A 3D view of the Dark Universe: illuminating intergalactic gas at high redshift with fluorescent Lyα emission

Sebastiano Cantalupo

In collaboration with:
MUSE GTO Team, Simon Lilly (ETH), J. Xavier Prochaska (UCSC), Sammy B. Slug (UCSC), Piero Madau (UCSC), Fabrizio Arrigoni-Battaia (ESO), Martin Haehnelt (IoA)
Talk Outline

Introduction: key questions

Narrow-band imaging surveys at $z \sim 2$

Integral Field Spectroscopy surveys with MUSE

Open questions / Summary
Introduction: key questions

1-10 kpc

How is gas converted into stars?
Is there a “dark” galaxy phase?

10-200 kpc

How do galaxies get their gas?
What are the density and temperature of the “Circum Galactic Medium”?

200-1000+ kpc

How are galaxies linked to each other? What are the morphology and the small scale properties of the “Cosmic Web”?
Ionizing sources: UVB + stars

Quasar fluorescence signal (in proximity of a quasar)

Simulated Lyα images at redshift 3

Cosmological simulation (RAMSES) + Radiative Transfer (RADAMESH): Cantalupo+12
**Ongoing Fluorescence Surveys [~200h + MUSE GTO]**

**FLASHLIGHT**: VLT, Keck and Gemini Narrow-Band surveys [at z~2]  
(Cantalupo, Prochaska, Arrigoni-Battaia, Hennawi, Madau)

- **targets**: 26 bright SDSS QSOs at z~2, custom-built NB filters (4)  
- **Data collected so far**: 3 QSOs (deep) + 5 (medium-deep) on Keck/LRIS  
  3 QSOs (deep) + 15 QSOs (shallow) on GMOS  

\[
1\sigma \sim 5-8 \times 10^{-19} \text{ cgs/arcsec}^2 \text{ (deep)}
\]

**MILES3D**: MUSE Intergalactic Line Emission Survey in 3D at [z~3] (GTO)  
(Cantalupo, Lilly, Borisova, Marino, Gallego + MUSE GTO Team)

- **targets**: 3 “pre-imaged” QSO fields + brightest QSOs at z>3  
- **Data collected so far**: 3 deep exposures (9-18h) on “pre-imaged” fields  
  20 QSO snapshot fields (1h)

\[
1\sigma \sim 1-3 \times 10^{-19} \text{ cgs/arcsec}^2 \text{ (deep)}
\]

long term goal: 80h on Quasar Field reaching \[
1\sigma \sim 3-5 \times 10^{-20} \text{ cgs/arcsec}^2
\]
NB imaging of a bright, radio-quiet quasar @ z=2.27
10h NB, 10h V-band (parallel)
1h B, 1h R (parallel)

FLASHLIGHT: First night Keck/LRIS results

“Slug” Nebula

FLASHLIGHT/Keck: other preliminary results

Other observed fields so far are also rich in Lyα-Slugs, but not around target QSOs, and Dark Galaxies, e.g.:

Giant Nebulae detection rate with Narrow-Band imaging around quasars at $z \sim 2$ is less than 10% (see also Arrigoni-Battaia+2016)
SLUG comparison with simulations: a filament of the Cosmic Web?

Simulation: Total Gas

Simulation: Gas “illuminated” by the QSO ($t_{qso} = 1$ Myr)

Size and overall morphology compatible with “Cosmic Web” illuminated by ~1Myr old QSO (and kinematics compatible with Intergalactic gas)

How about the Mass?

