Linking Galaxy Formation with Cosmic Reionization

Kristian Finlator
Assistant Professor
Department of Astronomy
New Mexico State University
Student Collaborators

Ivanna Langan (DAWN)
Yunjing Wang (Tsinghua U)

Non-Student Collaborators

Moiré Prescott (NMSU)
Chris Churchill (NMSU)
Zheng Cai (Tsinghua U)
Ben D. Oppenheimer (Colorado)
Sultan Hassan (CCA/Flatiron)

Romeel Davé (Edinburgh)
Daniel Ceverino (UAM, Spain)
Steven Finkelstein (UT)
Linhua Jiang (KIAA/Peking)
E. Zackrisson (Uppsala)
**Redshift (z):** As the Universe expands, the wavelength of light that traverses it expands at the same rate. When cosmologists measure the factor by which a source’s light has expanded in wavelength, then they are also measuring how much the Universe has expanded since the light was emitted. If we know how rapidly the Universe was expanding at different times, then we can compute how old the Universe was when the light was emitted. High redshift = early times.

\[ 1 + z \equiv \frac{\lambda(\text{observed})}{\lambda(\text{emitted})} \]

<table>
<thead>
<tr>
<th>z</th>
<th>t/Gyr</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.47</td>
</tr>
<tr>
<td>5.5</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>3.2</td>
</tr>
<tr>
<td>0.4</td>
<td>9.4</td>
</tr>
<tr>
<td>0</td>
<td>13.8</td>
</tr>
</tbody>
</table>

- reionization starts
- reionization ends
- cosmic Noon
- Sun forms today
- today
CDM: $300 \text{ kyr} < t < 50 \text{ Myr (z > 50)}$

Uniform (to $10^{-5}$) mixture of dark matter, neutral “baryons” (non-dark matter), and cosmic background radiation
Dark matter “curdles” under gravity into energetically bound dark matter halos of many sizes. Small halos merge to form bigger halos. Universe’s still-neutral matter becomes increasingly inhomogeneous.
The gas within large dark matter halos cools and collapses to form galaxies. Their stars emit UV light that ionizes and heats the Universe. “This is the last time that the average hydrogen atom did anything interesting.” (J. Rhoads) Universe is now a plasma. (This phase includes the epoch probed by EDGES; Bowman+2018)
There are now three phases for baryonic matter and two sources of light:

- matter: ISM, CGM, IGM
- light: CMB, UVB
<table>
<thead>
<tr>
<th>Magnitudes and Parsecs</th>
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</thead>
<tbody>
<tr>
<td><strong>Apparent Magnitude</strong></td>
</tr>
<tr>
<td>- Lower # = brighter object</td>
</tr>
<tr>
<td>- introduced by Hipparchus to classify stars by brightness.</td>
</tr>
<tr>
<td>- Vega = 0</td>
</tr>
<tr>
<td>- Jupiter &amp; Mars = -3</td>
</tr>
<tr>
<td>- faintest thing an 8-meter ground-based telescope can see = 27</td>
</tr>
<tr>
<td><strong>Absolute Magnitude</strong></td>
</tr>
<tr>
<td>- what an object’s apparent magnitude <em>would be</em> if it were a point-source 10 parsecs away</td>
</tr>
<tr>
<td>- Milky Way: -21</td>
</tr>
<tr>
<td>- HST limit @ z=6: -17</td>
</tr>
<tr>
<td>- JWST limit @ z=6: -15</td>
</tr>
<tr>
<td><strong>Parsec</strong></td>
</tr>
<tr>
<td>- “parallax-second”</td>
</tr>
<tr>
<td>- distance of a star that appears to wobble annually by 1 3600th of a degree on the sky owing to Earth’s orbital motion</td>
</tr>
<tr>
<td>- 1 pc ≈ 3.18 light-years</td>
</tr>
<tr>
<td>- distance btw neighboring stars in galaxies ∼ a few pc</td>
</tr>
<tr>
<td>- distance btw neighboring bright galaxies ∼ a few Mpc</td>
</tr>
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</table>
Vocabulary List

- redshift (z)
- dark matter halo
- interstellar medium (ISM)
- circumgalactic medium (CGM)
- intergalactic medium (IGM)
- HI, HII: atoms and protons
- AGN = QSO = quasar
- reionization
- magnitude
- pc (also kpc, Mpc, Gpc)
- CMB
- metal = !(H || He || Li)
- UVB = UV background from stars + QSOs; it is what drives reionization
My Tool: Cosmological Simulations

Model structure formation and reionization numerically, then compare predictions versus observations.

Strengths:
• accounts realistically for many processes on scales > 100 pc
• enables many complementary observational tests
• pretty movies

Weaknesses:
• computationally expensive
• dynamic range limitations:
  • miss large, rare things
  • miss small-scale processes (like what E. Scannapieco works on)
Broad Questions

(1) How did galaxies form stars during the first billion years?
(2) How did early galaxies enrich and irradiate their environments?
(3) How does the circumgalactic medium (CGM) respond to reionization?
Broad Question 1: How did galaxies form stars during the first billion years?

