Outline: The IGM/Galaxy Connection

- IGM introduction
  - Absorption line systems
  - \( f(N,X), l(X) \)
- Exploring the CGM at \( z \sim 0 \)
  - Extended gaseous halos
  - Origin of the Lya/OVI “IGM”
- The IGM/CGM at \( z \sim 2 \)
  - Evolution?
- A few contrarian remarks on galactic-scale winds and the CGM
  - If you ask for them...
A Strict Definition: The diffuse (and highly ionized gas) that permeates the volume between galaxies.
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Alternates: Any absorption lines in QSO spectra ("IGM")
The Intergalactic Medium (IGM)

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The Intergalactic Medium (IGM)

Our LCDM paradigm predicts a diffuse, ionized medium that permeates the volume between galaxies.

Miralda-Escudé+95
Rauch+96
Katz+96
Davé+99
Davé+11
etc., etc.
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Is this the proper picture? How does the IGM relate to galaxies?

Monday, August 8, 2011
The Intergalactic Medium (IGM)

Our LCDM paradigm predicts a diffuse, ionized medium that permeates the volume between galaxies. This gas is predicted to be distributed in sheets and filaments, forming the so-called “cosmic web”.

This gas is too diffuse to observe in emission. This forces us to absorption-line techniques.

Is this the proper picture? How does the IGM relate to galaxies?
IGM and Galaxy Formation (Why bother?)

1. The IGM feeds galaxies. There is too little neutral gas in galaxies at $z \sim 3$ to form all of the stars. Even the Galaxy needs a modest supply (e.g. Lehner & Howk 2011)

Cosmic mass density of HI
Prochaska+05
PW09
Notredaeme+09

e.g. “Cold stream” gas
Keres+05
Dekel+06
Fumagalli+11
2. IGM-type analysis is one of the most sensitive (often only) means of studying baryons in dark matter halos and the ISM of distant galaxies.

Cosmic mass density of HI
- Prochaska+05
- PW09
- Notredaeme+09

e.g. “Cold stream” gas
- Keres+05
- Dekel+06
- Fumagalli+11
IGM and Galaxy Formation (Why bother?)

3. This includes searching for the signatures/relics of feedback.

Cosmic mass density of HI
Prochaska+05
PW09
Notredaeme+09

e.g. "Cold stream" gas
Keres+05
Dekel+06
Fumagalli+11

Monday, August 8, 2011
Decades of research on gas that lies foreground to the quasar.

From pc to kpc to Mpc to Gpc scales, including the Intergalactic Medium (IGM)

Majority of spectral features lie in the UV (e.g. Lyα 1215)
The ‘fauna’ or zoology of Quasar Absorption Lines

Primarily characterized by the column density of atomic hydrogen (HI): $N_{\text{HI}}$
Quasar Absorption Lines

QSO $z \sim 3.2$

Ly$\alpha$ Forest

- Weak, most numerous lines
- $10^{12} \text{ cm}^{-2} < N_{\text{HI}} \ll 10^{17.2} \text{ cm}^{-2}$

Spectrum from Wallace Sargent
Quasar Absorption Lines

Lyman Limit System (LLS)

- Optically thick to ionizing photons
- \(10^{17.2} \text{ cm}^{-2} < N_{\text{HI}} < 10^{20.3} \text{ cm}^{-2}\)

Spectrum from Wallace Sargent

QSO \(z \sim 3.2\)
Quasar Absorption Lines

Damped Lyα System (DLA)

- galactic surface densities
- $N_{HI} > 10^{20.3} \text{ cm}^{-2}$
Absorption Line Basics

$N_{\text{HI}}$: Column of HI atoms

$W_{\lambda}$: Equivalent width

$b$: Doppler param.
Absorption Line Basics

\( N_{\text{HI}} \): Column of HI atoms

\( W_{\lambda} \): Equivalent width

\( b \): Doppler param.

