The study of these absorption lines is one of the most sensitive and powerful tools to understand the early evolution of galaxies and the intergalactic medium (IGM).

Absorption lines are used to study the physics of low luminosity galaxies, investigate feedback as well as the thermal and ionization history of the universe. In addition, they can be used to carry out fundamental tests, e.g., the time evolution of the cosmic microwave background (Srianand et al. 2000) and of dimensionless fundamental constants (Murphy et al. 2003; Srianand et al. 2004).

STIS = Space Telescope Imaging Spectrograph

Intergalactic Gas Clouds

A STIS absorption spectrum

A beam of light coming to Earth from a distant quasar passes through numerous intervening gas clouds in galaxies and the intergalactic medium. These clouds of primordial hydrogen subtract specific colors from the beam. The resulting absorption spectrum, recorded by Hubble's Space Telescope Imaging Spectrograph (STIS), is used to determine the distances and chemical composition of the intercloud clouds.

STIS = Space Telescope Imaging Spectrograph

Cumulative absorption spectra

Subtracted by cloud 1
Subtracted by cloud 2
Subtracted by cloud 3
Final absorption spectrum recorded by STIS
Cosmic Barcodes

- Each element has its own unique set of spectral lines.
- The sequence of lines is determined by the energy levels populated within the atom or molecule.
- These series of lines can be used to identify the chemical composition of the gas causing the absorption.

Decoding the Information in a Spectrum

- convert two-dimensional spectra into one-dimensional plots of intensity versus wavelength.
  - This allows precise line wavelengths, shapes, and strengths to be measured easily.
  - The line parameters contain information about the physical properties of the absorbing material.

Absorption-line techniques

Baryons with at least one electron will exhibit both resonant line absorption (e.g., Lyα) and continuum opacity (e.g., the Lyman limit feature), primarily at UV and X-ray frequencies. The principal observable of an absorption line is its equivalent width $W_e$, 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. This is the number density equivalence of a surface density.

Absorption-lines achieve extremely sensitive limits for studying diffuse gas. For example, the signal-to-noise and resolution easily afforded by current telescopes and instrumentation allows detection of the HI Lyα transition to column densities $N_{HI} \sim 10^{12} \text{ cm}^{-2}$.

Main disadvantages:
1. the majority of key diagnostics have rest-frame UV or X-ray frequencies, need space mission at low $z$
2. one requires a bright, background subjecting the final analysis to biases in the discovery and selection of these sources, as they are rare and sparsely distributed across the sky. With only a limited number of sightlines to probe the universe, the densest (i.e. smallest) structures are at best sparsely sampled.

No. of absorbing atoms

To find the number of absorbing atoms per unit area, $N_a$, that have electrons in the proper orbital to absorb a photon at the wavelength of the spectral line - the $T$, $p$ are used in the Boltzmann and Saha equations to calculate the excitation and ionisation.

This task is complicated by the fact that not all transitions between atomic states are equally likely. Each transition has a relative probably, or f-value (also called oscillator strength).

These can be calculated theoretically or measured in a lab, and they are defined so that the f-values for transitions from the same orbital add up to the number of electrons in the atom or ion, i.e., the effective number of electrons per atom participating in a transition.

Multiplying the number of absorbing atoms per unit area by the f-value gives the number of atoms in an absorbing layer.
A few strong atomic transitions

