Seeing Through the Trough: Detecting Lyman Alpha from Early Generations of Galaxies

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Schematic History of the Universe

- Big Bang
- CMB
- ‘Dark Ages’
- Reionization
- 400 kyr
- 1 Gyr
- 14 Gyr

Now

Time
Ly$\alpha$ From ‘First’ Galaxies

- First generation of galaxies: lower metallicity=hotter stars.

Tumlinson & Shull `00
Ly$\alpha$ From First Galaxies

- Hotter stars produce more ionizing radiation $\rightarrow$ Stronger nebular emission from HII regions around hotter stars.
- $\sim 0.6$-$0.7$ Lya photons / recombination $\rightarrow$ more Ly$\alpha$

Ly$\alpha$ line much stronger at higher z, EW higher by factor of $\sim 15$:
**Lyα From First Galaxies**

- Lyα line emission most robust predicted spectral feature of first generation of galaxies (e.g. TS00, Bromm+01, Schraer ‘02,’03, Johnson+09).

- EW~1500 Å (restframe).

- Lyα luminosity ~ 20% of bolometric luminosity.

- Hα flux lower by factor of ~ 8 (deeper in IR).

- HeII Hα (λ= 1640 Å) flux can be comparable to HI Hα, but this depends sensitively on stellar initial mass function (Johnson+09).

- Can we detect Lyα line?
Lyα From First Galaxies

• Can we detect Lyα line?

• First galaxies surrounded by neutral intergalactic medium. Optical depth to Lyα is \( \sim \) Gunn-Peterson (GP) optical depth.

\[
\tau_{GP,0} \approx 7.30 \times 10^5 x_{HI} \left( \frac{1 + z}{10} \right)^{3/2}
\]

• Note: observed flux not suppressed by \( \exp(-\tau_{GP}) \), instead Lyα scatters and observable is large (angular radius \( \sim 10-20" \)) faint halos (Loeb & Rybicki ’99):

\[
\text{SB} < 1\times10^{-21} \left( \frac{L_\alpha}{1\times10^{43} \text{erg/s}} \right) \text{erg/s/cm}^2/\text{arcsec}^2
\]

No.
Lyα From the First Galaxies

- But...GP optical depth reduces quickly with wavelength:
  \[
  \tau_{GP}(\Delta v) \approx 2.3 \left( \frac{\Delta v}{600 \text{ km s}^{-1}} \right)^{-1} \left( \frac{1 + z}{10} \right)^{3/2}
  \]

- The GP-optical depth is smaller for photons that first enter neutral intergalactic medium with some velocity off-set \( \Delta v \) (redward of line center).

- This is why Lya may be detected from galaxies that reside in large HII regions during later stages of the EoR, and why Lya emitting galaxies probe the EoR.
Lyα From the First Galaxies

- The GP-optical depth is smaller for photons that first enter neutral intergalactic medium with some velocity off-set $\Delta v$ (redward of line center).

$$\tau_{GP}(\Delta v) \approx 2.3 \left( \frac{\Delta v}{600 \text{ km s}^{-1}} \right)^{-1} \left( \frac{1+z}{10} \right)^{3/2}$$

- We know observationally that Lya emission lines are asymmetric, and--most importantly-- can contain flux at $\Delta v >> 500 \text{ km/s}$. 

\[\Delta v=+1000 \text{ km/s}\]
Ly$\alpha$ From the First Galaxies

- Off set attributed to outflowing winds. Winds appear present in all galaxies (e.g. Steidel+10, arxiv 1003.).

$\langle \Delta v \rangle = 650 \text{ km s}^{-1}$

Absorption by metals

Lya scattered from backside

Shapley+03
Lyα From the First Galaxies

• Off set attributed to outflowing winds. Winds appear present in all high-z galaxies (e.g. Steidel+10, arxiv 1003.0679). Outflows Doppler boost Lya photons out of resonance, and as a result, escapes more easily.

• Observations of local starburst galaxies indicate that Lya escape fraction strongly regulated by outflows (more so than dust!, Kunth+98, Atek+08).
Lyα From the First Galaxies

- Lyα line shape in observed galaxies (z=0-5) can be reproduced using spherical shells of outflowing HI gas, with column density $N_{HI}$ and outflow speed $v_{shell}$.
  
  (see Verhamme+08, Schaerer & Verhamme+08, Vanzella+10.)

'Backscattering' transforms originally Gaussian emission line into a redshifted (few hundred km/s) Lyα emission line. There can be flux at $|v| > 1000$ km/s.
Lyα From the First Galaxies

- Observations at $z<6$ typically require $\log N_{\text{H}_1} = 19-22$ and $v_{\text{shell}}=0-500$ km/s (Verhamme+08).

- Compute Lyα spectrum emerging from Lyα source surrounded by spherical shell with column density $\log N_{\text{H}_1} = 20-21$ and outflow speed $v_{\text{shell}}=0-200$ km/s. We used the MC RT code ‘McHammer’ (D et al ‘06). **Assume no dust.**

- Compute what fraction is transmitted through neutral IGM.