\( N_{\text{HI}} = 10^{13.0}\ \text{cm}^{-2} \)
Absorption Line Basics

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$N_{\text{HI}} = 10^{13.0}$ cm$^{-2}$

$N_{\text{HI}} = 10^{20.5}$ cm$^{-2}$

LLS

DLA

HI Ly$\alpha$

Monday, August 8, 2011
f(N_{HI}, X): Definition

J1016+4706 (HST/COS)
Tumlinson+11
• **$N_{HI}$ frequency distribution**
  ‣ Characterization of IGM
  ‣ Normalized to an “absorption path”
$f(N_{\text{HI}}, X)$: Definition

- $N_{\text{HI}}$ frequency distribution
  - Characterization of IGM
  - Normalized to an “absorption path”

- $f(N_{\text{HI}}, X)$
  - # of systems with $N_{\text{HI}}$ per $dN_{\text{HI}}$ per absorption path length
  - Akin to a Luminosity function
    - Counting lines per pathlength

**Graph Details**

- **Logarithmic Scale**: $\log f(N_{\text{HI}}, X)$ vs. $\log N_{\text{HI}}$
- **Data Points**:
  - Ly$\alpha$ Forest
  - LLS
  - DLA (21cm)
- **References**:
  - Penton+04
  - Lehner+07
  - Zwaan+05

**Axes**

- $x$-Axis: $\log N_{\text{HI}}$
- $y$-Axis: $\log f(N_{\text{HI}}, X)$
\( \ell(z) \) and \( \ell(X) \) Defined (Zeroth Moment)

\[ J1016+4706 \text{ (HST/COS)} \]

Tumlinson+11

Monday, August 8, 2011
\( \ell(z) \) and \( \ell(X) \) Defined (Zeroth Moment)

- \( \ell(z) \) [a.k.a. \( dN/dz \)]
  - Number of lines per unit redshift
    - Integrated over an \( N_{\text{HI}} \) interval
  - Simple observable
    - akin to ‘number counts’
    - Zeroth moment of \( f(N_{\text{HI}}, z) \)

![Graph showing \( \ell(z) \) and \( \ell(X) \) Defined (Zeroth Moment)](image.png)

\( \ell(z) \) and \( \ell(X) \) Defined (Zeroth Moment)

Tumlinson+11

Monday, August 8, 2011
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    - Zeroth moment of \( f(N_{HI}, z) \)

- \( \ell(X) \) [a.k.a. \( dN/dX \)]
  - Number of lines per unit pathlength
    - \( dX = \frac{H_0}{H(z)} (1+z)^2 \, dz \)
  - Defined to maintain a constant \( n_c \, A_p \)
    - \( n_c \): Comoving number density
    - \( A_p \): Physical (effective) area
  - Evaluated over an \( N_{HI} \) range

\[ \ell(X) \sim n_c \, A_p \]
\( \ell(X) \) and \( \ell(z) \) [at \( z=0 \)]
• **Approaches**
  - Count lines
    - Repeat for multiple quasars
  - Integrate $f(N_{HI}, X) dN_{HI}$

\[ \ell(X) \text{ and } \ell(z) \text{ [at } z=0] \]
\( \ell(X) \) and \( \ell(z) \) [at \( z=0 \)]

- **Approaches**
  - Count lines
  - Repeat for multiple quasars
  - Integrate \( f(N_{\text{HI}},X) \ dN_{\text{HI}} \)

- **Results**
  1. Several hundred Lya forest lines per \( \Delta X=1 \) (or \( \Delta z=1 \))
• Approaches
  ‣ Count lines
    ✦ Repeat for multiple quasars
  ‣ Integrate $f(N_{\text{HI}},X) \, dN_{\text{HI}}$
• Results
  1. Several hundred Lya forest lines per $\Delta X=1$ (or $\Delta z=1$)
  2. A handful of saturated lines
\begin{itemize}
  \item **Approaches**
    \begin{itemize}
      \item Count lines
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    \begin{enumerate}
      \item Several hundred Lya forest lines per $\Delta X=1$ (or $\Delta z=1$)
      \item A handful of saturated lines
      \item Fewer than 1 galaxy (DLA) hit per 10 quasars observed
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\end{itemize}
\( \ell(X) \) and \( \ell(z) \) [at \( z=0 \)]

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  3. Fewer than 1 galaxy (DLA) hit per 10 quasars observed
  4. \( \sim 10 \) metal systems per \( \Delta X \)
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  - Origin of the Lya/OVI "IGM"
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  - Evolution?
- A few contrarian remarks on galactic-scale winds and the CGM
  - As you wish...
The Interstellar Medium (ISM)

Cold gas and dust that fills the disks of star-forming galaxies.