<table>
<thead>
<tr>
<th>Ion</th>
<th>(\lambda_0) (Å)</th>
<th>(f)</th>
<th>(\log(\lambda_0 f))</th>
<th>(\log(\lambda_0^2 f))</th>
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</thead>
<tbody>
<tr>
<td>O VI</td>
<td>1031.927</td>
<td>0.130</td>
<td>2.128</td>
<td>5.141</td>
</tr>
<tr>
<td>O VI</td>
<td>1037.616</td>
<td>0.0648</td>
<td>1.828</td>
<td>4.844</td>
</tr>
<tr>
<td>H I</td>
<td>1215.670</td>
<td>0.4162</td>
<td>2.704</td>
<td>5.789</td>
</tr>
<tr>
<td>O I</td>
<td>1302.169</td>
<td>0.0486</td>
<td>1.801</td>
<td>4.916</td>
</tr>
<tr>
<td>C II</td>
<td>1334.532</td>
<td>0.118</td>
<td>2.197</td>
<td>5.323</td>
</tr>
<tr>
<td>Si IV</td>
<td>1393.755</td>
<td>0.528</td>
<td>2.867</td>
<td>6.011</td>
</tr>
<tr>
<td>Si IV</td>
<td>1402.770</td>
<td>0.262</td>
<td>2.565</td>
<td>5.712</td>
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<tr>
<td>C IV</td>
<td>1548.202</td>
<td>0.194</td>
<td>2.448</td>
<td>5.667</td>
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<tr>
<td>C IV</td>
<td>1550.774</td>
<td>0.097</td>
<td>2.177</td>
<td>5.368</td>
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<tr>
<td>Mg II</td>
<td>2796.352</td>
<td>0.592</td>
<td>3.219</td>
<td>6.666</td>
</tr>
<tr>
<td>Mg II</td>
<td>2803.531</td>
<td>0.295</td>
<td>2.918</td>
<td>6.365</td>
</tr>
</tbody>
</table>

Curve of Growth

This an important tool to determine \(N_a\), the number of absorbing atoms, and thus the abundances of elements in an absorbing layer, because EW varies with \(N_a\). It is a log-log plot of EW as a function of the number of absorbing atoms.

Voigt profile for varying numbers of absorbing ions

The shape of the line profile is also a function of the pressure which causes doppler broadening and also the global kinematics of the cloud.

Key Baryon Diagnostic Lines & Features

<table>
<thead>
<tr>
<th>Line</th>
<th>Phase</th>
<th>(T) (K)</th>
<th>(\lambda_{\text{rest}}) (Å)</th>
<th>(\lambda_{\text{c-1}}) (Å)</th>
<th>(\lambda_{\text{c-3}}) (Å)</th>
<th>(\lambda_{\text{c-9}}) (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyman-Werner</td>
<td>Molecular gas</td>
<td>10–100</td>
<td>(\sim 1000)</td>
<td>2000</td>
<td>4000</td>
<td>1</td>
</tr>
<tr>
<td>21 cm</td>
<td>Atomic gas</td>
<td>100–1000</td>
<td>21 cm</td>
<td>0.7 GHz</td>
<td>0.4 GHz</td>
<td>140 MHz</td>
</tr>
<tr>
<td>LyA</td>
<td>Atomic+Ionized gas</td>
<td>100–4000</td>
<td>1216</td>
<td>2400</td>
<td>4800</td>
<td>1.2</td>
</tr>
<tr>
<td>H I</td>
<td>Ionized gas</td>
<td>10000–40000</td>
<td>6560</td>
<td>13000</td>
<td>26000</td>
<td>65000</td>
</tr>
<tr>
<td>Lyman limit</td>
<td>Ionized gas</td>
<td>10000–40000</td>
<td>912</td>
<td>1800</td>
<td>3600</td>
<td>0.9</td>
</tr>
<tr>
<td>HeII</td>
<td>Ionized gas</td>
<td>10000–40000</td>
<td>304</td>
<td>450</td>
<td>912</td>
<td>0.2</td>
</tr>
<tr>
<td>CIV</td>
<td>Ionized Gas</td>
<td>20000–40000</td>
<td>1550</td>
<td>3000</td>
<td>6000</td>
<td>1.5</td>
</tr>
<tr>
<td>OVI, OVI</td>
<td>Warm/Hot Gas</td>
<td>20000–(10^6)</td>
<td>1030</td>
<td>2000</td>
<td>4000</td>
<td>1</td>
</tr>
<tr>
<td>OVI, OVI</td>
<td>Hot Gas</td>
<td>(10^6–10^7)</td>
<td>21.6,18.9</td>
<td>40</td>
<td>8</td>
<td>200</td>
</tr>
<tr>
<td>Ne VIII</td>
<td>Hot Gas</td>
<td>(10^7)</td>
<td>775</td>
<td>1550</td>
<td>3100</td>
<td>7750</td>
</tr>
</tbody>
</table>

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 system column densities

Any gas component with HI column densities in the range \(10^{12} - 10^{22} \text{ cm}^{-2}\) can be detected in absorption.

