The Cycle of Baryons in and out of Galaxies at z<1

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—in collaboration with—

Chris Howk (ND), Joseph Ribaudo (Utica), Todd Tripp (UMass), Jason Tumlinson, Andy Fox (STScI), Chris Thom (TBD), John O’Meara (St Michael), X Prochaska, Jess Werk (UCSC), Ben Oppenheimer (Leiden)
The Metallicity of the Circumgalactic Medium at $z<1$

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How do we study the Circumgalactic Medium (CGM)?

Galaxies build up gas mass in part by the accretion of gas flowing in along filaments. *This includes matter associated with, stripped from, or enriched by smaller galaxies.* Galactic winds also expel metals in the CGM. Galaxies may recycle gas through their CGM.

Simulations show that HI absorbers with $10^{15-17}$ cm$^{-2}$ best trace the CGM of galaxies within $\sim 300$ kpc.
While the weak H I absorbers are very loosely connected to galaxies, significant clustering between galaxies and strong H I ($N_{HI} > 10^{15} \text{ cm}^{-2}$) absorbers points to a strong physical connection.

e.g., Lanzetta+95, Penton+02, Bowen+02, Chen+05, Morris & Jannuzi 06, Prochaska+11
Lyman limit systems: HI vs. MgII

Lyman limit systems share significant parameter space with the well-studied Mg II systems.

- LLSs tracing *infall*
- LLSs tracing *outflows*

However, absorbers selected based on their H I content are not prone to a *metallicity bias.*
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What is the metallicity distribution of the CGM/IGM at z<1?

However, absorbers selected based on their HI content are not prone to a *metallicity bias.*
A seemingly pretty banal absorber at $z = 0.274$

Undetectable Si II

Strong Si III

Undetectable Si IV

Weak Mg II ($W_r = 0.06 \, \text{Å}$)

Strong C III

Undetectable C II

Ribaudo+ (2011b)
A very low metallicity absorber at $z = 0.274$

The ionization of the gas is well constrained by *upper limits* on:
- Si II/Si III
- Si IV/Si III
- C II/C III

**Final results:**

\[
\log U = -2.8 \pm 0.2 \\
\left[ X/H \right] = -1.71 \pm 0.06 \\
\text{(} \sim 2\% \text{ solar)}
\]
A probable cold accretion stream at $z = 0.274$

- $\log (N(\text{H I})_{\text{total}}) = 17.06 \pm 0.05$
- $[\text{X/H}] = -1.71 \pm 0.06$

The LLS and galaxy are separated by $\rho = 37$ kpc and $\Delta v \sim 25$ km/s.

They differ in metallicity by a factor of $\sim 30$. 

Ribaudo+11
Lyman limit systems and infall

Infall streams predicted to have:

- LLS-like column densities
- Low neutral fractions
- Covering factors \( \sim \) few\% within \( R_{\text{vir}} \)

\[ \text{[Larger for lower } N(\text{HI}), \text{impact parameter and higher } z] \]


A probable cold accretion stream at $z = 0.274$

This absorber is very similar to infalling streams seen in simulations (e.g., Birnboim & Dekel 03, Keres+05, Dekel+09, Fumagalli+11, Faucher-Giguere & Keres 11, van de Voort +12, etc.).

As pointed out in Ribaudo et al. (2011):
*Several such systems exist, most showing prominent $\text{C} \text{ III}$ and $\text{Si} \text{ III}$ with little other metal absorption (e.g., no Si II, Si IV, C II) [Zonak+04, Tripp+05, Cooksey+08]
Lyman limit systems as probes of infall and outflows

Metallicity distribution of $z \leq 1.0$ Lyman limit systems

$[16.1 \leq \log N(\text{H I}) \leq 18.5]$
SAMPLE: VARIETY OF COS AND KECK OBSERVATIONS
Lyman limit systems as probes of infall and outflows

Metallicity distribution of $z \leq 1.0$ Lyman limit systems

$[16.2 \leq \log N(\text{H I}) < 19.0]$

*16 new LLS measurements from COS.
*Where searches have been done, galaxies exist within $\rho < 100$ kpc.

Lehner+ (in prep)
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Friday, June 15, 12
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Battisti+, Peroux+, Pettini+, Rao+, Turnshek+, Meiring+

Lehner+ (in prep)
Metallicity distribution of $z \leq 1.0$ LLSs and super-LLSs

$[16.2 \leq \log N(\text{H I}) \leq 20.3]$
Lyman limit systems as probes of infall and outflows

Metallicity distribution of $z \leq 1.0$ LLSs and super-LLSs

$[16.1 \leq \log N(\text{H I}) \leq 20.3]$
A. Dekel

Have we detected cold gas accretion?

We have detected very low metallicity, ionized gas in the halos of galaxies.

The very low metallicity absorbers are not rare at $z<1$. 
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Summary

• Cleanly identifying infalling cold accretion streams in absorption is difficult at any $z$.

• We have detected a significant number of cold, metal poor gas clouds within the virial radius of several $z < 1$ galaxies.
  - There is little confusion with other metal poor phenomena at these redshifts.

• We have determined the metallicity distribution of the CGM at $z < 1$.
• Stay tuned, the statistics will improve dramatically soon, galaxy information...