Zwaan+05,08,10

Monday, August 8, 2011
The Interstellar Medium (ISM)

Cold gas and dust that fills the disks of star-forming galaxies.

The ISM (at least at $z \sim 0$) corresponds to the damped Lya systems (DLAs), but these are not the subject of today’s talk.

Zwaan+05,08,10

Monday, August 8, 2011
The “IGM”/Galaxy Connection (at z~0)
The “IGM”/Galaxy Connection (at z~0)
The Circumgalactic Medium (CGM)

Diffuse gas, including metals, in the halos of galaxies (and beyond).

HVCs

Wakker+08

Chynnoweth+08
The Circumgalactic Medium (CGM)

Diffuse gas, including metals, in the halos of galaxies (and beyond).

Do all galaxies at z~0 have a CGM?
How far does it extend?
Is the CGM metal enriched?
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How far does it extend?
Is the CGM metal enriched?

Does this medium feed galaxies?
Is there a hot (T>10^6 K) phase?
How does it relate to the “IGM”?

Chynnoweth+08

Monday, August 8, 2011
The Circumgalactic Medium (CGM)

Diffuse gas, including metals, in the halos of galaxies (and beyond).

Do all galaxies at z~0 have a CGM?  
How far does it extend?  
Is the CGM metal enriched?

Does this medium feed galaxies?  
Is there a hot (T>10^6 K) phase?  
How does it relate to the "IGM"?

e.g. "Cold" stream gas  
Fumagalli+11

Monday, August 8, 2011
Can galaxies (and CGM) ‘make’ the “IGM”?
Can galaxies (and CGM) ‘make’ the “IGM”?

• **Galaxies**
  ‣ Significant ISM
    ✦ Generate the observed DLA
  ‣ Gas in the CGM
    ✦ Optically thick (HVCs)
      ➡ May also have lower surface density ‘envelopes’
    ✦ Does this gas produce the cosmic web?!
Can galaxies (and CGM) ‘make’ the “IGM”?

- **Galaxies**
  - Significant ISM
    - Generate the observed DLA
  - Gas in the CGM
    - Optically thick (HVCs)
      - May also have lower surface density ‘envelopes’
    - Does this gas produce the cosmic web?!

- **Experiment**
  - Examine the CGM of galaxies
  - Via coincident, background quasars
    - Spinrad+93, Morris+93, Lanzetta+95, Tripp+98, Chen+01, Bowen+01, Wakker&Savage09, etc., etc., etc.

To HST

Monday, August 8, 2011
LCO/WFCCD Survey :: Probing the IGM/Galaxy Connection

- Magnitude-limited (R~19.5) survey for galaxies in 20 UV-bright QSO fields
  - Low-resolution spectra useful for redshifts only
    - Stay tuned for SFR, metallicities, etc. (Gemini/GMOS via J. Werk)
- IGM linelists from the literature (Tripp+08, Thom&Chen08, Danforth+08)

The LCO/WFCCD IGM/Galaxy Survey
Prochaska, Weiner, Chen, Mulchaey, Cooksey 2011
**Experiment: Probe Galactic Halos (CGM)**

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  - IGM linelists from the literature (Tripp+08, Thom&Chen08, Danforth+08)
• **L* Galaxies (L > L*)**
  ‣ Small sample (bright galaxies are rare!)
  ‣ See “COS-Halos” program for r < 150 kpc
    ✦ Tumlinson, Thom, Werk, etc.
• **Sub-L* Galaxies** ($L^* > L > 0.1L^*$)
  ▶ 100% covering with $W^{Ly\alpha} > 100$ mA to 300 kpc
  ✦ Early and late types
  ▶ Rarely a brighter galaxy also within 300 kpc
HI Gas Surrounding $z \approx 0$ Galaxies

**Prochaska+11**

- **$W_{\text{Ly}\alpha}$ (mA)** vs. **$\rho$ (kpc)**
- **$\log N_{\text{HI}}$** vs. **$\rho$ (kpc)**
• Dwarf Galaxies ($L < 0.1L^*$)
  ‣ Nearly 100% covering with $\text{W}^\text{Ly}_\alpha > 100\text{mA}$ to 300 kpc
  ‣ Early or late types

HI Gas Surrounding $z \sim 0$ Galaxies
• Dwarf Galaxies \((L < 0.1L^*)\)
  ‣ Nearly 100% covering with \(W_{\text{Ly}\alpha} > 100\,\text{mA}\) to 300 kpc
  ❧ Early or late types
  ‣ Largest \(W_{\text{Ly}\alpha}\) absorption has a nearby, brighter galaxy
  ❧ Or Virgo!

