A Faint Flux-Limited LAE Sample at z = 0.3

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Using LAEs to Study the Evolving Properties of Star-forming Galaxies

• A non-exhaustive figure demonstrating the large populations of LAEs identified over a wide redshift range.

• To understand what types of galaxies are selected in LAE surveys – and how this evolves with redshift – it is important to establish a low-redshift sample that can be directly compared to high-redshift samples.
Using LAEs to Study the Evolving Properties of Star-forming Galaxies

High-redshift objects are selected based on their strong Lyα emission.

Narrow Band Lyα Filters:
High-redshift objects are selected based on their strong Lyα emission.

No z=0 LAE survey instrument exists.

Typically z=0 LAEs are pre-selected from likely candidates and then followed up with HST.

z=0 LAE studies have provided insight into the physical conditions that facilitate strong Lyα emission.
GALEX: low-redshift (z=0.3) LAE survey instrument

Galaxy Evolution Explorer (GALEX)

- 1.2 deg diameter FOV
- FUV (~1500A) and NUV (~2300A) bands
- imaging or grism data
- imaging resolution of ~5”
- spectral resolution of 10A in FUV and 25A in NUV
High-redshift objects are selected based on their strong Ly$\alpha$ emission.

No z=0 LAE survey instrument exists.

Typically z=0 LAEs are pre-selected from likely candidates and then followed up with HST.

The existing z=0.3 sample is selected from the standard GALEX pipeline reductions which only extract objects with a bright continuum.
The limitations of the GALEX pipeline
The limitations of the current *GALEX* sample

![Graph showing the relationship between log \(f_{\text{Ly}\alpha}\) (erg cm\(^{-2}\) s\(^{-1}\)) and NUV magnitude (AB). The data points are indicated by red squares labeled "*GALEX pipeline.""

Using the GALEX sample to anchor LAE evolution

1. Ly\(\alpha\) EW distribution:

![Graph showing Ly\(\alpha\) EW distribution versus redshift.](image)

   - Blue Fill: IGM-corr. on Ly\(\alpha\)
   - Red Empty: No IGM-corr. on Ly\(\alpha\)

   \[ W_{\alpha} = 7.3 \times (1+z)^{1.356} \]
   \[ W_{\alpha} = 14.0 \times (1+z)^{1.159} \]

   Hayes et al. 2011
   see also:
   Ciardullo et al. 2012

2. Ly\(\alpha\) escape fraction:

![Graph showing Ly\(\alpha\) escape fraction versus redshift.](image)

   Hayes et al. 2011
   see also:
   Blanc et al. 2011
   Wold et al. 2014
   Konno et al. 2016
Evolution of LAE properties: EW distribution scale length

\[
EW = \frac{f_{Ly\alpha}}{f_{\lambda, \text{cont}}(1+z)}
\]

\[
N \propto e^{-EW/(\text{scale length})}
\]

scale length = 23.7 ± 2.2 Å

Cowie et al. 2010
Using the GALEX sample to anchor LAE evolution

1. Lyα EW distribution:

![Graph showing Lyα EW distribution with data points and fits.](image)

Zheng et al. 2014
see also:
Ciardullo et al. 2012

2. Lyα escape fraction:

![Graph showing Lyα escape fraction with data points and a fit.](image)

Hayes et al. 2011
see also:
Blanc et al. 2011
Wold et al. 2014
Konno et al. 2016
Evolution of the volumetric Lyα escape fraction
(the fraction of Lyα photons that escape from the survey volume)

\[ f_{esc}(\text{Ly} \alpha) = \frac{\rho_{\text{Ly} \alpha}^{\text{obs}}}{\rho_{\text{Ly} \alpha}^{\text{int}}} \]

\[ \rho_{\text{Ly} \alpha}^{\text{obs}} = \int L \phi(L) dL \]

\[ \rho_{\text{Ly} \alpha}^{\text{int}} = \rho_{SFR} \times 8.7 \times (1.26 \times 10^{41}) \]

\[ L_{\text{Ly} \alpha} = 8.7 L_{H \alpha} \]

(case B recombination)

\[ SFR = L_{H \alpha} / (1.26 \times 10^{41}) \]

(Kennicutt 1998)

Assumes: Case B recombination, Calzetti dust attenuation,
Salpeter IMF, and continuous SFH
Evolution of the volumetric Lyα escape fraction
(the fraction of Lyα photons that escape from the survey volume)

Hayes et al. 2011

- Compiling data from many Lyα surveys, there is evidence for a rapidly increasing Lyα escape fraction.

