THE LAST EIGHT-BILLION YEARS OF INTERGALACTIC CIV AND SiIV EVOLUTION

Kathy Cooksey
NSF Postdoctoral Fellow
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Collaborators: Rob Simcoe (MIT); Xavier Prochaska (UCSC); Chris Thom (STScI); Hsiao-Wen Chen (Chicago)
WHAT’S TO COME…

- Science drivers
- Observations, analysis, results
- Comparisons with simulations
- Summary
Metals form here. Metals in ISM.

Inflow:
Infall of previously ejected material; collapsing structure

Outflow:
Galactic winds driven by stellar winds and/or supernovae; AGN-driven winds

Metals in extended halo

Metals in low-density IGM.
WHY CIV AND SIIV ABSORBERS?

- Trace fairly common metals
  - And Si may trace O, which is most common
- Observable in optical pass bands for $1.5 \leq z \leq 5.5$
  - Well-studied with ground-based telescopes
- Resonant absorption-line doublets
  - Characteristic wavelength separation
  - Characteristic rest equivalent width ratio
    - 2:1 (unsaturated) to 1:1 (saturated) for 1548:1550 and 1393:1402
- Rest wavelengths red-ward of Ly$\alpha$ 1215
  - Outside Ly$\alpha$ forest
Metal Absorption Lines Affected by...

- Metallicity and relative abundances
  
- Ionizing background
  - Changes ionization balance

- Physical distribution
  - Function of density and physical size

(Wiersma+ 2009)
Metal Absorption Lines Affected by: Ionizing Background and Ionization Balance

C$^{+3}$ not necessarily dominate C ion but best tracer observationally.

Local sources (e.g., stellar radiation field) softens background.

At $z \approx 3$, HeII reionization affects UVB around 4 Ryd.

(Haardt & Madau 1996, 2005)
Metal Absorption Lines Affected by Physical Distribution

\[
\frac{dN}{dX} = \frac{c}{H_0} n_{\text{co-m}} \sigma_{\text{phys}}
\]

- Absorber line density \(\sim\) co-moving number density \(\times\) physical cross section of absorber
CIV and SiIV Survey and Final Samples

- 38 G = 1 CIV (43 G = 1+2)
  - $\log N(C^{+3}) = 13.2$ to $>15.3$
- 20 G = 1 SiIV (24 G = 1+2)
  - $\log N(Si^{+3}) = 12.9$ to $>14.4$
- 49 lines of sight (largest to date!)
  - HST STIS and GHRS
    - FUSE supplement
  - Pre-Servicing Mission 4
**Definition:**

\[
f(N(C^3)) \equiv \frac{\Delta N}{\Delta N(C^3) \Delta X(N(C^3))}
\]

**Power-law model:**

\[
f(N(C^3)) = k \left( \frac{N(C^3)}{N_0} \right)^\alpha
\]

No observed break in \( f(N) \).
DEFINING AND MEASURING C$^{+3}$ MASS DENSITY

- Relative to critical density of Universe
  \[ \Omega_{C^{+3}} = \frac{H_0 m_C}{c \rho_{c,0}} \int_{N_{\text{min}}}^{N_{\text{max}}} f(N(C^{+3})) N(C^{+3}) dN(C^{+3}) \]

- Approximate by summing column densities
  \[ \Omega_{C^{+3}} = \frac{H_0 m_C}{c \rho_{c,0}} \sum_{N} \frac{N(C^{+3})}{\Delta X(N(C^{+3}))} \]

- Assume power-law formulism and integrate
  \[ f(N(C^{+3})) = k \left( \frac{N(C^{+3})}{N_0} \right)^{2+\alpha} \]
  \[ \Omega_{C^{+3}} = \frac{H_0 m_C}{c \rho_{c,0}} \frac{k}{2+\alpha} \left( \frac{N_{\text{max}}^{2+\alpha} - N_{\text{min}}^{2+\alpha}}{N_0^\alpha} \right) \]

- Define finite bounds: $13 \leq \log N \leq 15$
**MASS DENSITIES OVER AGE OF UNIVERSE**

**C\textsuperscript{+3}:** Increases by 4\pm0.5 over high-\(z\) variance-weighted mean.

**Rate:** \((0.51\pm0.16) \times 10^{-8}\) Gyr\(^{-1}\)

**Si\textsuperscript{+3}:** Increases by 4\(+3/-1.9\) over high-\(z\) unweighted median.

**Rate:** \((0.61\pm0.13) \times 10^{-8}\) Gyr\(^{-1}\)

References:
**Absorber Line Density: Evolution?**

\[ \frac{dN_{\text{CIV}}}{dX} : \text{Yes! But...} \]
not significant, just statistically significant

\[ \frac{dN_{z=0.6}}{dX} / \frac{dN_{z=3.2}}{dX} = 1.8 \pm 0.4 \]

\[ dN_{\text{SiIV}}/dX: \text{No! But...} \]
high-redshift studies need to be improved...