**HI Gas Surrounding z~0 Galaxies**

\(W_{\text{Ly}\alpha}\) vs. distance (kpc)

\(\log N_{\text{HI}}\) vs. distance (kpc)
All together now

Galaxies of all luminosity and spectral type show extended 'halos' (or CGM) of HI absorption to 300 kpc

- Generally $W_{\text{Ly}\alpha} > 100$ mA
- e.g. Lanzetta+95, Tripp+98, Wakker+09
Extent of the CGM

Prochaska+11

(a) Extent of the CGM as a function of $\rho$ (kpc). The graph shows the relationship between $W_{\text{Ly}a}$ (mA) and $\rho$ (kpc), with data points indicating the detection rate of neutral hydrogen at various distances from the galaxy. The data is overlaid with a line that represents the trend observed in the study.

(b) Detection rate (%) as a function of $\rho$ (kpc) for different $W_{\text{Ly}a}$ thresholds: $W_{\text{Ly}a} > 50$ mA and $W_{\text{Ly}a} > 100$ mA. The graph highlights the decrease in detection rate with increasing distance from the galaxy for these two thresholds.
Extent of the CGM

- HI covering fraction drops rapidly beyond ~300kpc
  - Associate CGM with this scale
Extent of the CGM

- HI covering fraction drops rapidly beyond ~300kpc
  - Associate CGM with this scale
  - And/or the half-width of a thread in the cosmic web

$f_V < 1\%$
• **CGM Mass Estimate**
  
  ✦ Adopt (assume) a large ionization correction for $N_{HI}$
  
  ✦ With $N_{HI,CGM} = 10^{15} \text{ cm}^{-2}$, $x_{HI} = 10^{-4}$

  \[
  M_{CGM} \approx 3 \times 10^{10} M_\odot \left( \frac{N_{HI,CGM}}{10^{15} \text{ cm}^{-2}} \right) \left( \frac{x_{HI}}{10^{-4}} \right)^{-1} \left( \frac{r_{CGM}}{300 \text{kpc}} \right)^2
  \]

  ✦ Comparable to the baryonic mass of the galaxy!
  
  ✦ Enough ‘missing’ baryons for sub-$L^*$ galaxies

• **Cosmological mass density**  \[ \Omega_{CGM} \sim 0.1 \Omega_b \]
**Mass of the CGM from z~0 Galaxies**

- **CGM Mass Estimate**
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Is the “IGM” just CGM gas from galaxies?

Plots like these have generated strong (misplaced?) argument over the years.
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Is the “IGM” just CGM gas from galaxies?

Statistical argument: \( \mathcal{L}(X) \sim n_c A_p \)

Prochaska+11

\[
\begin{align*}
\text{Cumulative } & \mathcal{L}_{\text{Ly}\alpha}(X) \\
\text{Luminosity } (L*) \\
\end{align*}
\]
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Statistical argument: $\ell(X) \sim n_c A_p$

Prochaska+11

Cumulative $\ell_{\text{Ly}^\alpha}(X)$

Luminosity ($L^*$)

$W^{\text{Ly}^\alpha} > 300 \text{ mA}$

$W^{\text{Ly}^\alpha} > 100 \text{ mA}$

$W^{\text{Ly}^\alpha} > 30 \text{ mA}$

Monday, August 8, 2011
Is the “IGM” just CGM gas from galaxies?

Statistical argument: $\mathcal{L}(X) \sim n_c A_p$

Prochaska+11

- $W_{\text{Ly}\alpha} > 30 \text{ mA}$
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- $W_{\text{Ly}\alpha} > 300 \text{ mA}$

Cumulative $\mathcal{L}_{\text{Ly}\alpha}(X)$

$L_{\text{Ly}\alpha}$

Cumulative $\mathcal{L}_{\text{Ly}\alpha}(X)$

Luminosity ($L^*$)

$A_p = \pi r_{\text{vir}}^2$
Is the “IGM” just CGM gas from galaxies?