Narrower Question: What was the minimum mass of dark matter halo in which galaxy formation proceeded efficiently?
Observational motivation: in order for galaxies to drive HI reionization, there must be many faint ones. To have many faint galaxies, low-mass halos must have been efficient at forming stars.

Yan & Windhorst 2004; see also Finkelstein+2019
Theoretical Motivation:
Models for galaxy formation were being proposed in which galaxy formation was suppressed in halo masses below an assumed minimum:
• $10^9 M_0$: Iliev+2007; Mesinger+2008; Alvarez+2012
• $10^{10} M_0$: Krumholz & Dekel 2012; Kuhlen+2012
• $10^{11} M_0$: Bouché+2010
• variable: Finkelstein+2019

Do observations constrain this minimum?
By throwing out galaxies in successively larger halos, we introduce successively larger conflict with observations. At what halo mass is the conflict significant?
Models in which the minimum halo mass for galaxy formation is $> 2 \times 10^9 M_0$ are ruled out at $z = 6$. 
Broad Question II: How did early galaxies enrich their environments with metals?

Narrower Question: How does the observed line incidence of CIV absorbers constrain feedback models?
Ordinary galaxies already had lots of dust and therefore metals at $z = 7.5$ ($t = 700$ Myr). So the Universe had metals then. How many and where were they?
(2) Incidence of CIV absorbers

The black curve shows that the carbon mass fraction in the IGM is predicted to grow steadily as new stars eject new metals out of galaxies.

How can we test this?
How to Observe Most of the Universe

**Metal Absorber**: traces overdense gas associated with galaxies where metallicity, density, and the UVB all fluctuate strongly on small scales.

**Lyman-α Forest**: traces filamentary gas that is far from galaxies; its properties fluctuate gently.

**CIV** ("carbon 4"): carbon atoms that are missing three of their electrons. Very easy to see in absorption.
• extract local $Z$, $T$, $v$, $\rho$, and $J_\nu$
• compute ion abundance ratios using a custom ionization solver
• add noise, instrumental response
• synthetic absorbers are then detected & measured realistically
Simulated Sightlines (Theuns+1998)

- Extract local $Z$, $T$, $v$, $\rho$, and $J$.
- Compute ion abundance ratios using a custom ionization solver.
- Add noise, instrumental response.
- Synthetic absorbers are then detected and measured realistically.

Characterizing absorption lines

*Equivalent Width (EW)*: measures the geometric area of an absorption feature in a spectrum.

- Unit: Å or km/s.
- Easy to measure, difficult to predict.

*Column density*: number of ions per unit area along the sightline that are required to produce that level of absorption.

- Unit: ions/cm$^{-2}$
- Difficult to measure, easy to predict.

KF+2016
(2) Incidence of CIV absorbers

A preliminary comparison at $z=3$ suggested that the simulation ejected too much carbon.

Weaknesses of this study:
- formed too many stars
- UVB too strong
- small simulation volume
- column densities hard to measure consistently.

Better models, more data!

KF+2015

weak systems

strong systems
(2) Incidence of CIV absorbers

New model with:
• correct number of stars
• correct UVB amplitude
• 15x the cosmological volume

Also, absorbers characterized in a more consistent way via EWs.

…same result.
**Broad Question II:** How did early galaxies enrich their environments with metals?

**Narrower Question:** How does the observed line incidence of CIV absorbers constrain feedback models?

**Takeaway:** By cosmic noon, the model robustly overproduces weak CIV absorbers. Possible explanations:

- forming or ejecting too much C
- enriched gas is too diffuse (not clumpy enough)
- dust depletion important
- UVB is too strong around low-mass galaxies
Broad Question III: How did early galaxies irradiate their environments?

Narrower Question: How do the statistics of metal absorbers reflect the intensity and spectral hardness of the ionizing background in the CGM?
Definitions

**intensity:** the overall amount of ionizing light

**spectral hardness:** the ratio of high-energy to low-energy ionizing light. For example, the spectral slope from 91.2—912 Å.

Concept

**ionization equilibrium:** the condition that ionizations out of and recombinations into each ionization state are in equilibrium. Higher ionization states are favored in diffuse media with an intense and/or hard UVB.

CIV and SiIV are (relatively) high-ionization ions.
In 2016, a model that produces too few stars and a UVB that is too weak (though reionization completes at $z=6$): *underproduces* both CIV and SiIV at $z\sim6$.
In 2018, a model that produces enough stars, a realistic UVB, and the same reionization history: *underproduces* CIV but *matches* SiIV (again, at z~6). What gives?
The Escape Scenario can Changes the UVB’s Spectral Slope

f_{esc} is a function of energy
→ expect spectral filtering
If I assume that the way in which light escapes galaxies favors hard UV \((\text{density-bounded escape})\) then CIV is nearly reproduced.
If galaxies emit a harder ionizing background, then they produce CIV more efficiently.

→fewer neighboring galaxies are expected per strong CIV absorber.

