The First Stars: Clues from Lyman Break Galaxies and QSO Absorption Systems

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Current View of Cosmic History
What is the Reionization Era?
A Schematic Outline of the Cosmic History

- The Big Bang
  The Universe filled with ionized gas
- The Universe becomes neutral and opaque
  The Dark Ages start
- Galaxies and Quasars begin to form
  The Reionization starts
- The Cosmic Renaissance
  The Dark Ages end
- Reionization complete, the Universe becomes transparent again
- Galaxies evolve
- The Solar System forms
- Today: Astronomers figure it all out!

S.G. Djorgovski et al. & Digital Media Center, Caltech
“The epoch of reionisation is the last directly observable phase of cosmic evolution which remains to be verified and explored”

(Fan, Carilli, & Keating 2006, ARAA, 44, 415).

It is acting as a catalyst, focusing the attention of astronomers studying:

- The Cosmic Microwave Background
- The Lyman $\alpha$ forest at $z \gtrsim 6$
- The highest redshift galaxies up to $z_{\text{max}} \simeq 7$
- The chemical composition of the oldest stars in the Galactic halo
Galaxies detected up to $z \sim 7$

Reddy et al. 2007
Four Strands

Metals in the Intergalactic Medium at $z \gtrsim 6$: Pop III Stars or ‘Normal’ Star-Forming Galaxies?
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- The Most Metal-Poor Damped Ly$\alpha$ Systems: Clues to Nucleosynthesis at Low Metallicities

- ‘First Stars’ in Galaxies at $z \sim 2$
Can now probe the IGM to $z > 6$ using SDSS QSOs (and GRB afterglows)

Little information left in the Ly$\alpha$ forest itself, but still plenty of signal longwards of Ly$\alpha$ emission line, where metal absorption lines occur
Most common tracer of metals in the Lyα forest is $\text{C IV}$ $\lambda\lambda 1548, 1550$

$z = 2.910$

$z = 2.945 - 2.948$

$z = 2.961 - 2.976$

$z = 2.999$

$z = 3.035 - 3.037$

$z = 3.063 - 3.071$

$z = 3.087 - 3.091$

Songaila 2001

Ellison et al. 2000
Metals in the Intergalactic Medium

Integration of $f(N)$ gives $\Omega_{\text{CIV}}$

Surprising result: $\Omega_{\text{CIV}} \approx$ constant from $z = 1.5$ to $5$

Songaila 2001; Pettini et al. 2003
Are we seeing carbon produced by the ‘first stars’ at $z \gg 5$?

Not necessarily—Oppenheimer & Davé (2006) can reproduce the approx. constant behaviour of $\Omega_{\text{CIV}}$ in models (with feedback) in which $C_{\text{TOT}}$ increases with time, but $C^{3+}/C_{\text{TOT}}$ decreases with time.
Metals in the Intergalactic Medium

Searches for $\text{C}^{\text{IV}}$ at $z > 6$ may provide clues to the origin of C in the IGM. Require high resolution spectroscopy in the near-IR ($\sim 1 \mu$)

C IV Absorption Systems in SDSS 1030+0524

VLT-ISAAC (Ryan-Weber, Pettini, & Madau 2006)

Similar results with Gemini-NIRS (Simcoe 2006)

$\text{O I, C II}$ up to $z = 6.26$ (Keck-HIRES; Becker et al. 2006)
Strong hints that we are not yet seeing a fall in $\Omega_{\text{C IV}}$.

How typical of the IGM is this particular sight-line? Excess of galaxies in the field, two within 100 kpc from QSO sight-line.
Lyman Continuum Radiation from LBGs

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Is this also the case at higher redshifts?
GALACTIC SCALE OUTFLOW

\[ M_{\text{out}} \geq 80 M_\odot \text{yr}^{-1} \geq M_{\text{in}} \approx 40 M_\odot \text{yr}^{-1} \]

2.5 x 10^5 stars

\[ v_- = 250 \text{ km s}^{-1} \]

\[ v_+ = 300 \text{ km s}^{-1} \]

IS abs. lines

Lyα Em. line

Lyman Cont. photons?

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- p. 14/40
Overdensity of galaxies at $\langle z \rangle = 3.09$ in the H’ii SSA22 field
Deep (30 000 – 80 000 s) spectroscopy of 14 galaxies
With LRISB can now reach to $\lambda_{\text{obs}} \simeq 3200 \text{ Å}, \lambda_0 \simeq 800 \text{ Å}$. 

Lyman Continuum Radiation from LBGs
Shapley et al. 2006
Lyman Continuum Radiation from LBGs

Composite of 14 spectra

Two out of 14 show signal below the Lyman edge
Metagalactic Ionising Background

\[ \log J_{\text{gals}}^g \simeq 2.6 \times 10^{-22}; \quad \log J_{\text{QSOs}}^Q \simeq 2.4 \times 10^{-22} \] (Hunt et al. 2004)

Together \( \Gamma_{-12} \simeq 1.3 \), in good agreement with Bolton et al. (2005).
**C, N, O in Damped Lyman $\alpha$ Systems**

- DLAs are a valuable complement to Galactic studies of element abundances in metal-poor stars.
- Abundance measurements are relatively straightforward, provided relevant absorption lines are not saturated.
- Samples of DLAs increased by an order of magnitude by SDSS.
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These are the only DLAs where (C/O) may be measurable (the C\textsc{ii} and O\textsc{i} absorption lines are normally too strong).
Most metal-poor DLAs have $[\text{Fe/H}] \approx -2.5$

Q0913+072, $z_{\text{em}} = 2.785$
DLA at $z_{\text{abs}} = 2.61844$
$N(\text{H} \text{I}) = 2.3 \times 10^{20}$
$(\text{O/Hi}) + 12 = 6.22; [\text{O/Hi}] = -2.44$
High S/N VLT-UVES spectrum
An Additional Source of C at low Metallicities?