Statistical argument: $\ell(X) \sim n_c A_p$

- Galaxies are simply too rare for low $N_{HI}$ gas
  - Majority of IGM arises from gas at $r \gg 300$ kpc from galaxies
- But, the CGM does explain all of the strong Lya systems

Prochaska+11

Monday, August 8, 2011
Is the IGM just CGM gas from galaxies?

Statistical argument: $\xi(r)$

- Galaxies only cluster with strong Lya lines
  - $N_{\text{HI}} > 10^{14} \text{ cm}^{-2}$
  - Weak lines are the IGM

See also:
- Chen+05
- Wilman+07
- Shone+10
- Borthakur+1X
- Tejos+1X

Chen&Mulchaey 09

Monday, August 8, 2011
Is the “IGM” just CGM gas from galaxies?

No! But the majority of strong Lya lines certainly are.
The IGM/Galaxy Connection (at z~0)

The diagram shows a plot of \( \log f(N_{HI}, X) \) vs. \( \log N_{HI} \) with data points indicating the Ly\( \alpha \) Forest, LLS, and DLA (21cm) regions. The IGM is depicted in a 3D cube. The data points are spread across the log-log scale, indicating a power-law relationship. The graph is titled and dated Monday, August 8, 2011.
The IGM/Galaxy Connection (at $z \sim 0$)

The diagram shows the relationship between the logarithm of the number density of hydrogen ($N_{HI}$) and the logarithm of a function $f(N_{HI}, X)$, plotting various astronomical phenomena such as Lyα Forest, IGM, CGM, LLS, and DLA (21cm). The x-axis represents $log N_{HI}$, ranging from 12 to 22, and the y-axis represents $log f(N_{HI}, X)$, ranging from -10 to -30. The diagram illustrates the connection between the intergalactic medium (IGM) and the galaxy's circumgalactic medium (CGM), with LLS and DLA (21cm) representing extreme cases.
The IGM/Galaxy Connection (at $z \sim 0$)

![Diagram showing the IGM/Galaxy Connection](image)

- **Lyα Forest**
- **IGM**
- **CGM**
- **LLS**
- **DLA (21cm)**
- **ISM**

Monday, August 8, 2011
The IGM/Galaxy Connection (at z~0)

What about metals? How does this picture evolve at high z? And what about outflows?!

Monday, August 8, 2011
‘IGM’ Metals: O VI

Advantages:
- highest T probe available in FUV
- strong doublet, easily detected
- Most common metal system
- IGM samples for comparison
- peak ionization fraction at T = 300,000K, still significant at $10^6$ K
- catches gas heating and/or cooling through coronal regime.

Disadvantages:
- must be redshifted to detect w/ HST (mirror absorbs at < 1150A)
- peak abundance lies where rad cooling is efficient, so there are significant non-equilibrium issues

O VI has also been widely used to count hot gas (WHIM) or “missing baryons”, so general IGM samples are well characterized.

Tripp+08, Thom+Chen08, Danforth+Shull08

See: H.-W. Chen for MgII, CIV

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- Magnitude limited \((R \sim 19.5)\) survey for galaxies in UV-bright QSO fields
  - Low-resolution spectra useful for redshifts only
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- IGM linelists from the literature (Tripp+08, Thom&Chen08, Danforth+08)
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- Dwarf Galaxies ($L < 0.1L^*$)
  - Many fewer positive detections of OVI than Lyα

**Monday, August 8, 2011**
• Dwarf Galaxies ($L < 0.1L^*$)
  ▶ Many fewer positive detections of OVI than Lyα
  ▶ Most of the cases where OVI is observed have a second, brighter galaxy nearby
- **L* Galaxies (L > L*)**
  - Positive detections to ~250 kpc
  - No detections at 250-300 kpc
  - Small sample (stay tuned for HST/COS results)
• Sub-L* Galaxies (L* > L > 0.1L*)
  › Almost all positive detections, to 300 kpc
  › Independent of spectral type
Sub-L* Galaxies (L* > L > 0.1L*)

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Is the enriched “IGM” simply CGM gas?

Prochaska+11

Monday, August 8, 2011
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Prochaska+11

$W^{1031} > 30$ mA

$W^{1031} > 70$ mA

$W^{1031} > 100$ mA
Is the enriched “IGM” simply CGM gas?

