Global properties of circumgalactic medium at high-redshift: spectroscopic study of strong Lyman-α forest absorbers

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Forging Connections
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The Circum Galactic Medium (CGM): Inflow and Outflow Caught in the Act

The challenge:
Numbers! Numbers! Numbers!

* Stars <-> ISM: Continuous cycles of star formation and stellar demise enrich the ISM with metals

* Galaxy evolution governed by: star formation, gas flow interactions of galaxies with their surroundings, mergers.

large samples of CGM data hard to acquire in detail at all epochs
To Earth

Metal absorption

Emission lines from the Quasar

Hydrogen absorption due to galaxies

DLA

Lyman alpha forest

Si IV 1393 Å

C IV 1548 Å

Observed wavelength (Å)

• Pettini (2004)
Different QSO absorbers:

- **Lyman-α forest**: $N(\text{HI}) < 10^{17.2}$ cm$^{-2}$.

- **Lyman Limit systems**: $10^{17.2}$ cm$^{-2} < N(\text{HI}) < 10^{19}$ cm$^{-2}$.

- **Sub-damped Ly-α systems (sub-DLAs)**: 
  
  $10^{19}$ cm$^{-2} < N(\text{HI}) < 10^{20.3}$ cm$^{-2}$.

- **Damped Ly-α systems (DLAs)**: $N(\text{HI}) > 10^{20.3}$ cm$^{-2}$.
\[ f(N) = \beta N^\alpha \]
\[ \log \beta = 8.03 \pm 0.30 \]
\[ \alpha = -1.49 \pm 0.02 \]

Lyman-alpha Forest

\[ <z> = 2.8 \]
bleached HI as a proxy for CGM

Lyman α absorbers around galaxies are blended on SDSS resolution scales (Rakic et al. 2012, Turner et al. 2014) ... 

... have $10^{14.5} < N_{HI} < 10^{16.5}$ 100-300 kpc scales (Rudie et al. 2012) ...

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Perfect data

BOSS with noise

BOSS no noise

Perfect data

\( \lambda \) [Å]
GALAXIES IDENTIFIED IN ABSORPTION

- Lyman break galaxies near bright quasar sightlines: VLT LBGs (Crighton et al 2011), subset of KBSS (Rudie et al 2012)
- Compare by matching BOSS resolution and binning

Rudie et al. (2012) working definition

“near galaxies” = CGM

±300 km/s

300 pkpc

\[ \text{Flux selected} \]

\[ \text{Fraction near galaxies} \]

\( N_{\text{bin}} \)

Corrected
Uncorrected

Pieri+2014
- 1 of 4 in SDSS-III 2009-2014
- 10k deg^2
- Goal: 1.6M galaxies and >150k forest quasars
- Resolution R = 2000

2<z<3.4 forest

z<0.7 galaxies

DR12 with 158k QSOs
Composite Spectrum of Lyman α Forest Absorbers using BOSS Quasars

Lyα absorbers @ 2.4<z<3.1
Complete DR12 Sample

Multiple lines/ elements/ions - breaking degeneracies:
- physical conditions of gas
- abundance patterns
- UV background shape, intensity
Composite Spectrum of Lyman $\alpha$ Forest Absorbers using BOSS Quasars

Ly$\alpha$ absorbers @ $2.4 < z < 3.1$
Complete DR12 Sample

Multiple lines/elements/ions - breaking degeneracies:

- physical conditions of gas
- abundance patterns
- UV background shape, intensity

$-0.05 < F < 0.050$
HI Column Density: Optically Thin Gas

7 Lyman series lines and opacity to ionizing photons (Lyman limit)

Impact of a subset of optically thick selected systems?

Even with ‘perfect’ selection of all LLS+DLA, they wouldn’t dominate any metal line in the composite spectrum
Metal Column densities
Compared with **Simple** Models

Each model constrained by measured $N(\text{H I})$, solar abundance, UV background @ $z \sim 2.7$
Compared with **Simple** Models

Each model constrained by measured $N(\text{H I})$, solar abundance, UV background @ $z \sim 2.7$

Lower ionization potential

$[\text{X/H}] \sim$ solar, $\sim 90$ pc scale clumping

Column density

Log $N$
Compared with a Simple Multi-phase Model

\[ \log \rho / \langle \rho \rangle = 1.0, \log T = 4.5, [\text{X/H}] = -2.0, f = 0.1 \]
\[ \log \rho / \langle \rho \rangle = 3.2, \log T = 4.0, [\text{X/H}] = -0.4, f = 0.8 \text{ (76 pc)} \]

Lower ionization potential
Summary

• Strong Lyman $\alpha$ forest lines arising in CGM regions show clustering

• Clustered strong Lyman $\alpha$ forest lines are blended in BOSS spectra: appropriate selection of flux decrement in BOSS spectra picks out CGM tracers

• Stacking CGM tracers retrieve the metal signal associated with the CGM regions: power of large numbers

• The picture emerging is of a clumpy, multi-phase CGM: dense, metal-rich clumps $\sim$100pc and more ionised, slightly overdense gas.
Stay tuned …

- Further exploration of the parameter space for multi-phase models, including:
  - The effect of abundance pattern: dust, $\alpha$ enhancement?
  - Exploring the effect of background ionising radiation: proximity to galaxies

- Exploring line strength scatter: variance between various elements/ ion species to get a better picture of the multi-phase nature of the gas

- Future large spectroscopic surveys such as DESI and WEAVE promise an order of magnitude increase in the spectra numbers and/or higher resolution and sir $> \text{Cosmic Web Mapping}$
Thanks!