Akerman et al. 2004
(Meynet & Maeder 2002 yields)
An Additional Source of C at low Metallicities?

(Chieffi & Limongi 2002 Pop III yields)
An Additional Source of C at low Metallicities?

The few DLA measurements available appear to confirm the rise in [C/O] at [O/H] $\lesssim -1$ seen in MW halo stars

(Pettini et al. 2007)
Primary Nitrogen from Massive Stars?

N and O Abundances in H II regions and DLAs

A floor at (N/O) $\approx -2.3$?
The ‘First’ Galaxies?

Taniguchi et al. 2005
High Redshift Galaxies: How Do We Find Them?

I. Efficient Photometric Preselection

Galaxies at redshifts spanning most of the Hubble time can now be found efficiently using photometric pre-selection tuned to well-defined redshift intervals. (Steidel et al. 2004)
$LBG\ (\langle z \rangle = 3.0),\ BX\ (\langle z \rangle = 2.2),\ BM\ (\langle z \rangle = 1.7)$

Photometric Selection
High Redshift Galaxies: How Do We Find Them?

II. Multi-object Follow-up Spectroscopy

Relatively easy to assemble samples of thousands of galaxies at $z \gtrsim 1.5$, e.g.

940 Lyman break galaxies
2050 ‘BX’ galaxies

with $R < 25.5$, i.e. $L \gtrsim 0.2L^*$ at $z = 2.2$
**Infrared Observations**

**of a sub-sample of ‘BX’ (z ≃ 2) Galaxies**

114 with NIRSPEC K-band spectra ($R \simeq 1400$): Hα, [N II], [S II] emission lines.

90 with ground-based (WIRC) $J$- and $K$-band photometry to $J \simeq 24.0$, $K \simeq 22.3$ (3σ, Vega)

35 with Spitzer IRAC photometry (3.6, 4.5, 5.8, 8.0 μm)
Assembled Stellar Masses

Deduced from best fitting Bruzual & Charlot models to rest-frame UV-optical-(near-IR) SEDs.

Relatively insensitive to exact details of star-formation history

Results: $M_{\text{stars}} = 10^9 - 10^{11.5} M_\odot$, $\langle M_{\text{stars}} \rangle = 3 - 4 \times 10^{10} M_\odot$
Metallicities

The ratio of the intensities of \([\text{N} \ II]\) and \(\text{H}\alpha\) measures the oxygen abundance (Pettini & Pagel 2004):

- **Advantage:** only two emission lines needed, close in wavelength
- **Disadvantages:** Saturates at near-solar metallicity

Dependence on ionisation parameter
A Stellar Mass-Metallicity Relation at High Redshift

(Erb et al. 2006)
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Note:

Most galaxies have

$(O/H) \gtrsim 1/3 (O/H)_\odot$
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- Offset from present-day (SDSS) $M - Z$ relation
Star-Forming Galaxies at $z \sim 2$

Recent progress in determining their masses in (a) stars; (b) gas; (c) metals; and (d) dark matter (Erb et al. 2006a,b, and c)
Interpretation

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- Some have apparently just ‘turned on’, with:
  1. Low stellar masses: $M_{\text{star}} \lesssim \text{few} \times 10^9 \, M_\odot \ll M_{\text{dyn}}$
  2. Young best-fitting ages: $t \sim t_{\text{dyn}} \lesssim \text{few} \times 10^7 \, \text{years}$
  3. High gas fractions: $\mu \sim 1$
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Others have nearly exhausted their fuel supply:

(i) $\mu \lesssim 0.2$
(ii) $M_{\text{stars}} + M_{\text{gas}} \gtrsim 10^{11} \, M_\odot$
(iii) $z_{\text{form}} > 4$ (15% of the sample has ages $\approx$ age of the universe)
(Entirely consistent with number density of $z \simeq 5.5 - 6.5$ galaxies in GOODS fields — Yan et al. 2006)
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Galaxies of similar $M_{\text{tot}}$ began forming stars at different times

At a given redshift, galaxies with a wide variety of $M_{\text{tot}}$ have just begun forming stars
Q2343-BX418 $z = 2.305$:

A Lower Redshift Analogue to $z = 6.5$ Ly$\alpha$ Emitters?

Pettini et al. 2007
$Q2343$-$BX418 \ z = 2.305$

Oxygen Abundances in BX Galaxies

$R_{23}$ gives \((O/H) \simeq 1/5 \ (O/H)_{\odot}\) — i.e. already relatively metal-rich after less than 100 Myr from the onset of star formation
Conclusions

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Near-IR observations of DLAs at $z > 5$ (if they can be found) are more likely to take us close to uncovering the nucleosynthetic products of the ‘First Stars’.