Measurable w/ JWST.
3. Aligned Absorber Statistics Reflect UVB

The QSO-driven model fares best, confirming that a harder UVB is required than the one predicted out-of-the-box. (This does not have to come from QSOs though.)
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The QSO-driven model fares best, confirming that a harder UVB is required than the one predicted out-of-the-box. (This does not have to come from QSOs themselves.)

Table 1. Normalized probabilities for all aligned pairs. The lower and upper confidence levels are given at the 16 and 84 percentiles and calculated using bootstrapping with $10^4$ iterations.

<table>
<thead>
<tr>
<th></th>
<th>$C_{\text{IV}}/Si_{\text{IV}}$</th>
<th>$C_{\text{II}}/C_{\text{IV}}$</th>
<th>$Si_{\text{II}}/Si_{\text{IV}}$</th>
<th>$O_{\text{II}}/C_{\text{IV}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated</td>
<td>0.32 $^{+0.51}_{-0.14}$</td>
<td>0.33 $^{0.33}_{0.33}$</td>
<td>0.21 $^{0.58}_{0.21}$</td>
<td>0.33 $^{1.00}_{0.33}$</td>
</tr>
<tr>
<td>HM12</td>
<td>0.16 $^{0.32}_{0.03}$</td>
<td>0.33 $^{0.33}_{0.33}$</td>
<td>0.58 $^{0.58}_{0.58}$</td>
<td>0.33 $^{1.00}_{0.33}$</td>
</tr>
<tr>
<td>QSO-only</td>
<td>0.52 $^{0.58}_{0.31}$</td>
<td>0.33 $^{0.33}_{0.33}$</td>
<td>0.21 $^{0.58}_{0.21}$</td>
<td>0.33 $^{0.33}_{0.33}$</td>
</tr>
</tbody>
</table>

The column density cut-off values used are as follows: log $N_{C_{\text{IV}},\text{min}} = 13.25$, log $N_{C_{\text{II}},\text{min}} = 12.9$, log $N_{Si_{\text{II}},\text{min}} = 12.12$, and log $N_{O_{\text{II}},\text{min}} = 13.49$. 

Doughty, KF+2018
*Broad Question III:* How did early galaxies irradiate their environments?

*Narrower Question:* How do the statistics of metal absorbers reflect the *intensity* and *spectral hardness* of the ionizing background in the CGM?

*Takeaway:* The incidences of CIV and SiIV absorbers and the statistics of aligned absorbers are sensitive to the history of star formation and to the slope of the escaping ionizing continuum. Data favor relatively hard UVBs as expected in density-bounded escape scenarios, but do not require QSO-driven reionization.
Broad Question III: How did early galaxies enrich their environments with metals?

Narrower Question: How do the statistics of metal absorbers reflect the intensity and spectral hardness of the ionizing background in the CGM?

On QSO-driven HI reionization: it
• is impossible (Shapiro & Giroux 1987, Yan & Windhorst 2004; Parsa+2018);
• overheats the IGM (D’Aloisio+2017);
• underproduces the CMB optical depth to Thomson scattering or overproduces observed ionizing emissivity at z=5 (Hassan+2018)
Broad Question IV: How does the circumgalactic medium (CGM) respond to reionization?

Narrower Question: Does the line incidence of neutral oxygen (OI) absorbers respond to the progress of HI reionization?
**OI Absorbers Notice HI Reionization**

*Background:* Prior to HI reionization, H and He were neutral and metals were in low-ionization states. OI, SII, CII, and MgII should be in regions where the Universe has not yet been reionized. Can we use them like “clocks” to time reionization?

*Theory:* Oh 2002; Furlanetto & Loeb 2003; KF +2013,2015; Keating+2014; Doughty, KF+2019; Hennawi+2020

*Observations:* Becker+2011,2019; Codoreanu +2018
Despite ongoing metal enrichment, the number density of OI absorbers is flat or declines in time. It drops when HI reionization completes. This may have been observed by Becker +2019.
Broad Question IV: How does the circumgalactic medium (CGM) reflect the progress of reionization?

Narrower Question: Does the line incidence of neutral oxygen (OI) absorbers respond to the progress of HI reionization?

Takeaway: Yes! Recent measurements indicate qualitative agreement with predictions in two ways:
• OI incidence does not grow the way CIV does;
• It shows a feature around z=5–6 consistent with the completion of HI reionization.
What have we learned
• halos more massive than $2 \times 10^9 \, M_0$ grow galaxies
• models overproduce weak CIV absorbers at $z = 3$ and underproduce all of them at $z = 6$
• density-bounded escape can eliminate the latter gap (testable w/ JWST)
• OI absorbers should (and do) “notice” HI reionization in that their line incidence is flat or declining and drops around $z = 5–6$

Things that we sure would love to know
• ionizing emissivity from massive, low-metallicity stars
• the wavelength-dependence of the ionizing escape fraction (well...the mass- and redshift-dependences too)
• the small-scale structure of the CGM (computation!)
• the galaxy mass-metallicity relation at $z \geq 5$