Radiative transfer modeling of Lyα emitters during the epoch of reionization

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Lyα fraction

\[ X_{\text{Ly} \alpha} = \text{Fraction of continuum-selected galaxies with Ly} \alpha \text{ emission above given EW threshold} \]

Observations show \( X_{\text{Ly} \alpha} \) drops rapidly from \( z \approx 6 \) to 7

(Fontana+10, Stark+10, Pentericci+11, Ono+12, Schenker+12, Caruana+14, Schmidt+16, Dan. Stark & Mark Dijkstra talks)

Luminosity-dependent effect

Ono+2012
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Signature of reionization or intrinsic galaxy evolution (or both)?

Luminosity-dependent effect

Ono+2012
What can cause the reduction in Ly$\alpha$ flux?

Intrinsic Ly$\alpha$ emission (before IGM attenuation) itself is possibly reduced towards high-z due to:

- Evolution of dust distribution in galaxies (Dayal & Ferrara 2012)
- $f_{\text{esc}}$ increases towards high-z (e.g. Kuhlen & Faucher-Giguere 2012)

but Ly$\alpha$ LF evolves more rapidly than UV LF
What can cause the reduction in Ly\(\alpha\) flux?

IGM Ly\(\alpha\) opacity increases during epoch of reionization because:

- **Global HI fraction increases in diffuse IGM ('bubble' models)**
  Requires \(\Delta x_{\text{HI}} \sim 0.5\) over \(\Delta z \sim 1\) or \(\Delta t \sim 200\) Myr (e.g. Dijkstra 2014)

- **Abundance of self-shielded absorbers increases due to rapid evolution of ionizing background ('web' models)**

  Can reproduce \(X_{\text{Ly}\alpha}\) evolution (Bolton & Haehnelt 2013) but abundances may have been overestimated (Mesinger+14)

- **Both of the above ('web-bubble' models): Mesinger+14, Kakiichi+2016**

Pentericci+2014
What can cause the reduction in Lyα flux?

• Possible alternative we want to test:

  CGM gas around galaxies can become optically thick to Lyα if it can self-shield against the rapidly evolving external ionizing background

• We construct radiative transfer models of Lyα emitting galaxies (LAEs) which include:
  - Analytical description of gaseous environment (density+velocity) around typical high-z LAE
  - Self-shielding calculations to get corresponding neutral gas distribution for given ionizing background level
  - Full 3D radiative transfer calculations to predict Lyα properties
LAE model: total gas density

NFW Halo (replaced with constant density core at $r < r_{\text{core}}$) + IGM density profile around collapsed structures from Barkana 2004

Model Parameters: $M_{\text{halo}}, r_{\text{core}}$
LAE model: gas velocity

$V_{\text{tot}}$ [km s$^{-1}$]

$M_{\text{halo}} = 10^{10.5} M_\odot$

Dispersion dominated region (DM halo) + Infall region (CGM) + Hubble-flow dominated region (IGM)

$0 < r < r_{\text{core}}$

$0 < r < r_{\text{vir}}$

$r_{\text{vir}} < r < r_{\text{infall}}$

$r > r_{\text{infall}}$
We solve photoionization equilibrium with

$$\Gamma_{\text{LAE,ss}}(r) = \int_{\nu_L}^{\infty} \frac{f_{\text{esc}} L_{\nu} e^{-\tau_{\nu,\text{cen}}}}{4\pi r^2 h\nu} a_{\nu} d\nu + \Gamma_{\text{UV,ss}} = \int_{4\pi} d\Omega \int_{\nu_L}^{\infty} \frac{I_{\nu} e^{-\tau_{\nu,\text{out}}}}{h\nu} a_{\nu} d\nu$$

$$(L_{\nu} \propto \text{SFR} \propto M_{\text{halo}})$$
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\]

\((L_{\nu} \propto \text{SFR} \propto M_{\text{halo}})\)
Monte-Carlo Ly\(\alpha\) radiative transfer

Parallel version of Monte-Carlo Ly\(\alpha\) RT code from Zheng & Miralda-Escude (2002)

1. Photons are launched from center of cloud with initial frequency \(\nu_i = \nu_{\text{Ly}\alpha}\)
2. Choose random propagation direction, draw \(\tau\) from \(\exp(-\tau)\) distribution and find scattering location corresponding to \(\tau\) along chosen direction
3. Calculate new \(\nu\) after scattering
4. Repeat 2-3 until photons escape gas cloud

Number of photons used for each individual RT calculations = \(10^5\)
Predicted Ly$\alpha$ spectra

**Full spectra** (all photons)

$\Delta v$ [km s$^{-1}$]

\[ F_\lambda [10^{-20} \text{ erg s/cm}^2/\text{Å}] \]

- dashed, intrinsic
- black, at $r_h$
- blue, at $10r_h$

$\Delta \lambda_{\text{obs}}$ [Å]

**Effect of finite aperture size** (photons within 1"

$\Delta v$ [km s$^{-1}$]

\[ F_\lambda [10^{-20} \text{ erg s/cm}^2/\text{Å}] \]

- green, $\Gamma_{\text{UV}} = 10^{-13}$ s$^{-1}$
- blue, $\Gamma_{\text{UV}} = 10^{-14}$ s$^{-1}$

Sadoun, Zheng & Miralda-Escudé (1607.08247)