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**Example:**

$z=10$, $v_{\text{shell}}=200$ km/s, $\log N_{\text{H}_1} = 20$
Lyα From the First Galaxies

• Observations at z<6 typically require log N_{HI} = 19-22 and v_{shell}=0-500 km/s (Verhamme+08).

• Compute Lyα spectrum emerging from Lyα source surrounded by spherical shell with column density log N_{HI} = 20-21 and outflow speed v_{shell}=0-200 km/s. We used the MC RT code ‘McHammer’ (D et al ‘06). Assume no dust.

• Compute what fraction is transmitted through neutral IGM.

Example:
- z=10, v_{shell}=200 km/s,
- log N_{HI} = 20

4% directly transmitted to observer.
Lyα From the First Galaxies

- Directly transmitted fraction $f_{\text{trans}}$ as a function of $N_{\text{HI}}$ and $v_{\text{shell}}$.

\[ f_{\text{trans}} = 3\% \]

$z = 10$

$N_{\text{HI}} = 10^{20}$ cm$^{-2}$

$N_{\text{HI}} = 10^{21}$ cm$^{-2}$

MD & Wyithe, in prep
Lyα From the First Galaxies

- Consider a suite of models with different $N_{\text{HI}}$ and $v_{\text{shell}}$. 

![Graph showing transmitted fraction vs. $v_{\text{sh}}$ at $z=15$]

$\text{f}_{\text{trans}} = 3\%$

MD & Wyithe, in prep
Lyα From the First Galaxies

• It may be possible to directly transmit $f_{\text{trans}} > 3\%$ of Lyα flux directly to observer through fully neutral IGM at $z=10-15$ (without HII `bubbles'!).

• Translates to observed restframe EW\~45($f_{\text{trans}}/0.03)(EW_{\text{int}}/1500)$ A -> Strong LAEs.

• Lyα provides opportunity for spectroscopic confirmation.
  
  − E.g. SFR\~1M$_{\odot}$/yr, -> Lya luminosity \~1e43 erg/s. The flux at $z=10$ S\~2e-19($f_{\text{trans}}/0.03$) erg/s/cm$^2$, while continuum flux density at \~1216+ is \~3 nJy.
  − Line flux: NIRSPEC, R=1000, integration time 1e5 s, S/N \~3
  − Continuum NIRCAM wide filter, same integration time, S/N\~2.
LAEs During (and after) the EoR

- Outflows affect the detectability of LAEs during and even after reionization.

- Without outflows, even the ionized IGM can be quite opaque to Lya.
The Opacity of Ionized IGM to Lyα photons.

- Infall of denser intergalactic gas \((r>r_{\text{vir}})\) onto massive DM halos can strongly suppress observed Lya flux.

- IGM transmits 10-30% of emitted flux (D, Lidz & Wyithe +07, also see Iliev+08, Dayal+10, Zheng+10).
The Opacity of Ionized IGM to Lyα photons.

- Outflows shift ‘intrinsic’ line to frequencies where ionized IGM has smaller impact.

- I.e. because of outflows in ISM, subsequent transfer in IGM is uncertain.
What do LAEs Presently say on the EoR?

- Observed number density of LAEs drops suddenly beyond $z=6$?

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Log (Lyα Luminosity)

- 89 LAEs observed at $z=5.7$ (Shimasaku+06, blue squares),
- 57 LAEs observed at $z=6.5$ (Kashikawa+06, red circles)

Restframe UV LF remains constant!
What do LAEs Presently say on the EoR?

• Why does observed number density of LAEs drops suddenly beyond z=6?

For galaxies of a given restframe UV flux density, their corresponding measured Lya flux from galaxies at z=6.5 is lower than at z=5.7 (Kashikawa+06).

• Additional opacity in IGM at z=6.5 provides natural explanation. Opacity evolution may be attributed to reionization (Haiman & Wyithe ‘07).

To be continued.....
Conclusions

- The first galaxies were strong Ly$\alpha$ emitters (LAEs). Restframe EW~ 1500 A. Ly$\alpha$ luminosity can be 20% of bolometric luminosity.

- Outflows may cause a few percent or more of the emitted Ly$\alpha$ radiation can be observed from galaxies at z$>>$6 to be detected even through a fully neutral IGM.

- Only a few per cent transmission may facilitate the detection/spectroscopic confirmation of z $>>$ 6 galaxies.

- Understanding outflows and their impact on Lya is crucial when assessing the impact of IGM (as well as of dust) on Lya emission line.

- Lya line shape alone not enough to observationally constrain outflow properties. Polarization provides additional constraints (D & Loeb ‘08, Ahn & Lee ‘98).
Appendix
III: Polarization of Scattered Lya

- Scattered photons can appear polarized to an observer (electric vectors of photons have some preferred directions).
- Consider photon whose path is indicated with
III: Polarization of Scattered Lya

- Scattered photons can appear polarized to an observer (electric vectors of photons have some preferred directions).

