**Intergalactic Medium (IGM)**

- Essentially, baryons between galaxies
- Its density evolution follows the LSS formation, and the potential wells defined by the DM, forming a web of filaments, the so-called **"Cosmic Web"**
- An important distinction is that this gas unaffiliated with galaxies samples the low-density regions, which are still in a linear regime
- Gas falls into galaxies, where it serves as a replenishment fuel for star formation
- Likewise, enriched gas is driven from galaxies through the radiatively and 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

**The Cosmic Chemical Evolution**

A schematic view:

- Infall of intergalactic material, primordial H, He
- Cooling and collapse
- Mixing of processed gases with ISM
- Star formation
- 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.
Another schematic view:

From Pagel (1997)

The Cosmic Chemical Evolution

Typical predictions of modern models:

Pei & Fall 1995

The Star Formation Rate Evolution

Redshift

Evolution of the Metal Production

It must track the star formation in galaxies …

Connolly et al. (1997)
Galactic Winds

Starburst can drive winds of enriched gas (e.g., from supernova ejecta) out to the intergalactic medium. This gas can then be accreted again by galaxies. In a disk galaxy, the winds are generally bipolar outflows.

M82 (Subaru): Hα + optical

Numerical Simulation

QSO Absorption Line Systems

- An alternative to searching for galaxies by their emission properties is to search for them by their absorption.
- Quasars are very luminous objects and have very blue colours which make them relatively easy to detect at high redshifts.
- Nowadays, GRB afterglows provide a useful alternative.
- Note that this has different selection effects than the traditional imaging surveys: not by luminosity or surface brightness, but by the cross section (size) and column density.

Types of QSO Absorption Lines

- Lyman alpha forest:
  - 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:
  - 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
Types of QSO Absorption Systems

Table 1. A few strong atomic transitions

<table>
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<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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<td>1031.927</td>
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<td>0.295</td>
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</table>

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.
Ly α Absorbers

- Ly α Forest: \(10^{14} \leq N_{\text{HI}} \leq 10^{16} \text{ cm}^{-2}\)
  - Lines are unsaturated
  - Primordial metallicity < solar
  - Sizes are > galaxies
- Ly Limit Systems (LLS): \(N_{\text{HI}} \gtrsim 10^{17} \text{ cm}^{-2}\)
  - Ly α Lines are saturated
  - \(N_{\text{HI}}\) is sufficient to absorb all ionising photons shortward of the Ly limit at 912Å in the restframe (i.e., like the UV-drop out or Lyman-break galaxies)
- Damped Ly α (DLA) Systems: \(N_{\text{HI}} \gtrsim 10^{20} \text{ cm}^{-2}\)
  - Line heavily saturated
  - Profile dominated by “damped” Lorentzian wings
  - Almost surely proto-disks or their building blocks

Fitting the Forest:

A Damped Lyman α System

\[Q1331+170 \quad z_{\text{em}}=2.084 \quad z_{\text{abs}}=1.7764 \quad \text{(WHT)}\]
Measuring the Absorbers

We measure equivalent widths of the lines, and in some cases shapes of the line profiles.

They are connected to the column densities via curves of growth.

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

Evolution of the Hydrogen Absorbers

The numbers are higher at higher $z$'s, but it is not yet clear how much of the effect is due to the number density evolution, and how much to a possible cross section evolution - nor why is there a break at $z \sim 1.5$.

Absorber - Galaxy Connection

- Metallic line absorbers are generally believed to be associated with galaxies (after all, stars must have made the metals).

An example with multiple metallic line systems:
A plausible galaxy near line of sight is found for every absorber:

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

While the H I seems to decline in time (being burned out in stars?), the density of metals seems to be increasing, as one may expect.

**Clustering of Metallic Absorbers**

**Number Density Evolution of Absorbers**
But different types of systems may be evolving in different ways ...

(from M. Pettini)

GRBs vs. QSO Absorbers

GRBs show higher gas densities and metallicities, presumably because they originate in high-density, central star forming regions of their host galaxies, which otherwise present a too small cross section to hit with a random line of sight

Pettini et al. Lu et al.
The Evolution of the Mass-Metallicity Relation

Galaxies at $z \sim 0$

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