- The decline at z=7 may indicate the increasing opacity of the IGM and the onset of reionization.
Evolution of LAE properties: A consistent picture?

1. Lyα EW scale length:

   ![EW distribution scale length vs. Redshift graph]

   - Blue Fill: IGM-corr. on Lyα
   - Red Empty: No IGM-corr. on Lyα

   \[ W_\text{L} = 7.3 \times (1+z)^{1.756.1} \]
   \[ W_\text{L} = 14.0 \times (1+z)^{1.159} \]

   Zheng et al. 2014
   see also:
   Ciardullo et al. 2012

2. Lyα escape fraction:

   ![f_esc(Lyα) vs. redshift graph]

   Hayes et al. 2011
   see also:
   Blanc et al. 2011
   Wold et al. 2014
   Konno et al. 2016
Baseline model for LAEs

• In star-forming galaxies massive stars produce ionizing radiation.

• Much of this ionizing radiation is reprocessed as Lya emission via the recombination of hydrogen

• Lyα photons are resonantly scattered by neutral hydrogen until they escape or are absorbed by dust

\[ E\!W^{L_y\alpha}_{\text{obs}} (\text{extinction, scattering, SFH}) \]
Evolution of LAE properties: A consistent picture?

1. Lyα EW scale length:

![EW scale length graph]

\[ W_e = 14.0 \times (1+z)^{1.156} \]

Zheng et al. 2014
see also:
Ciardullo et al. 2012

2. Lyα escape fraction:

![Escape fraction graph]

Hayes et al. 2011
see also:
Blanc et al. 2011
Wold et al. 2014
Konno et al. 2016

Evidence for increasing dust content and/or neutral column density at lower redshifts?
The limitations of the GALEX pipeline

![Graph showing the relationship between NUV magnitude and log of Lyα flux.]
Data cube $z=0.3$ LAE survey of CDFS, GROTH, NGPDWS, and COSMOS

- Total survey area of 7400 arcmin$^2$ from $z=0.195$ – 0.44
- Total survey volume of $10^6$ Mpc$^3$
- 173 candidate LAEs
- 97% with optical spectroscopic data
- 16% are false detections with $z_{UV} \neq z_{OPT}$
- Deep X-ray imaging ($10^{41}$ erg s$^{-1}$) is available for 49% of the survey area.
Example LAEs with corresponding optical spectra
Classify LAEs as AGN or star-formation dominated

- 24% of the LAEs are AGN
- 13 Broad-line AGN (not shown in figure)
- 6 objects with no clear AGN / SF classification.
The GALEX data cube sample

![Graph showing the relationship between log f_{Ly} (erg cm^{-2} s^{-1}) and NUV magnitude (AB).]
The GALEX data cube sample

- **84 LAEs**
- **25 LAEs**

![Graph](image)

- **GALEX pipeline**
- **GALEX data cube**

Data cube sample
- 84 LAEs
Pipeline sample
- 25 LAEs
The advantages of the data cube sample

1. Our new sample doubles the size of star-forming *GALEX* LAEs at $z=0.3$. We find 84 SF LAEs in 4 *GALEX* fields. Cowie et al. found 41 SF LAEs by examining the pipeline spectra in 9 *GALEX* fields.

2. We obtain a low-redshift sample that is not biased against high-EW LAEs. This sample can be directly compared to high-redshift LAE samples.

3. Many of the same conditions that facilitate the escape of Ly$\alpha$ photons may also facilitate the escape of ionizing radiation. Thus, extreme EW LAEs may be efficient emitters of ionizing photons and potential analogs of reionization-era galaxies. We note that the pipeline sample contains no SF LAE with an EW larger than 120Å. With our data cube sample we find a total of 17 extreme EW LAEs.
Using the GALEX sample to anchor LAE evolution

1. Ly\(\alpha\) EW distribution:

   ![EW distribution plot]

   - Blue Fill: IGM-corr. on Ly\(\alpha\)
   - Red Empty: No IGM-corr. on Ly\(\alpha\)

   - \(W_\nu = 7.3 \times (1+z)^{1.73\pm0.1}\)
   - \(W_\nu = 14.0 \times (1+z)^{1.15\pm0.1}\)

   - Zheng et al. 2014
   - see also: Ciardullo et al. 2012

2. Ly\(\alpha\) escape fraction:

   ![Escape fraction plot]

   - \(f_{\text{esc}}(\text{Ly}\alpha)\)

   - Hayes et al. 2011
   - see also: Blanc et al. 2011
   - Wold et al. 2014
   - Konno et al. 2016
Evolution of LAE properties: EW distribution scale length

\[ N \propto e^{-\frac{EW}{(\text{scale length})}} \]
Evolution of LAE properties: EW distribution scale length

