Shedding Light on the Properties of the Circum/Inter-galactic Gas in Emission around Quasars

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Defining the Circum/Inter-Galactic Gas...

Rosedahl & Blaizot 2012
Defining the Circum/Inter-Galactic Gas...

Virial Radius

QSO $z=2-3$

$M_{DM} \sim 10^{12.5} M_\odot$

$R_{\text{vir}} = 160$ kpc

Roslund & Blaizot 2012

White+2012
The CGM encodes Precious Information on Structure Formation

- Feedback?
- Cold flows?
- Amount of cold vs hot gas
- ....

R_{\text{vir}}

Rosdahl & Blaizot 2012

Nelson+2016

van de Voort+2011
Spectroscopic Absorption Studies @ $z \sim 2$

$M_{DM} \sim 10^{12.5} \, M_\odot$

$R_{vir} = 160 \, \text{kpc}$
A Large Reservoir of cold $T \sim 10^4$ K gas!

Prochaska, Hennawi, Simcoe, 2013

Background QSO

$M_{\text{DM}} \sim 10^{12.5} \, M_\odot$

$R_{\text{vir}} = 160$ kpc

$T \sim 10^4$ K

$M_{\text{gas}} > 10^{10} \, M_\odot$

Prochaska, Hennawi, Simcoe, 2013
A Large Reservoir of cold $T \sim 10^4$ K gas!

Prochaska, Hennawi, Simcoe, 2013

Background QSO

$M_{DM} \sim 10^{12.5} M_\odot$

$R_{vir} = 160$ kpc

Prochaska+2014
Fluorescent Ly$\alpha$ Emission

Zoom-in simulation (RAMSES) + RADAMESH (Cantalupo+ 2011)

$SB_{Ly\alpha}$ (cgs/arcsec$^2$)

Pseudocolor
Var: $SB_{fluor}$

1.0e-17
1.0e-18
1.0e-19
1.0e-20
1.0e-21

10 comoving Mpc

UVB+Stars
Fluorescent Lyα Emission

$SB_{\text{Ly}\alpha}$ (cgs/arcsec$^2$)

Pseudocolor
Var: SB$_{\text{fluor}}$

Zoom-in simulation (RAMSES) + RADAMESH (Cantalupo+ 2011)

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UVB+Stars

10 comoving Mpc
Fluorescent Lyα Emission

Zoom-in simulation (RAMSES) + RADAMESH (Cantalupo+ 2011)

SB_{Lyα} (cgs/arcsec^2)

UVB+Stars + QSO

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Fluorescent Lyα Emission

Image credit: S. Cantalupo

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Giant Lyα Nebulae

![Graph showing the projected maximum extent vs. Lyα luminosity for QSOs (radio-loud) and QSOs (radio-quiet).]

- **J2233-606** $z=2.238$
- **Q0730+257** $z=2.686$

Bergeron+1999

Heckman+1991

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Giant Ly$\alpha$ Nebulae

![Graph showing the projected maximum extent and Ly$\alpha$ luminosity for QSOs (radio-loud) and QSOs (radio-quiet), with LAB1 $z=3.1$ indicated.](image)

200 kpc

Steidel+2000, Matsuda+2004

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Giant Ly$\alpha$ Nebulae

4C 41.17 $z=3.8$

150 kpc

Reuland+2003, Miley&De Breuck2008

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Giant Lyα Nebulae

- UM287, z=2.279
- SDSSJ0841, z=2.04

Projected Maximum Extent [kpc]
- QSOs (radio-loud)
- QSOs (radio-quiet)
- Lyα "blob"
- Radio galaxies
- UM287
- SDSSJ0841

Hennawi+2015, Science
Cantalupo, FAB+2014, Nature

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Giant Lyα Nebulae

HS1549+19 \( z = 2.843 \)

\[ 160 \text{ kpc} \]

Martin+2014

\[ 630 \text{ kpc} \]

Cantalupo, FAB+2014, Nature

UM287 \( z = 2.279 \)

\[ 460 \text{ kpc} \]

SDSSJ0841 \( z = 2.04 \)

Hennawi+2015, Science
Continuum-subtracted NB image

Slug Nebula (UM287)

Cantalupo, FAB+2014, Nature

1' (500 kpc)