Fiducial RT model: $M_{\text{halo}}=10^{10.5}M_\odot$, $r_{\text{core}}=0.25r_{\text{vir}}$, $f_{\text{esc}}=0.1$
**Predicted Lyα spectra**

**Full spectra**
(all photons)

- **Δλ [Å]**
- **F_λ [10^-20 erg/s/cm^2/Å]**

- **intrinsic**
- **at r_h**
- **at 10 r_h**

**Observed spectra**
(Red peak + Photons within 1")

- **Γ_{UV} = 10^{-13} s^{-1}**
- **Γ_{UV} = 10^{-14} s^{-1}**

We find significant apparent flux reduction in the red peak within typical 1" aperture.
Self-shielded neutral infall region causes additional spatial diffusion which flattens SB profile.
Lyα flux ratios: dependence on halo mass

(Weak) dependence of flux ratio on halo mass can potentially explain luminosity-dependent effect in observed Lyα fraction evolution
Predictions for the Ly$\alpha$ fraction evolution

\[ X_{\text{Ly}\alpha} = \int_{\text{EW}_t} p(\text{EW}) d\text{EW} \]

Sadoun, Zheng & Miralda-Escudé (1607.08247)

$p(\text{EW})_{z=6}$ based on observed $p(\text{EW})$ of LBGs at $z \sim 3$ (Shapley+2003)

$p(\text{EW})_{z=7} = p(\text{EW}/f)_{z=6}$ where $f$ is the Ly$\alpha$ flux ratio predicted by the RT model for a given change in $\Gamma_{\text{UV}}$
Modeling LAEs in cosmological reionization simulations

AMR reionization simulations (RadHydro) from Trac, Cen & Mansfield 2015
Modeling LAEs in cosmological reionization simulations

The simulation reproduces well the:

**UV LFs of LBGS and LAES**

The figure shows a graph of the UV luminosity function (UV LF) with data points and error bars for various models, including model predictions and observations. The x-axis represents the UV magnitude ($M_{UV}$), and the y-axis represents the UV luminosity density ($\dot{L}_{UV}$) in units of $\text{mag}^{-1} \text{Mpc}^{-3}$.

**Global reionization history**

The graph on the right shows the reionization history with different models and data points. The x-axis represents redshift (z), and the y-axis represents the parameter $1 - Q_{HI}$, indicating the fraction of ionized hydrogen. The models include ML + 68% Credibility Interval, Robertson et al. 2013, Forced Match to WMAP $\tau$. Additional data points and markers are also shown for different astronomical phenomena such as Ly-$\alpha$ transmission, dark Ly-$\alpha$ forest pixels, quasar near zone, GRB damping wing absorption, Ly-$\alpha$ emitters, Ly-$\alpha$ galaxy clustering, and Ly-$\alpha$ emission fraction.
Modeling LAEs in cosmological reionization simulations

Evolution of the Ly$\alpha$ luminosity function

Sadoun, Zheng, Trac & Cen (in prep.)
Modeling LAEs in cosmological reionization simulations

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Evolution of the Ly$\alpha$ luminosity function

Rapid evolution of the Ly$\alpha$ LF between $z\sim5.7$ and $z\sim6.6$ predicted by the model in tension with observed evolution.

Possible cause: reionization topology more complicated than the simulation can capture?

Sadoun, Zheng, Trac & Cen (in prep.)
Summary

• We quantified the reduction in Ly$\alpha$ flux caused by self-shielding of the CGM gas around LAEs at z~6-7 as a response of the rapidly evolving UV background

• We find that the self-shielded gas becomes optically thick to Ly$\alpha$ at z~7 which induces a flattening of the Ly$\alpha$ SB profile and a factor of ~1.5-2 reduction in Ly$\alpha$ flux within 1''

• The model can reproduce well the observed Ly$\alpha$ fraction evolution at different UV luminosities and Ly$\alpha$ EW detection thresholds

• Caveats: Unable to constraint $\Gamma_{UV}$ evolution because of large observational error bars, no clumping considered, idealized isotropic gas distributions

• Currently working on modeling LAEs in cosmological reionization simulations...stay tuned!
Thanks!
Model uncertainties: effect on neutral gas distribution

$r_{\text{core}} = 0.5 \ r_h$

$f_{\text{esc}} = 0.2$

$\Gamma_{\text{LAE}} = 0$

$n_{\text{HI}} \ [\text{cm}^{-3}]$

$r \ [\text{physical kpc}]$

$\Gamma_{\text{UV}} = 10^{-14} \ \text{s}^{-1}$

$\Gamma_{\text{UV}} = 10^{-13} \ \text{s}^{-1}$
Model uncertainties: effect on Lyα line profile

within 1''
Model uncertainties: effect on Ly$\alpha$ fraction

$X_{\text{Ly}\alpha}$ vs $z$

- **EW > 55 Å**
- **$M_{\text{UV}} > -20.25$**

- **Fiducial**
- **$r_{\text{core}} = 0.5 \, r_h$**
- **$f_{\text{esc}} = 0.2$**
- **$\Gamma_{\text{LAE}} = 0$**

**Data Sources:**
- Ono+2012
- Stark+2011
- Schenker+2012
- Treu+2013
- Schenker+2014

**Definition:**
- $V_0 = V > 20.25$