New Insight into the Reionization Era from Spectroscopy of z>6 Galaxies

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Galaxies in the Reionization Era

Large samples: >600 z>6.5 galaxies from HST+ground-based imaging

Large dynamic range in luminosity: $\Delta M_{\text{UV}} \sim 6$

SFR $\sim 0.5 - 300 \, M_\odot/\text{yr}$

(from z~7-8 SFR functions in Smit+15, arXiv:1511.08808)

see also Finkelstein+15, McLure+13, Bowler+14,15, McLeod+15

Data from Bouwens et al. 2015ab
Census of Galaxies in the Reionization Era

- Next step: detailed spectroscopic studies
  - Bright, luminous sources uncovered in wide area imaging campaigns
  - Intrinsically faint galaxies discovered via gravitational lensing

Stark 2016, ARAA, 54, 761
Specific Star Formation Rates Increase at $z>2$

adapted from Salmon+15

(see also Gonzalez+14, Duncan+14)
Extreme Optical Line Emitters at \( z \sim 6.6-6.9 \)


Extremely large EW [O\textsc{iii}]+H\( \beta \) emission (>1500 Å) evident from Spitzer photometry.
Extension to $z \sim 7-9$


Perhaps up to 50% of $z > 7$ galaxies in extreme optical line EW phase.

Suggests very young stellar populations, with large ionizing output per unit 1500Å luminosity -> expect different spectral properties.

New sample of large EW [OIII]+Hβ emitters recently located at $z \sim 7-9$. 

EGSY–2008532660, $z=8.6$

best fit template

$F_\nu$ (nJy)

$\lambda$ (μm)

0 1 2 3 4 5 6

0 500 1000 1500

[OIII], [NII], Hβ, [OII]1,2, HeI
Spectroscopic Studies of $z>7$ Galaxies: Ly\(\alpha\) Emission as Probe of Reionization

Partially neutral IGM will scatter Ly\(\alpha\) from early galaxies.

Expect Ly\(\alpha\) emission to be less common in UV-selected sample of galaxies in reionization era

credit: Wise, Cen, and Abel
Influx of new LAEs confirmed at $z>7$ in 2010-2012 following deep imaging campaigns from ground (Subaru, VLT) and with HST.
Lyman-alpha Disappearance?

- Lyman-alpha emission is rare in \( z > 7 \) star forming galaxies.
- Consistent with reionization coming to end over \( 6 < z < 7 \)

New $z>7$ Lyman-alpha Detections in Luminous Galaxies

- In last year, 5 new galaxies spectroscopically confirmed with MOSFIRE (Oesch+15, Zitrin+15, Roberts-Borsani+16, Stark+16, Song+16).
- 11 galaxies now have Lyman-alpha confirmation at $z>7$. 
100% Lyman-alpha fraction in Luminous [OIII]+Hβ Emitters?

Stark+17

EGS–zs8–2
$z_{\text{Ly} \alpha} = 7.477$

COSY–0237
$z_{\text{Ly} \alpha} = 7.151$

How does Lyman-alpha escape from this sample while being so strongly attenuated in other galaxies at $z>7$?
Accelerated Reionization around the Most Luminous Galaxies?

Transmission is boosted in most luminous galaxies by

(1) Location in largest ionized bubbles.

(2) Hard ionizing spectra associated with extreme EW [OIII] emitters? Effective at ionizing surrounding HI.
How can we learn more about the spectroscopic properties of reionization-era galaxies?

UV lines provide insight into gas conditions and radiation field.

If same EW as z~3 composite, they will be undetectable ($\lesssim 7 \times 10^{-19}$ erg cm$^{-2}$ s$^{-1}$) in z>7 galaxies.

Far UV spectra of metal poor, large sSFR galaxies at z>6 may be very different!
Early Indications of Intense CIII] at Large sSFR

Erb et al. 2010

Low stellar mass ($\sim 10^9 M_\odot$), metal poor ($Z \sim 0.17 Z_\odot$) galaxy with large sSFR (17 Gyr$^{-1}$).

- $W_{\text{He} \text{II}} = 2.7 \text{ Å}$
- $W_{\text{OIII}]1661,1666} = 2.3 \text{ Å}$
- $W_{[\text{CIII}]1907,\text{CIII}]1909} = 7.1 \text{ Å}$
High Ionization Lines Present at Low Metallicity

Stark et al. 2014

$M^* \sim 2.9 \times 10^7 \, M_\odot$

$\beta = -2.0$

$sSFR = 35 \, \text{Gyr}^{-1}$

$W_{\text{Ly}\alpha,0} = 73 \, \text{Å}$

$W_{\text{C}III\lambda1908,0} = 14 \, \text{Å}$

$W_{\text{CIV}\lambda1549,0} = 8 \, \text{Å}$

$W_{\text{O}III\lambda1666,0} = 7 \, \text{Å}$

$W_{\text{Si}III\lambda1883,0} = 3 \, \text{Å}$

$W_{\text{He}II\lambda1640,0} < 1.4 \, \text{Å}$
New Rest-Optical Spectroscopy of CIII\[] Emitters

Large EW CIII\[] found in galaxies with

- large specific star formation rate.
- large ionization parameter
- large EW [OIII]+H-beta
- moderately low metallicty

Similar to properties of reionization-era galaxies.
Measure strength of far-UV lines in bright (24<H<26) galaxies at z~6-9.

First prioritize galaxies with spectroscopic redshift from Ly$\alpha$. 

Characterizing the Far-UV Spectra of Reionization Era Galaxies

First CIII\] detection at $z \gtrsim 6$

- Ly$\alpha$ redshift allows us to nail down observed wavelength of CIII\] (1.341$\mu$m).

