Faint Lyman Alpha Emission at $z \sim 3$

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LCO data:
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Use Lyman alpha emission as a tool to study high z structure formation

Multiple sources of Lyman alpha:

- AGN
- star-formation
- radiative shocks (mergers, wind shells)
- cooling radiation (gas accretion)
- Lya fluorescence (UV sources irradiate IGM)
Our knowledge of the early universe is limited to the bright end of everything.
Motivation for a really deep survey for Lyα emission

(1) probe faint galaxy populations

can we observe the (hidden?) majority of z~3 galaxies in emission?

what are the hosts of damped Lyα systems?

is there a true faint end to the luminosity function?
Study gas physics of high $z$ galaxy formation

How do galaxies accrete matter from the IGM?
- cold / warm / hot gaseous accretion
- gas dynamics of mergers

How do galaxies return matter and radiation to the IGM?
- nature and extent of galactic outflows
- escape of line/ionizing radiation from galaxies
Prior evidence for a largely hidden population of high redshift galaxies from Damped Lyman Alpha Systems:

- First known population of high redshift galaxies
- Main reservoir of neutral hydrogen
- Low metallicity ($z \sim 1/10 - 1/100$ solar)
- Mostly very little dust
- Surface density of any extended star formation very low
- Gas kinematics consistent with groups of CDM dwarf halos
The few existing detections of DLA hosts in emission:
- exceedingly faint
- very close to the QSO line of sight

Fynbo et al 1999; Moller et al 2004

DLA absorption trough

Ly alpha emission from DLA host

Q2209-199, z=1.9205
8h w. Magellan echelle, in prep.
Searches for DLA hosts tough because of proximity of QSO

Observing to sufficient depth, (star forming) DLA hosts should show up as numerous, faint Lyman alpha emitters

Narrow band (FWHM ~ 50 -100 A) imaging surveys for Lyalpha emitters generally too shallow to see such objects

Spectroscopic searches (FWHM ~ 5A) better able to suppress the sky background
strategies for blind spectroscopic searches:

1) Venetian Blind Spectroscopy:

multi-longslit mask + filter + disperser

w. Sargent, Simcoe & Burles

cf. Cantalupo et al 2005

Pro: sky suppression + (sparsely sampled) 2-D image

Con: difficult to ID object w. short spectra; cosmic variance
2) Single Long Slit Spectroscopy:

- **longslit mask + disperser**

**Pro**: highest sensitivity; long spectral coverage (helps to ID interlopers)

**Con**: lower dimensionality (essentially pencil-beam); “edge effects”
Accidental discoveries from a long-slit, blind spectroscopic survey for Lyman alpha fluorescence:

27 single line emitters, mostly without detectable continuum, over 4457 - 5776 Å. Fluxes a few $\times 10^{-18} \text{erg cm}^{-2} \text{s}^{-1}$; mean redshift 3.2

Rauch et al 2008
2-d spectra, 2” x 15” x 1510 km/s wide;
turquoise contour corresponds to
$1.5 \times 10^{-20} \text{ergs}^{-1} \text{cm}^{-2} \AA^{-1}$
About half of the Lyalpha emitters can be seen as individually extended, have compact core, wide, low SFB apron:

Stack shows median detectable SFB out to at least 4":

very large total cross section on the sky, suggestive of DLAS
Lyman alpha luminosity function probes uncharted territory:

detections within \( 5 \times 10^{-3} \, L_* < L_{\text{obs}} < 0.2 \, L_* \)

\[ \alpha \sim -2.2, \, L_* = 9.1 \times 10^{42} \, \text{erg s}^{-1} \]

for 2''x2'' aperture

luminosity function steeper than expected for modelling with constant Lya escape fraction:

escape fraction (extinction) simply may not be constant:

dust diminishing towards fainter objects?
\[ 7 \times 10^{-2} \, M_\odot \, \text{yr}^{-1} < \text{SF rate} < 1.5 \, M_\odot \, \text{yr}^{-1} \]

\[(2.67 < z < 3.75) \quad \frac{\partial^2 N}{\partial z \partial \Omega} = 98 \, \text{arcmin}^{-2} \]

- comoving density \[3 \times 10^{-2} \, \text{Mpc}^{-3}\]
- total masses \[> 3 \times 10^{10} \, M_\odot\]
- virial velocities \[v_c > 50 \, \text{km} \, \text{s}^{-1}\]

(Mo & White 2002, Wang et al 2007)
Do these emitters have the right luminosity to be drawn from the DLA host population?

Independent evidence comes from stacked spectra of DLAS from the SDSS.

Idea:
Search bottom of stacked DLA troughs for Lyman alpha emission within the 3” wide fiber centered on each QSO. Obtain average luminosity of DLA host.

(Rahmani et al 2010).
Tilted bottom of DLA trough exhibits Lya flux, very similar to the average flux of our Lya sample.

\[ L_{L \alpha} \approx L_{DLA} \]

(Rauch & Haehnelt 2011)

Asymmetric emission profile is expected for Lya emission from high z gals.