R_{vir}
Fluorescent Lyα Emission: 2 cases
(Hogan & Weymann 1987; Gould & Weinberg 1996; Cantalupo+2005)

a) Optically thin gas (fully ionized): emission proportional to gas density squared

a) Optically thick gas: behaves like a mirror, about 60% of incident ionizing radiation is converted in Lyα
Fluorescent Lyα Emission

Optically thin \( (\log N_{\text{HI}} << 17.2) \)

\[
SB_{Ly\alpha} \propto f_c n_H N_H
\]

\[
M_c = \pi R^2 f_c N_H \frac{m_p}{X}
\]

Optically thick \( (\log N_{\text{HI}} >> 17.2) \)

\[
SB_{Ly\alpha} \propto f_c L_{\nu_{LL}}
\]

Given the luminosity of the QSO, the nebula cannot be optically thick. The Lyα emission would have been much brighter than observed.

FAB+2015b; Hennawi+2015; FAB+2016
Why CIV (1549 Å) and HeII (1640 Å)?

- If present, should be the strongest lines after Lyα (redshifted into the optical)

- Extent of HeII → probe radiative transfer of Lyα

- HeII/Lyα: - hardness of the ionizing sources
  - density indicator
  - speed of shocks

- CIV/HeII: - hardness of the ionizing sources
  - speed of shocks
  - metallicity indicator

- Extent of CIV: metal enrichment + outflows scale
$\chi_{\text{SB}} \approx 7.04 \times 10^{-18} \text{ cgs/arcsec}^2$

(In agreement with NB imaging)

Slim Nebula (UM287)

2 hours on LRIS/Keck

smoothed

psf subtracted

2d spectrum

FAB+2015b

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Slug Nebula (UM287)

2 hours on LRIS/Keck

- Smoothed
- psf subtracted
- 2d spectrum

FAB+2015b

Hell/Lyα < 0.18 and CIV/Lyα < 0.16 (3σ limits)

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Comparison with other Lyα Nebulae

- HzRGs (Villar-Martín et al. 2007)
- HzRG composites (McCarthy 1993, Humphrey et al. 2006)
- RLQ Nebulae (Heckman et al. 1991)
- RLQ Nebulae (Humphrey et al. 2013)
- LAB (Dey et al. 2005)
- LABs (Prescott et al. 2009/2013)

HzRG = High-z Radio Galaxies
RLQ = Radio-Loud Quasar
Photoionization Modeling of Extended Emission

$R \sim 160 \text{ kpc}$

$n_H$

$N_H$

$f_C$

$L_\nu$ (or $i_{QSO} = 17.28$)

$U = \frac{\Phi}{c n_H} \propto \frac{L_\nu}{n_H}$
Photoionization Modeling of Extended Emission: Cloudy (Ferland+2013)

\[ \alpha_{\text{EUV}} = -1.7 \]

Lusso+2016

Slab – plane parallel geometry
$\text{SB}_{\text{Ly} \alpha} \sim 7 \times 10^{-18} \text{ cgs/arcsec}^2$

$\text{SB}_{\text{Ly} \alpha} \propto f_\text{c} n_H N_H$

Model parameters:

- $\log N_H = 18$ to 22
- $n_H = 0.01$ to 100 cm$^{-3}$
- $f_\text{c} = 1.0$
- $Z = 0.001, 0.01, 0.1, 1 Z_\odot$
- Three different input spectra
Photoionization Modeling: Optically Thin Models

Model parameters:

- $\log N_H = 18$ to 22
- $n_H = 0.01$ to 100 cm$^{-3}$
- $f_C = 1.0$
- $Z = 0.001, 0.01, 0.1, 1 Z_\odot$
- Three different input spectra

$S_B_{Ly\alpha} \sim 7 \times 10^{-18}$ cgs/arcsec$^2$

$S_B_{Ly\alpha} \propto f_C n_H N_H$

$\alpha_{EUV} = -1.7$

$\text{HeII/Ly}\alpha \sim 0.35$ theoretical limit from recombination
Photoionization Modeling: Optically Thin Models

Model parameters:

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$\alpha_{EUV} = -1.7$

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FAB+2015b
Photoionization Modeling: Optically Thin Models

$$SB_{L\gamma\alpha} \sim 7 \times 10^{-18} \text{ cgs/arcsec}^2$$

$$SB_{L\gamma\alpha} \propto f c n_H N_H$$

Model parameters:

- $\log N_H = 18$ to 22
- $n_H = 0.01$ to 100 cm$^{-3}$
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- Three different input spectra