- Lyman alpha forest: \(10^{14} \leq N(\text{HI}) \leq 10^{18} \text{ cm}^{-2}\)
  - 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: \(N(\text{HI}) \geq 10^{17} \text{ cm}^{-2}\)
  - 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.
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 large for galaxies. Chemical abundances similar to the Galactic halo.

Lyman-$\alpha$ forest

Ly$\alpha$ forest is highly ionised, so that the HI we see directly is only a small fraction ($\lesssim 10^{-3}$ to $\sim 10^{-6}$) of the total amount of hydrogen present. With this large ionisation correction it appears that the forest can account for most of the baryons at high, as well as low, redshift, $\Omega_{\text{Ly}\alpha} = 0.02$ h$^{-2}$

the physics of the absorbing gas is relatively simple and the run of optical depth $\tau(\text{Ly}\alpha)$ 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), $\tau(\text{Ly}\alpha) \propto (1 + \delta)^{1.5}$, where $\delta$ is the over-density of baryons $\delta = (\rho_b/\rho_{\text{av}} - 1)$. At $z = 3$, $\tau(\text{Ly}\alpha) = 1$ corresponds to a region of the IGM which is just above the average density of the universe at that time ($\delta = 0.6$).

Fitting the Forest

Lyman Limit Systems

LLS, $N(\text{HI}) > 10^{17}$ 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 ofr Lyman break galaxies). They are associated with strong metal absorption lines and are believed to arise in the halos of galaxies.

Fit the forest by comparing the observed spectrum with a theoretical model. 

- The Lyman-$\alpha$ forest is a series of absorption lines in the spectrum of a distant galaxy, caused by gas clouds along the line of sight.
- Lyman Limit Systems (LLS) have a high column density of hydrogen, typically $N(\text{HI}) > 10^{17}$ cm$^{-2}$.
- These systems are used to study the distribution of baryons in the universe.
10% of LLS are heavily saturate and show damping wings in the Lyman-\( \alpha \) 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.

Most of the mass density neutral gas in the Universe (Lanzetta et al. 1995 ApJ, 440, 435) has a Voigt profile, consistent with natural broadening of an absorption line in the limit \( \nu \ll 1 \).

Clustering of Metallic Absorbers

Metallic absorbers are found to cluster in redshift space, even at high \( z \)'s, while Ly \( \alpha \) clouds do not. This further strengthens their association with galaxies.

Identification of Metallic Absorbers

A plausible galaxy near line of sight is found for every absorber:
Absorber Cross Sections

Column density of neutral H is higher at smaller radii, so LLS and DLA absorbers are rare.

Metals are ejected out to galactic coronae, and their column densities and ionization states depend on the radius.

Comparing DLAs to MW

DLAs at z = 2 – 3 and of stars belonging to the disk (Wyse & Gilmore 1995) and halo (Laird et al. 1988) populations in the Milky Way.

DLAs

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.

Outflows in line profiles

1406 galaxy spectra at z ~ 1.4 from the DEEP2 redshift survey.

The outflows have column densities of order N_H ~ 10^{20} cm^{-2} and characteristic velocities of ~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_w = 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 ~ 1 indicates that galactic winds occur in the progenitors of massive spirals as well as those of ellipticals.

Wolfe et al. (1986), proposed from the outset 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).

Pettini 2003 astro-ph/0303272

Theoretical Expectations

Einstein-de Sitter Universe

Distribution fn of column density at z=2.4

HI column densities

Metallicity in solar units

assuming initial HI density, \( \Omega_{HI} \approx 4 \times 10^{-3} h^{-1} \)

Co-moving density of HI as a fn of redshift


Estimates of the baryonic mass density

relative to \( \Omega_0 \) for various phases of baryons in the \( z=3 \) universe.