Inferring the cold gas content of the Slug Nebula

\[
\frac{4\pi j_{\text{Ly}\alpha}}{h\nu_{\text{Ly}\alpha}} = n_e n_\text{p} \alpha_{\text{Ly}\alpha}^{\text{eff}}(T) + n_e n_{\text{HI}} q_{\text{Ly}\alpha}^{\text{eff}}(T) + P(I_v, n_{\text{HI}}, T)
\]

ionized gas \hspace{2cm} partially ionized \hspace{2cm} neutral gas

**SB - column densities relations from RADAMESH simulations:**

**“Photon-pumping” case**  
(gas mostly neutral)

\[
N(\text{HI}) \propto (SB/b^2)^2
\]

**“Recombination” case**  
(gas mostly ionized)

\[
N(\text{HII}) \propto (SB/C)^{0.5}
\]

\[
b = \text{impact parameter} \hspace{2cm} C = \text{clumping factor} = \frac{<n^2>}{<n>^2}
\]

Cantalupo+ 2014
Inferring the cold gas content of the Slug Nebula: 2 cases


“Photon-pumping” case (gas mostly neutral)

“Recombination” case (gas mostly ionized)

Inferred N(HI)

Inferred N(HII)

M(HI) \sim M(“cold” H) \sim 2.5 \times 10^{11} M_\odot

M(HII) \sim M(“cold” H) \sim 10^{12} M_\odot / C^{0.5}

NB: depends on Clumping Factor

Observed SB

CM

SB

Continuum-subtracted NB image

SNR (a/sec)

SB (a/sec)

arcsec
Comparison with simulations: more IGM “clumps” needed!

Simulation (all)

Slug Nebula “ionized” case

C = 1

Slug Nebula “neutral” case

Subgrid Clumping Factor (<1 kpc)

Slug Nebula “ionized” case

C = 50

Subgrid Clumping Factor (<1 kpc)

3D! with MUSE: MILES3D first year survey strategy

1) Medium-deep exposures (9h-20h) on “pre-imaged” fields:

- QSO Nebula at z~3, VLT/FORS
- “galaxy” Nebula in z=3 QSO field, CTIO
- Slug Nebula (z~2.3), HeII and CIV search

2) Snapshot blind survey (1h) on brightest radio-quiet (17) quasars at z>3:

- Broad-band images (1’x1’)
“galaxy nebula” in a QSO field at z~3, CTIO (20h)

Cantalupo+, in prep.
MILES3D Deep Fields: the Bulb Nebula

Contour Var: SNR

MILES3D Deep Fields: the Bulb Nebula

Contour Var: SNR

2σ~3x10^{-19} cgs/arcsec²

10A ~ 600km/s
MILES3D Deep Fields: the Bulb Nebula

Lyα  

HeII

CIV

CIII

Lyα

NV

~180kpc

Cantalupo+, in prep.
Extended HeII emission from the Slug Nebula
Extended HeII emission from the Slug Nebula

$2\sigma \sim 3 \times 10^{-19}$
cgs/arcsec$^2$

$10\AA \sim 600\text{km/s}$
What/where is source “c”? Another component to the Slug?

\[ z(c,\text{HeII}) = 2.286 \text{ (red side of “disk”!)} \]
\[ z(\text{QSO-a,NIR}) = 2.279 \text{ (+600\text{km/s})} \]
\[ z(\text{QSO-a,CO}) = 2.283 \text{ (+270\text{km/s})} \]

source “c” and HeII emission only on the “red side”

Ly\(\alpha\) (CWI); Martin,…SC+, Nature 2015

Cantalupo+, in prep.
2D line-ratio maps: very high densities (“clumps”) required

HeII/Lyα

~0.08

<0.005!

CIV/Lyα (all upper limits)

Expected HeII/Lyα ratio

D = 50 kpc
D = 160 kpc
D = 350 kpc
D = 1 Mpc

implied densities: n>10-1000 cc ! (depending on actual distances)

—> pc-sized CLUMPS required

(preliminary detection of H-α with MOSFIRE suggests similar densities)

Analytical model (Pezzulli & Cantalupo, in prep.)
MUSE observations of QSOs at z~3:

Targets:
brightest radio-quiet QSOs at 3<z<4 (and two radio-loud, R1 & R2)

Exposure times:
1h only total integration (“snapshot” survey)

“White-light” images
obtained by collapsing the datacube along the wavelength direction.