THE C+3 MASS DENSITY “STORY”... NOW UNDER FIRE

Monotonically increasing?
Plateau?

Simcoe et al. (in prep)
No evolution with redshift
- Both samples drawn from same parent population

\[ \frac{N(\text{Si}^{+3})}{N(\text{C}^{+3})} \approx 0.16 \text{ for 12 Gyr!} \]
- No signature for HeII reionization at \( z \approx 3 \)

Balanced interplay of three processes:

\[
\frac{N(\text{Si}^{+3})}{N(\text{C}^{+3})} = \left( \frac{L_{\text{Si}}}{L_{\text{C}}} \right) \left( \frac{n_{\text{Si}}}{n_{\text{C}}} \right) \left( \frac{\chi_{\text{Si}}}{\chi_{\text{C}}} \right)
\]

Must turn to simulations...
OVERWHELMINGLY LARGE SIMULATIONS

See Schaye et al. (2010)

- **Hydrodynamic cosmological simulations,** $z = 127 \rightarrow 0$
  - Gadget III
  - Periodic boundary conditions
  - $2 \times 512^3$ (baryonic+dark matter) particles
  - $100 \, h^{-1} \, \text{Mpc}$ on a side

- **Chemical evolution physics:**
  - Radiative cooling by 11 elements
  - Photoionization by UV background in addition to collisional ionization equilibrium
  - Chemodynamics (production and dispersal of elements)

(Schaye & Dalla Vecchia 2008; Dalla Vecchia & Schaye 2008; Wiersma et al 2009a, b; Booth & Schaye 2009; and more!)
Effects of Changing “Feedback”

- (i.e., movement of material and energy by stars and active galactic nuclei
  - Winds, jets, bubbles, ...)
- Feedback affects...
  - Star formation rate
  - Ionization balance
  - Physical distribution...
- Effects felt near, far, and over time

Haas et al. (in prep.)
**PROBING CIV AND SIIV IN OWLS UNIVERSES: SIMULATIONS DESCRIPTION**

<table>
<thead>
<tr>
<th>Simulation</th>
<th>What does each really test?</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEFAULT</td>
<td>How well can reference (kinetic) model reproduce observations?</td>
</tr>
<tr>
<td>AGB0_SNIa0</td>
<td>Absence of delayed metal production and feedback.</td>
</tr>
<tr>
<td>AGN</td>
<td>Effect of AGN (thermal) feedback plus kinetic winds.</td>
</tr>
<tr>
<td>MILL</td>
<td>Effect of cosmology (higher $\sigma_8$) and more mass in winds.</td>
</tr>
<tr>
<td>NOFB</td>
<td>How much can dynamics do for enrichment?</td>
</tr>
<tr>
<td>THERMAL_FB</td>
<td>“Next generation”: feedback model, cooling, ionizing, cosmology,…</td>
</tr>
<tr>
<td>WML4</td>
<td>Effect of more mass in winds and reference for MILL ($\sigma_8$).</td>
</tr>
<tr>
<td>WMOM</td>
<td>Effect of scaling kinetic wind parameters with $v_c$ (halo mass).</td>
</tr>
<tr>
<td>ZCOOL0</td>
<td>Absence of metal-line cooling.</td>
</tr>
</tbody>
</table>

Also use variants of **DEFAULT** to test convergence, resolution, ionization balance (UV background), and abundances (yields).
Comparing Simulations to Observations: $N(C^{+3})$ and $N(Si^{+3})$ Frequency Distributions

$C^{+3}$: Just need feedback and cooling to reproduce shape. Too few CIV absorbers! Except for THERMAL_FB...?

$Si^{+3}$: Just need feedback to reproduce shape but too few. SiIV observations better reproduced with higher $\sigma_8$?

So much more to be explored...!
$C^+3$ Column Density Maps: Galaxies?

Complements of Serena Bertone
C$^{+3}$ COLUMN DENSITY MAPS: GALAXIES!

Complements of Serena Bertone
**Summary**

- $z < 1$ C$^{+3}$ and Si$^{+3}$ mass densities increased compared to $1.5 < z < 5$ mean/median

- Physical distribution of absorbers “work” to keep $dN/dX$ within factor of two for 12 Gyr
  - Interplay of co-moving number density and cross section
  - CIV and SiIV absorbers likely trace circumgalactic medium more than IGM
  - At low redshift? At all redshifts?!

- Ionic ratio $N$(Si$^{+3}$)/$N$(C$^{+3}$) constant for 12 Gyr
  - Processes balance to produce constant ratio…
  - … future work with OWLS to disentangle