Total mass density

Absorption line systems traced by HI gas

Crude estimate to lie near stellar and atomic mass densities

Prochaska & Tumlinson 2008, review arXiv:0805.4635

Baryonic mass density

The mass densities of stars, molecular gas, and HI are unlikely to contribute significantly to \( \Omega_0 \) at \( z \approx 3 \). Unless one invokes an exotic form of dense baryonic matter (e.g. compact objects), the remainder of baryons in the early universe must lie in a diffuse component outside of the ISM of galaxies.

The absence of a complete Gunn-Peterson trough in \( z < 6 \) quasars demonstrates that the majority of baryons are highly ionized at these redshifts. Because it is impossible to directly trace H+ for the vast majority of the mass in the diffuse IGM, we must probe this phase through the remaining trace amounts of HI gas.

Evolution of HI absorbers

Low redshift QSO

High redshift QSO

theoretical expectations

Estimates of the baryonic mass density
Evolution of Ly-α forest

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


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 IGM

IGM metallicity provides information on:

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

Metals in Lyα forest

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 λ1548, 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) $\sim 10^{-2} - 10^{-3}$, indicative of a carbon abundance of about 1/300 of the solar value, or $[C/H] = -2.5$ with a scatter of $\sim 3$ (Davé et al. 1998).
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 $N(\text{H I}) \approx 10^{14}$ 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 OVI 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).

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

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

How Does Matter Get Out of Galaxies?

A slice of the cosmic web

**Enrichment**

the IGM was enriched with the products of stellar nucleosynthesis from the earliest times we have been able to probe with QSO absorption line spectroscopy, only ~ 1 Gyr after the Big Bang. The measurements of CIV suggest a metallicity $Z_{\text{CIV}} \approx 10^{-3}$ $Z_{\odot}$; this is a lower limit because it assumes that the ionisation of the gas is such that the ratio C IV/C tot is near its maximum.

This metallicity can in turn be used to infer a minimum number of hydrogen ionising photons (with energy $h\nu \approx 13.6$ eV, corresponding to $\lambda \approx 912$Å) in the IGM. Because the progenitors of the SN which produce Oxygen, for example, are the same massive stars that emit most of the (stellar) ionising photons. Assuming a solar relative abundance scale (i.e. [C/O] = 0), Madau & Shull (1996) calculated that the energy of Lyman continuum photons emitted is 0.2% of the rest-mass energy of the heavy elements produced.

Thus, if the Lyα forest at $z = 5$ had been enriched to a metallicity $Z_{\text{LyC}} = 10^{-2}Z_{\odot}$, then stars had emitted approximately three Lyman continuum (LyC) photons per baryon in the universe. Whether this photon production is sufficient to have reionised the IGM by these redshifts depends critically on the unknown escape fraction of LyC photons from the sites of star formation.
Sizes & Metallicities

Abundances at High Redshift (z = 3)

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

The sum of the central values for the various components is significantly less than unity.

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

Uncertainties: stellar population models & IMF

Crude estimate to lie near stellar and atomic mass densities

HI alone

Total mass density

Absorption line systems traced by HI gas

HI column density distribution function

Prochaska & Tumlinson 2008, review arXiv:0805.4635

Zwaan et al. 2005

Prochaska & Tumlinson 2008, review arXiv:0805.4635
HI in galaxies throughout the Hubble time

Need for continuous gas accretion from the IGM

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.

Cosmological simulations predict a warm/hot intergalactic medium (WHIM) comprising 30 to 40% of today's baryons, at $10^5 < T < 10^7$ K

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.


Cosmic Chemical Evolution

infall of intergalactic material primordial H, He

cooling & collapse

star formation

mixing of processes gas with ISM

Mass loss due to PN, stellar winds and SN

nucleosynthesis in stars

Mass loss due to galactic winds

details of these processes are very messy and hard to model or simulate. So, simplified (semi)analytical models and assumptions are often used, e.g., the "closed box" model, or the "instantaneous recycling" approximation.

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 α 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