Borisova, Cantalupo+, 2016
MUSE observations of QSOs at z~3: 100% detection rate of giant nebulae!

Targets:
brightest radio-quiet QSOs at 3<z<4
(and two radio-loud, R1 & R2)

Exposure times:
1h only total integration
(“snapshot” survey)

Optimally extracted pseudo-NB images with QSO PSF-subtraction
obtained with CubExactor (Cantalupo in prep.)

All nebulae larger than 120 kpc
with various morphologies.

Borisova, Cantalupo+, 2016
A 3D view of the Muse Quasar Nebula 3 (MQN03), >320kpc in size:

CubExtractor (Cantalupo, in prep.) + VisIt
QSO PSF and continuum subtracted cube

$2\sigma \sim 1 \times 10^{-18}$
cgs/arcsec$^2$

10A $\sim$ 600 km/s

Borisova, Cantalupo+., 2016
2D Velocity maps:
- no clear signs of “rotation” (with some exceptions);
- radio-quiet nebulae (1-17) are kinematically “narrow”.

Borisova, Cantalupo+, 2016
How do they compare with other Lyα Nebulae and “haloes”?

Circularly averaged SB profiles
(NB: this is not an accurate representation of the “local” SB values for asymmetric nebulae)

All giant quasar nebulae have similar circularly-averaged SB profiles and are consistent with fluorescence (including Steidel LBG-stack “halo”!)

Borisova, Cantalupo+, 2016
Open Questions and Future Directions

What sets the **frequency**, **size** and **luminosity** of the giant quasar Nebulae? (quasar lifetime, opening angle, halo mass, redshift, quasar luminosity,...)

What is the origin of the IGM/CGM **clumps** traced by the Nebulae? (thermal/gravitational instabilities, quasar radiation effects,...)

How this **affects** galaxy and QSO formation? (fast gas accretion, violent disk instability,...)

**Exploring a larger parameter space:**
- include lower luminosity quasars;
- extend the redshift range to 2<z<3 (not possible with MUSE, (K)CWI required)

**Improving our theoretical understanding of IGM “clump-formation”:**
- hydrodynamical and thermal stability analysis;
- detailed comparison with observational data.

**Going deeper on >100kpc filaments around quasars (with Adaptive Optics):**
- detect larger and lower density structures at higher spatial resolution.
Where are the “clumps” coming from? Instabilities from filament accretion:

subsonic “cold” filament flowing through hot gas

Vossberg, Cantalupo & Pezzulli, in prep.
(see also Mandelker et al. 2016)
A MUSE-Mosaic on MQN03: tracing the largest filaments

Preliminary data from last run in September (2h-deep, 1x3 mosaic):

previous 1h-deep snapshot (single pointing)

~320 kpc

plan: >40h in AO in 2017/18

~400 kpc
Fluorescent Ly\(\alpha\) emission surveys show that giant emission nebulae are ubiquitous around \(z>3\) quasars and much rarer at \(z\sim2\).

Is this a real redshift evolution in quasar/gas properties or due to selection/observational techniques?

Modelling of both H-Ly\(\alpha\) and HeII emission suggest that clumps with large densities (\(n>10\, \text{cm}^{-3}\)) and small sizes (\(\sim\text{pc}\)) should be present on intergalactic scales around quasars.

What is the origin of the clumps and their effect on galaxy formation and evolution?

Preliminary stability analysis of cosmological filaments suggests that clump “seeds” may be generated by hydrodynamical instabilities.

What is the effect of cooling, heating, gravity and thermal conduction on clump growth or suppression?

Next future:
- Ultradeep MUSE (and KCWI) observations to detect cosmic filaments at low density also \textit{away} from quasars;
- new theoretical/numerical models for intergalactic gas emission studies and cosmic structure formation.

Stay tuned!