$\alpha_{\text{EUV}} = -1.7$
SB_{Lyα} \sim 7 \times 10^{-18} \, \text{cgs/arcsec}^2 \\
SB_{Lyα} \propto f_c n_H N_H \\

Model parameters:
- \log N_H = 18 \text{ to } 22
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- Three different input spectra

\alpha_{EUV} = -1.7

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Models require high gas densities

$\frac{\text{HeII}}{\text{Ly} \alpha} < 0.18$

$\frac{\text{CIV}}{\text{Ly} \alpha} < 0.16$

$\text{SB}_{\text{Ly} \alpha} \sim 7 \times 10^{-18} \text{ cgs/arcsec}^2$
Large Reservoir of Cool ($10^4$ K) Gas

HeII/Ly$\alpha$ < 0.18

$N_H < 10^{20}$ cm$^{-2}$

$M_{\text{cool}} < 6.4 \times 10^{10}$ M$_{\odot}$

(rough estimate for the whole nebula)
Models require clouds with parsec size

$$S_{B_{\text{Ly}\alpha}} \sim 7 \times 10^{-18} \text{ cgs/arcsec}^2$$

$$R \approx \frac{N_H}{n_H} \ll 1 \text{ kpc}$$

Cosmological simulations miss subkiloparsec gas-clumps...

How important is the physics on these scales for simulations?
(see also Chrighton+2015 and Hennawi+2015)
Take-Home Messages:

• The nebula should be illuminated by the QSO

  The nebula is optically thin

• Optically-thin models suggest:

  1. $n_H > 3 \text{ cm}^{-3}$
  2. $N_H < 10^{20} \text{ cm}^{-2}$
  3. $R < 20 \text{ pc}$
Continuum-subtracted NB image

Slug Nebula (UM287)

Cantalupo, FAB+2014, Nature
FLASHLIGHT-GMOS: a Narrow-band Survey

**Targets:** brightest SDSS QSOs at $z = 2.253$

**Sample:** 15 QSOs on GMOS-S

**How:** custom-built narrow-band filter ($\lambda = 3955\text{Å}; \text{FWHM} = 32.7\text{ Å}$)

$1\sigma \sim 2 - 4.5 \times 10^{-18} \text{erg/s/cm}^2/\text{arcsec}^2$

(1 arcsec$^2$ aperture)

Exp. Time (narrow-band) = 2-5 hrs

Exp. Time (g-band) = 0.7-3 hrs
PSF and continuum subtracted Lyα maps

$S_{B_{\text{Ly}\alpha}}[10^{-17}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}]$
Example of a masked NB image
Example of a masked NB image
We extract the radial profile of 15 QSOs
Determining the Point Spread Function (PSF) from Stars

For the NB, about 100 stars are used.

The error budget includes statistical and systematic errors.

FAB+2016

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The average QSO profile differs from the PSF

FAB+2016

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The Average Radial Emission Profile of the z~2 QSO CGM

FAB+2016

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Radio quiet; quasar; @; z = 2.041; (FOV = 7'; x; 5')

3hrs; NB,; 3hrs; V; (parallel)

305'' (400 kpc)

1' (500 kpc)

Cantalupo, FAB+2014, Nature

Hennawi, +FAB, Science, 2015
Different densities in the cool CGM?

\[ n_H \gtrsim 1 \text{ cm}^{-3} \quad R \lesssim 20 \text{ pc} \]

Cantalupo+2014, FAB+2015b, Hennawi+2015

\[ M_{\text{cool}} \propto f_c N_H \]

\[ S_{B_{\text{Ly}\alpha}} \propto f_c N_H n_H \]

FAB+2016

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Summary

• No extended Lyα emission (>50 kpc) around 15 QSOs

• We compute the average radial emission profile of the typical QSO CGM.

• \(n_H < 0.1 \text{ cm}^{-3}\) within diffuse gas on large scales.

• The CGM of typical QSOs seems to show densities lower than those in giant Lyman-alpha nebulae around QSOs. Comparisons with simulations are needed...

• Large surveys are needed to uncover the brightest nebulae on the sky.
QSO MUSEUM

Quasars Speedy Observations with MUse: Search for Extended Ultraviolet eMision-lines

Targets: QSOs at z ~3

So far: ~ 59 QSOs (11 radio-loud)

1σ ~ 3 x 10^{-18} erg/s/cm^2/arcsec^2 (1 arcsec^2 aperture in 30A band)

Exp. Time = 45 mins

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