DLA hosts and faint Lyman alpha emitters have similar mean luminosities.
many similarities suggest an identification of the faint Lyalpha emitters with Damped Lyman alpha systems:

rate of incidence similar to DLAS (large HI extent, large comoving density of objects)

low star formation rate \((0.07 - 1.5 \, M_\odot \, yr^{-1})\) → low metallicity of DLAS

steep luminosity function - low dust contents of DLAS (?)

low mass and small size of SF region in Lya emitters consistent with upper limits on extended SF in DLAS Wolfe & Chen (2006).

average Lya luminosities of stacked DLAS very similar to faint Lya emitters

DLA hosts and Lyman alpha emitters can be reconciled with the same low mass DM halos (Barnes & Haehnelt 2009,2010)
Spectroscopy deep enough to probe gas dynamics of high redshift galaxies

Fundamental questions we may be able to address:

- How does gas get into galaxies?
- How do metals / ionizing radiation escape from galaxies?

(Work in progress)
spectral profile and surface brightness profile of Lyalpha encode information on:

gas column density (halo mass, density profile, degree of ionization)

kinematics (inflow vs. outflow)

spatial distribution of ionizing sources (star forming center vs. halo cooling)

central point source (e.g. galaxy) uniform emissivity (e.g., cooling rad.)
Most Lyalpha emitters have compact core, wide, low SFB halo, are symmetric in the spatial direction, relative to the continuum.

Four of the brightest of our objects:
Note small blue peak and dominant, anvil shaped red peak

Pattern suggests mild expansion of the gas and/or partial suppression of blue peak by intervening IGM absorption.

Not all emitters conform to this pattern, though ...
There are tensions between the clustering and number density of Lya emitters.

(Coone et al 2004)

Close pairs of Lybreak galaxies tend to be Ly alpha emitters.

(Cooke et al 2010)

The reason(s) for this behavior are unclear. Galaxy interactions may be a factor.
Interaction may trigger Lya emission, escape of ionizing photons

(a) undisturbed HI halo

(b) interaction with passing galaxy

- disturbed velocity field may open low opacity channel for Lya

- more violent disturbances of the gaseous halo may allow escape of ionizing radiation, too.
Sub-population of emitters apparently associated with tidal interaction:

\( z \approx 3.444 \) Lyman alpha emitting \( V \approx 27 \) galaxy

Lyman alpha emission line

Lyman alpha forest  |  DLA trough
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Lyman alpha emission line

Lyman alpha forest

DLA-trough

$1000 \text{ km/s}$

$6''$ slit

Rauch et al. 2011b
DLA sits in front of blueshifted, extragalactic gas --> Infall

infalling filament fluoresces in Lyalpha (double-humped profile!)

profile FWHM narrower than slit - filament ?
tilted towards continuum - accelerated infall ?

Detection of a cold accretion filament ? (or in-falling tidal gas?)
~50% of ionizing photons escape galaxy to hit blue infalling gas

stellar ionizing photons account for the entire Lya emission seen.

Rauch et al. 2011b
Escape of Lyalpha, ionizing radiation, apparently triggered by interaction. Mergers are more common at high redshift.

Is this how the universe gets reionized?
Another extended Lyman alpha halo at $z \sim 2.63$:

Again there is an extended (tidal?) smudge associated with a multi-galaxy Lyalpha emitting halo

enhanced cross-sections for Lya emission, and presumably for DLA

longslit spectrum (61h) w. LDSS3 in the HUDF
Protogalactic groups

complex and asymmetric in space and velocity.
Tidal features.
Escape of Lya (and LyC ? metals ?) triggered by interaction.

Lyman break galaxies

compact, symmetric wrt. continuum in the spatial direction.

what is the signature of outflows in Lya ?
“Protogalactic groups”

Space density: $\mathcal{O}(10^{-3}) \text{Mpc}^{-3}$

Fluxes: a few $\times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2}$

Sizes: tens of kpc
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High redshift analogues to this?

Intergalactic HI near M81/82; Chynoweth et al 2008
Conclusions

Blind spectroscopic surveys have uncovered a population of faint Ly alpha emitters with high space density, z~3.

Many common features, and theoretical models suggest that we have retrieved the host galaxies of DLAS in emission.

At z~3, studying the gasdynamics of galaxy formation becoming possible with low surface brightness Lyman alpha emission: kinematics, accretion (cold and otherwise), photon budget, mergers, outflows.

Interacting groups of protogalaxies key to a number of cosmic phenomena, including DLA cross-section and kinematics, the escape of Lya and ionizing radiation and probably, to the reionization of the universe.
Future:
(1) new deep Lya surveys in HDFN/HUDF
- identify underlying continuum sources
- study morphology, small scale clustering
- establish faint end luminosity functions
(2) target bright individual emitters:
- model emitter properties with radiative transfer codes
- search for evidence of accretion, winds
- understand the relation between the escape of Lya and ionizing radiation

spatially resolved spectroscopy inevitable:

2-D higher resolution spectroscopy of bright z~2.2 SXDS emitter with Magellan/MagE

3-D spectroscopy of SXDS bright z~3.1 emitter with Keck ESI-IFU