Halo Dwarfs

\[ W_{1031} > 30 \text{ mA} \]

\[ W_{1031} > 70 \text{ mA} \]

\[ W_{1031} > 100 \text{ mA} \]
• Yes! The extended CGM of sub-L\textsuperscript{*} gal
  ‣ Halo gas is not enough
  ✦ Only for strong OVI

See also
  Tumlinson\&Fang 05
  Stocke\+06
  Oppenheimer \& Davé 09

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- Other Implications
  - I speculate that ALL metals are located within 300 kpc of galaxies

- OVI: most common metal-line in the IGM

Yes! The extended CGM of sub-L* gal is not enough. Only for strong OVI. I speculate that ALL metals are located within 300 kpc of galaxies.

OVI: most common metal-line in the IGM.

See also:
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- Stocke + 06
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- There are no metals in the WHIM?!
- Metals were transported to large distances
- Winds?
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- OVI: most common metal-line in the IGM
- There are no metals in the WHIM?!?
- Metals were transported to large distances
- Winds?
- Key open question
  - Are there many OVI lines with W<30mA?

See also
- Tumlinson & Fang 05
- Stocke +06
- Oppenheimer & Davé 09

Monday, August 8, 2011
Star-forming galaxies at z<1 often exhibit blue-shifted (outflow) absorption by metals.

**Graphs:**
- **Weiner+09:** [OII] and MgII relative flux vs. relative velocity (km s\(^{-1}\)).
- **Rubin+11:** Max. Δv(Mg II) (km s\(^{-1}\)) vs. log SFR (M_☉ yr\(^{-1}\)).

**Legend:**
- Wind
- No Wind
Metal Transport: Galactic-scale Winds?

Star-forming galaxies at $z<1$ often exhibit blue-shifted (outflow) absorption by metals.

But are these “winds” propagating to 300kpc? Or were the metals transported long ago?
The IGM/Galaxy Connection (at z~0)

\[ \log N_{\text{HI}} \]

\[ \log f(N_{\text{HI}}, X) \]

Lyα Forest

IGM

CGM

LLS

DLA (21cm)

ISM
No strong evidence for metals in the IGM (or the WHIM) at $z \sim 0$. 
Statistically, the picture is well developed. But the precise relationship of gas to galaxies requires further research.

Monday, August 8, 2011
How Galaxies Acquire their Gas: A Map of Multiphase Accretion and Feedback in Gaseous Galaxy Halos

Principal Investigator: Dr. Jason Tumlinson
Institution: Yale University

Data Division
Jessica Werk & Xavier Prochaska (Santa Cruz)
Joseph Meiring & Todd Tripp (UMass)
Christopher Thom & Ken Sembach (STScI)

Theory Division
Amanda Ford & Romeel Davé (Arizona)
Neal Katz (UMass), David Weinberg (The OSU),
Ben Oppenheimer (Leiden), Molly Peeples (UCLA)

39 galaxies in 134 HST orbits
(13 “red and dead”,
26 star-forming)

“COS-Halos”
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“COS-Halos”
COS-Halos Survey Design:

Blue and red, $L \sim L^*$ galaxies at impact parameters of 20-150kpc. (Much easier at $z \sim 0$)
How is that for 134 HST orbits?!
Gas Halos and Galaxy Bimodality

GALEX+SDSS (Schiminovich et al. 2007)

log (sSFR [yr⁻¹])

log (M*/M_{sun})

-13
-12
-11
-10
-9

Star-forming galaxies
Passive galaxies
“Blue cloud” galaxies have 92% detection rate (100% inside 90 kpc)
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“Red sequence” galaxies have 44% detection rate.
“Blue cloud” galaxies have 92% detection rate (100% inside 90 kpc)
“Red sequence” galaxies have 44% detection rate.
And much of this gas may be the extended CGM of neighbors.
Star Forming Galaxy Halos: Lots of Oxygen Mass!