Stark et al. 2015a, MNRAS
First CIII] detection at $z \approx 6$

- CIII] $\lambda$1909 detected at expected wavelength with EW ~ 22Å using X-Shooter.
- More than 10x larger EW than $z \sim 3$ composite LBG spectrum.
CIII] in \( z=7.73 \) Lyman-alpha Emitter

\textbf{Oesch+15}

\( z=7.73 \) galaxy in EGS, confirmed in Oesch+15
- \( H=25.0 \)
- \( W_{\text{Ly} \alpha,0} = 21 \text{ Å} \)
- \( W_{\text{[OIII]}+\text{H} \beta} \approx 900 \text{ Å} \)
CIII] in z=7.73 Lyman-alpha Emitter

Stark+16

[CIII]1907,CIII]1909 detected in 3.5 hrs with MOSFIRE.

Total CIII] doublet equivalent width of 22Å.

• ~10x greater EW than in composite z~3 galaxies.

• Larger than most z~2-3 metal poor galaxies.

CIII] EWs in Lyman-alpha Emitters at z~6-7 very large in some systems
What about High Ionization Lines?

Stark et al. 2015b

- H=25.9, z=7.045 galaxy previously confirmed via Lyα (Schenker+12).
- Gravitationally-lensed, low mass Lyman-alpha emitter
- SED similar to typical z~7 galaxies.
Detection of CIV in z=7.045 Galaxy

- 2.78 hrs with MOSFIRE in J-band (1435-1678 Å)
- 3 emission features (nebular CIV +OIII]1661) visible in single J-band exposure.
- Nebular CIV EW ~ 20 Å

Requires very hard ionizing spectrum with large supply of >47.9eV photons
High Ionization Emission Lines are Common among Low Mass Lyman-alpha Emitters

Mainali+16, submitted, arXiv:1611.07125

- CIV + OIII] detection in gravitationally lensed LAE at z=6.11 with FIRE
- CIV1549+1551 EW ~ 24.5 Å

Radiation field implies greater contribution to reionization than often assumed
Origin of UV Metal Lines: Stars or AGN?

1. CIV and OIII
   - Requires spectrum with substantial flux of 34-48 eV photons.

2. OIII
   - If significant flux of 55 eV photons, OIII weakens as oxygen becomes triply ionized.

3. He II
   - Powered by 54.4 eV photons.

UV flux ratios constrain shape of ionizing spectrum
Progress with Magellan/FIRE Spectroscopy

Mainali+16, submitted, arXiv:1611.07125

- Strong CIV, OIII] emission.
- Non-detection of He II.

Faint lensed LAE at z=6.11
- Implies hard spectrum with break at ~54 eV.
  - Low metallicity stellar spectrum.
Evidence of Hard Ionizing Spectrum Powered by Low Metallicity Stars

Mainali+16, submitted, arXiv:1611.07125

- OIII]/He II ratio
  - Inconsistent with AGN photoionization models
  - Can be explained by ionization from metal poor (<10%) stars.

Do we see such intense radiation fields in nearby metal poor galaxies?
Stellar Populations at Low Metallicity: Lessons from Nearby Galaxies

Senchyna, Stark, Charlot+17, in prep

UV spectra change dramatically at 12+log O/H≈8.0 (0.2 Z⊙)

- CIII] equivalent width increase
- CIV P-Cygni disappears
- Broad He II (from WR stars) disappears
- High ionization nebular lines appear.

CIII] equivalent widths approach 15Å, comparable to those at z~7-8.

HST/COS spectra from cycle 23
Implications of Hard Radiation Fields: I. Impact on \([\text{CII}] / [\text{OIII}]\)

Emerging picture: galaxies at \(z>7\) are low metallicity with hard radiation fields which produce a large filling factor of highly ionized gas.
Implications of Hard Radiation Fields: II. Impact on Lyman-alpha Escape

Transmission is boosted in most luminous galaxies by

(1) Location in largest ionized bubbles.

(2) Hard ionizing spectra associated with extreme EW [OIII] emitters. Effective at ionizing surrounding HI?

Image credit: Barkana
Lyman-alpha typically emerges from galaxy redshifted by several hundred km/s.

The further Ly$\alpha$ is redshifted from resonance (1215.67 Å) by time it reaches HI, the less likely it will be scattered by IGM.

Large initial velocity offset = greater transmission of Lyman-alpha through IGM.
Velocity Offsets are Largest in Luminous Galaxies

Mainali+16, submitted, arXiv:1611.07125

Large velocity offsets in luminous galaxies enhance Lyα transmission through partially neutral IGM.
Lyman-alpha Escape from Young, UV Luminous z>7 Galaxies

Transmission is boosted in most luminous galaxies by

1. Location in largest ionized bubbles.
2. Hard ionizing spectra associated with extreme EW [OIII] emitters. Effective at ionizing surrounding HI?
3. Large velocity offsets decrease attenuation from IGM.

Image credit: Barkana

Stark+16, arXiv:1606.01304
Summary

• Lyα downturn at z>6, consistent with late reionization. New detections suggest Lyman-alpha more common in luminous galaxies.

• UV line (CIII], CIV, OIII]) detections suggest very hard radiation field is present in subset of z>7 galaxies.
  • Flux ratios point to metal poor stars rather than AGN as source of hard ionizing spectrum.
  • Consistent with metallicities in range 0.02 - 0.2 Z☉ for single star population synthesis models.

• Lyα enhanced in young, luminous galaxies for several possible reasons: 1) large ionized bubbles, 2) large velocity offsets and 3) hard radiation fields.

• Spectroscopic samples small: larger sample of bright galaxies required to tell if current conclusions are robust.