Gas in and around z > 2 galaxies

In collaboration with:

Xavier Prochaska  Daniel Ceverino
Daniel Kasen  Joel Primack
Avishai Dekel

Michele Fumagalli
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Gas in galaxies from theory

Gas is a fundamental component in galaxies, since ultimately feeds star formation and regulates galaxy evolution.

Simulations make specific predictions on how gas is accreted and distributed in galaxies.
Some observational tests

HI and CO in emission

Kinematics, metals and hydrogen (HI and H$_2$) in absorption

DLA 0812+32B (z=2.6) – Jorgenson+2009
Focus on neutral gas

![Graph showing the relationship between log [f(N_{HI}X)] and log N_{HI} for various values of beta, with markers for LLS, SLLS, DLA, and the Ly-alpha region at z~3.7.](image)
Focus on neutral gas

HI in absorption: different flavors of absorbers

Neutral hydrogen (DLAs): $N_{\text{HI}} > 10^{20} \text{ cm}^{-2}$

Gas in overdensities (galaxies and satellites)
Focus on neutral gas

HI in absorption: different flavors of absorbers

Optically thick gas (LLSs/SLLSs): \( N_{\text{HI}} > 10^{17} \, \text{cm}^{-2} \)

Ionized gas in and around galaxies(?)

![Graph showing absorption of HI gas](image)
Focus on neutral gas

HI in absorption: different flavors of absorbers

Optically thin/thick transition:
$N_{HI} > 10^{15} \text{ cm}^{-2}$

An important contributor to the mean opacity

Need to reconnect these observations to the predictions from simulations!
Imaging of HI selected galaxies

J0731+2854

Probe the size of HI around \( z > 2 \) galaxies

Survey of \(~40\) QSO fields using Keck and HST

Constrain the luminosity function of DLAs
A sample of simulated galaxies

Cosmological simulations provide statistics that can be compared with observations from large surveys.

Simulations of individual galaxies provide high resolution (~60 pc) where the relevant ISM physics probed in absorption can be explored.

Assemble a sample of individual galaxies (7 galaxies). Reproduce statistical observations from high resolution simulations.

Halos of $M = 10^{11} \, M_{\text{sun}}$ - $10^{12} \, M_{\text{sun}}$ at $z=2$. Redshift range $z = 4$ to $z=1.5$. 
Neutral gas fraction

Accurate predictions of neutral fraction are important to compare against observations.

Monte Carlo radiative transfer code (Kasen et al, in prep.) which includes collisions, UVB, dust and ionizing radiation from local sources.

Halo $3.7 \times 10^{11} \, M_{\odot}$ at $z=2.3$
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Where is the optically thick gas?

A test with a $3.7 \times 10^{11} M_{\text{sun}}$ galaxy at $z=2.3$
Where is the optically thick gas?

Looking through the galaxy: what is the probability to intersect optically thick gas?
Looking through the galaxy: what is the probability to intersect optically thick gas?
The incidence of absorbers

How does this covering fraction compare with observations?

A back of the envelope calculation

\[ P(X) \propto n_A s \]

\[ l(z) \propto n_{co} A_{co} f_{als} \frac{ds}{dz} \]

\[ n_{co}(4 \times 10^{11} M_{\odot}) \sim 8 \times 10^{-4} Mpc^{-3} \]

\[ \frac{ds}{dz} \sim 1300 Mpc \& A_{co} \sim 0.6 Mpc^2 \]

\[ l_{dla}(z) \sim 0.007 \sim 0.04 \text{ observed} \]

\[ l_{lls}(z) \sim 0.05 \sim 0.15 \text{ observed} \]
The optical depth in the universe

An important source of opacity to Lyman limit continuum radiation is gas at the transition optically thin/thick

This is a fundamental quantity in the EUVB calculation

$$\lambda_{mfp} \sim 250 \, h_{72}^{-1} \, \text{Mpc} \ @ \ z \sim 2.3$$

$$\lambda_{mfp}^{-1} \propto n_{co} \, A_{\text{eff}}$$

$$n_{co} \left(4 \times 10^{11} \, M_{\odot}\right) \sim 8 \times 10^{-4} \, \text{Mpc}^{-3}$$

$$f_{als} \sim 0.25 - A_{\text{eff}} \sim 0.06 \, \text{Mpc}^{-2}$$

$$\lambda_{mfp}^{\text{sim}} \sim 6000 \, h_{72}^{-1} \, \text{Mpc}$$

$$\frac{\kappa_{\text{sim}}}{\kappa_{\text{obs}}} \sim 0.04$$

Some extrapolations!

$$\lambda_{mfp} = 48.4 - 38 y(z_{q} - 3.6) \, [h^{-1} \, \text{Mpc}]$$

$$\lambda_{mfp} = 37.0 [(1+z_{q})/(1+3.9)]^{-\gamma} \, [h^{-1} \, \text{Mpc}]$$

$$\gamma = 5.0$$

Prochaska+2010
What's next?

Can we find galaxy/cold flows signatures in the f(N,X)?

Simulated

Observed

Learn about HI rich galaxies (DLAs) and also some ionized gas in cold flows (LLSs)

Prochaska+2010
What's next?

A look at kinematics: are inflows visible?

Study Lyα optical depth in velocity space
Conclusions

Imaging of HI rich galaxies at z > 2
An ongoing program to characterize emission properties and gas extension of galaxies detected in absorption
(MF, O'Meara, Prochaska, Kanekar, 2010, MNRAS)
Conclusions

Neutral gas in galaxies from $> 10^{11} \, M_{\odot}$ halos at $z \sim 2$
with proper radiative transfer

A small fraction of the sky is covered by optically thick gas ($\sim 7\%$)

$\frac{1}{4}$ of the sky is covered by gas that contributes little to the mean opacity of the Universe.

Most of neutral gas is in smaller halos and $15\%$ of LLSs can be in “stream-fed” galaxies.

More on kinematics and redshift evolution coming soon!
$\beta_{\text{PLLs}} = [-1, -1.5, -1.8, -2.0]$
Our strategy...

We use a Lyman limit drop out technique, similar to the one adopted for LBGs, but to avoid the QSO light (O'Meara+2006)
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Cosmic-weighted distribution of DLAs

Pontzen+, 08

Weighted on HIMF and HI cross section. Toy model: radius evolution ($1+z)^{-1}$ at constant $\Sigma_{HI}$.

Walter+, 08

OBSERVATIONS – Imaging of DLAs
\[ f \left( N_{HI}, X \right) \propto \frac{n}{\Delta N_{HI} \Delta X} \]

The column density distribution in an ensemble of objects

What are we looking at?

How many and how big?

What shape?

IGM/outflows/inflows?

Merging clumps?

Massive disks?

(Dekel +, 2009)

(Pontzen +, 2008)

(Ceverino +, 2010)

Modeling with simulations can help... and observations of the host galaxies