$R = 150 \text{ kpc}$

Monday, August 8, 2011
Star Forming Galaxy Halos: Lots of Oxygen Mass!

\[ M_{\text{OVI}} = \pi R^2 N_{\text{OVI}} 16 m_H M_\odot \]

...then apply ionization correction \( f_{\text{OVI}} \) ...
M_{OVI} = \pi R^2 N_{OVI} 16m_H M_\odot

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M_{Oxygen} = 1.2 \times 10^7 \left(0.2/f_{OVI}\right) M_\odot
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An ISM worth of metals at \( r \sim 100 \) kpc!!
O VI Kinematics

O VI gets stronger by getting broader (not by getting optically thick and saturated).

There is little if any O VI-traced material outside beyond the escape velocities of the host halos.
O VI can fit into the “Multiphase Accretion” scenario as the tracer of interface gas between the cooler condensed clouds and the hot coronal halo.

But the covering fraction predicted by “cold mode” or “multiphase” accretion is ~10-20%, not ~100%.

e.g. Keres & Hernquist 2009
The large oxygen mass in the ionized halos of galaxies implies at least 1 Gyr worth of star formation and oxygen yield, efficiently transported out to > 150 kpc. Current simulations – even those with extreme winds – fail to reproduce these observations.

Monday, August 8, 2011
"Recycled" winds = half of accretion at $z < 1$?

The O VI we represents significant mass and metal outflow from galaxies, yet does not appear to exceed the escape velocity. This finding is consistent with the expectation that much of $z < 1$ accretion is recycled outflows.

Stinson, Brook+, in prep.

The O VI we represents significant mass and metal outflow from galaxies, yet does not appear to exceed the escape velocity.

This finding is consistent with the expectation that much of $z < 1$ accretion is recycled outflows.
Outline: The IGM/Galaxy Connection

- IGM introduction
  - Absorption line systems
  - $f(N,X)$, $l(X)$
- Exploring the CGM at $z \sim 0$
  - Extended gaseous halos
  - Origin of the Lya/OVI “IGM”
- The IGM/CGM at $z \sim 2$
  - Evolution?
- A few contrarian remarks on galactic-scale winds and the CGM
  - If you like..
Do these z~0 IGM/CGM Results Apply at z>1?

H1821+640
z_{QSO} = 0.297

PSS0209+0517
z_{QSO} = 4.17

Monday, August 8, 2011
Do these $z \approx 0$ IGM/CGM Results Apply at $z > 1$?

Yes, quite probably... (see Steidel+10, Rudie+11, O’Meara+12)

e.g. Halos of gas and metals around SF galaxies to $r \approx 200 \text{kpc}$
The IGM/Galaxy Connection at z~2

- Lya forest
  - Very similar $f(N)$
    - Mildly steeper at low $z$
- ISM
  - Same $f(N_{HI})$ distribution
    - Nearly identical HI mass density
- CGM
  - SF galaxies surrounded by gas and metals to $\sim 300$ kpc
    - Rudie+11
  - This includes massive galaxies (traced by quasars)
    - Hennawi+06, PH10
- Only galaxies are changing!

Penton+04, Lehner+07, Zwaan+05, Prochaska+05, O’Meara+06, Prochaska+10, O’Meara+11
See Altay+11 for a theoretical perspective
The IGM/Galaxy Connection at $z\sim 2$

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See Altay+11 for a theoretical perspective
Summary

"IGM"/Galaxy connection

- Lya
  - Strong Lya lines = Galaxy CGM
  - Weak Lya lines = The proper IGM
- OVI
  - Strong OVI lines = Galactic halos
  - Weak OVI = CGM (of sub-L*)
    - No WHIM component needed (or allowed?!

CGM at z~0

- HI to 300kpc around every galaxy
  - Beyond $r_{\text{vir}}$ for most galaxies
  - Width of cosmic web threads?
    - Less than a 1% volume filling factor
- Baryonic Mass
  - $>3\times10^{10} M_{\text{Sun}}$
  - Most (all) of the ‘missing’ galactic baryons

IGM/CGM at high z (vs low z)

- Similar $f(N,X)$ distributions
- Remarkably little evolution in the IGM over 10 Gyr
- CGM
  - Also is qualitatively similar

Key open questions

- What/when transported the metals?
- Does the CGM balance the galactic baryon budget?
- Is there any major evolution outside galaxies (and clusters) from z=3?

Metals (L* galaxies)

- Strong OVI around SF galaxies
  - Equivalent to an ISM mass
- Substantial metal transport (recently?)
  - Stay tuned for more HST/COS results