- Lya scattering can in practise be described accurately by Rayleigh scattering, for which scattering by $\theta$ deg, results in $100\left[\sin^2 \theta / (1+\cos^2 \theta)\right]$ % polarization.
III: Polarization of Scattered Lya

- Compute polarization of backscattered Lya radiation using a Monte-Carlo radiative transfer code (D & Loeb ‘08, also see Lee & Ahn ‘98). In this code:
  - the trajectories of individual photons are simulated as they scatter off H atoms (microphysics of scattering is accurate)
  - can attach a polarization vector to each photon, and
  - compute observed quantities such as the Lya spectrum, surface brightness profile, and the polarization

- Polarization quantified as $P=|I_l-I_r|/(I_l+I_r)$. Single photon contributes $\cos^2\chi$ to $I_l$ and $\sin^2\chi$ to $I_r$ (Rybicki & Loeb 99).

- Apply Monte-Carlo code to a central Lya emitting source, completely surrounded by a thin, single, expanding shell of HI gas (as in Verhamme+06,08). Free parameters are $N_{HI}$ and $v_{exp}$. 
III: Polarization of Scattered Lya

- Lya can reach high levels of polarization (~40%, D & Loeb ’08)
- Polarization depends on $N_{\text{HI}}$ and $v_{\text{sh}}$, and therefore provides additional constraints on scattering medium (frequency dependence of polarization also constrains sign of $v_{\text{sh}}$, see D & Loeb ‘08).
This mechanism is affected by dust, but not eliminated.

- Photons that are most effectively trapped interior to the shell scatter mostly on the surface and ‘see’ little dust.
Discussion.

- This mechanism is affected when the covering factor of HI gas is $<< 100\%$ and/or by clumpiness of the outflow.
Introduction: Lyα from Collisions

- Lyα: n=2->n=1 (groundstate) transition of atomic hydrogen λ=1216 Å; ΔE = 10.2 eV ~1e5 K.
- Collisional excitation following `impact' by electron.
- Collisional excitation rate depends on $n_e$, $n_{HI}$, and T, and must be computed quantum mechanically (e.g. Scholz+91, Aggarwal+91)
- Very important in partially neutral gas (> 1 part neutral in $10^3$ !) at T > 1e4 K.
Introduction: Equivalent Width

Observationally, galaxy is ‘Lyman Alpha Emitter’ if restframe EW \(\geq 20\) \(\text{Å}\).

\[ \text{EW} \sim 0.5 \times \text{FWHM} \times \frac{f_{\text{peak},\nu}}{f_{\text{cont},\nu}}. \]

FWHM \sim 1-2 \text{ Å}, EW \sim 20-400 \text{ Å}. Line flux density \sim 10 -100 \text{ cont. flux density}
Introduction: Ly$\alpha$ from recombination.

- Radiative cascades following recombination into H level n,l

\[
P(\text{create Ly} \alpha | \text{recombination}) \sim 0.6-0.7
\]

\[
\begin{array}{cccccc}
1 & 2 & 3 & 4 & 5 \\
0 & 0 & 1 & 0.58 & 0.47 \\
1 & - & 1 & 0 & 0.06 & 0.08 \\
2 & - & - & 1 & 0.74 & 0.67 \\
3 & - & - & - & 1 & 0.91 \\
4 & - & - & - & - & 1 \\
\end{array}
\]
Introduction: Ly$\alpha$ from recombination.

- Star forming galaxies can emit a substantial fraction (~10%) of their bolometric luminosity in the Lyman Alpha line.

Partridge & Peebles '67
Introduction: Radiative Transfer in 1 slide

- Following absorption - reemission occurs instantly -> ‘scattering’.

- As Ly\(\alpha\) scatters through real space, it **diffuses** in frequency space. Further from line center, Ly\(\alpha\) photons escape easier from very opaque media.

\[ \Delta v = \pm 160 \left( \frac{N_{\text{HI}}}{1e20} \right)^{1/3} \left( \frac{T}{1e4} \right)^{1/6} \text{ km/s} \]
Ly$\alpha$ From the First Galaxies

HI Outflows

$\Delta v \sim H\Delta r$
Observations imply we receive ~ 10-80% (~95% CL) less Lya photons per restframe UV continuum photon from z=6.5 compared to z=5.7 (D, Wyithe & Haiman+07).

Why?

- Evolution in $f_{\text{esc}}$? (Because Llya $\sim [1-f_{\text{esc}}]$).
- Dust?
- Both These effects involve a detailed understanding of galaxies at $z>5.5$.
- Less Lya is transmitted through IGM?

Gas densities evolve as $(1+z)^3$; $n_{\text{HI}}(1+z)^6$. (Re)ionized gas can be significantly more opaque at $z=6.5$ than at $z=5.7$.

But ionized IGM less relevant when winds are strong. Require neutral patches of IGM??
Dust quenches Lya flux from galaxies.

Shapley+03

Verhamme+08
But no one-to-one relation between dust content and Lya escape fraction.

Dusty galaxies can be strong Lya emitters (Ono+10, arxiv 0911.2544).

Blue galaxies can emit no Lya at all (Kunth+98).

`We …find that the velocity structure of the neutral gas in these galaxies is the driving factor that determines the detectability of Lyalpha in emission.’

Galaxies become bluer towards higher redshift, which implies dust attenuation is less important (Bouwens+10)