$z = 1.9 - 3.8$ Blanc et al. 2011

$z = 0.67 - 1.16$ Wold et al. 2014

$z = 2.1, 3.1$ Ciardullo et al. 2012

$z = 2.25$ Nilsson et al. 2011

$z = 0.195 - 0.44$ This study
Using the GALEX sample to anchor LAE evolution

1. Lyα EW distribution:
   - 
   ![Graph showing Lyα EW distribution](image)
   - Zheng et al. 2014
   - see also:
     - Ciardullo et al. 2012

2. Lyα escape fraction:
   - 
   ![Graph showing Lyα escape fraction](image)
   - Hayes et al. 2011
   - see also:
     - Blanc et al. 2011
     - Wold et al. 2014
     - Konno et al. 2016
Evolution of the volumetric Lyα escape fraction
(the fraction of Lyα photons that escape from the survey volume)

Why are there two data points for the escape fraction?

Two groups independently computed the $z=0.3$ Lyα luminosity function from same GALEX pipeline dataset and applied very different corrections for incompleteness.

\[
\frac{f_{\text{esc}}(\text{Ly}\alpha)}{\rho_{\text{Ly}\alpha}^\text{obs}} = \frac{\rho_{\text{Ly}\alpha}^\text{int}}{\rho_{\text{Ly}\alpha}^\text{obs}} \\
\rho_{\text{Ly}\alpha}^\text{obs} = \int L\phi(L)dL
\]
The $z=0.3$ Ly$\alpha$ luminosity function

![Graph showing the Ly$\alpha$ luminosity function with data points from Deharveng et al. 2008 and Cowie et al. 2010.](image)
Evolution of the volumetric Lyα escape fraction
(the fraction of Lyα photons that escape from the survey volume)

\[ f_{\text{esc}}(\text{Ly}\alpha) = \frac{\rho_{\text{Ly}\alpha}^{\text{obs}}}{\rho_{\text{Ly}\alpha}^{\text{int}}} \]

\[ \rho_{\text{Ly}\alpha}^{\text{obs}} = \int L\phi(L) dL \]

\[ \rho_{\text{Ly}\alpha}^{\text{int}} = \rho_{\text{SFR}}(8.7)(1.26 \times 10^{41}) \]

\[ \rho_{\text{Ly}\alpha}^{\text{int}} = \rho_{\text{H}\alpha}(8.7) \]

Assumes: Case B recombination, Calzetti dust attenuation,
Salpeter IMF, and continuous SFH
The $\text{H}\alpha$ luminosity functions

Self-consistently measured $\text{H}\alpha$ luminosity functions are now available out to a redshift of 2.23.

\[
f_{\text{esc}}(\text{Ly}\alpha) = \frac{\rho_{\text{Ly}\alpha}^{\text{obs}}}{\rho_{\text{Ly}\alpha}^{\text{int}}}
\]

Sobral et al. 2013
Evolution of the volumetric Lyα escape fraction
(the fraction of Lyα photons that escape from the survey volume)

\[ f_{esc}(Ly\alpha) \sim \frac{\rho_{Ly\alpha}^{obs}}{\rho_{H\alpha}} \]
Evolution of LAE properties: A consistent picture?

1. **Lyα EW scale length:**

   - Zheng et al. 2014

   ![Graph showing EW scale length vs. redshift](image1)

   - \( W_\alpha = 7.3 \times (1+z)^{1.25} \)
   - \( W_\alpha = 14.0 \times (1+z)^{1.15} \)

2. **Lyα escape fraction:**

   - Hayes et al. 2011

   ![Graph showing escape fraction vs. redshift](image2)

   - \( f_{esc}(Ly\alpha) \sim \rho_{Ly\alpha}^{obs}/\rho_{H\alpha} \)
FUV LAE summary

1. The sample size of known star forming GALEX LAEs at z=0.3 has been doubled.

2. Larger flux-limited sample has allowed for a better determination of the EW distribution, LF, and volumetric Lyα escape fraction.

3. The dramatic decline previously suggested in the Lyα EW distribution scale length and volumetric Lyα escape fraction from z=2.2 to 0.3 may be largely due to selection effects. The evolution of these parameters does not provide convincing evidence for increasing dust content or neutral column density at lower redshifts.

4. Larger LAE surveys are needed to further constrain the evolution of these quantities. The limited facilities in the ultraviolet prevent significant improvement below z=2. However, the HETDEX survey which will detect close to one million LAEs will help to resolve whether these quantities evolve from z=2 to 3.5.