Joint analysis of Ly$\alpha$ emitting galaxies & QSO absorption spectra

— Probing reionization (and cosmology) —

Koki Kakiichi
University College London

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Mark Dijkstra (Oslo), Richard Ellis (UCL/ESO), Nicolas Laporte (UCL)
Anna-Christina Eilers (MPIA), Benedetta Ciardi (MPA), Adi Zitrin (Caltech)

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Two big questions:
Epoch of reionization and first galaxies

Galaxy formation

“What are the sources of reionization?”
LyC escape fraction & ionising capabilities of galaxies and QSOs

Physics of IGM

“What are the history and morphology of reionization?”
Measuring the ionisation state of the IGM & ionized bubbles
Galaxy-IGM connection at $z>6$

**Joint analysis of Ly$\alpha$ emitting galaxies & QSO absorption spectra**

Analytical models & hydrodynamical, radiative transfer simulations of galaxies, Ly$\alpha$ forest, reionization $\rightarrow$ tools to interpret the data

**Spectroscopic galaxy survey in 4$<z<7$ QSO fields**

$\rightarrow$ Direct map of galaxies & IGM at the end of reionzation
Landscape of the galaxy-IGM connection at $z>5-6$

Spectroscopic survey of Ly$\alpha$ emitting galaxies in QSO fields

- Galaxy spectra
- QSO absorption spectra
- Ly$\alpha$ halo
- Post-reionized IGM
- small-scale absorbers

QSO

$z>6$
Landscape of the galaxy-IGM connection at $z \sim 3$

$z \sim 3$

QSO

IGM

CGM

QSO absorption spectra

Spectra of Ly$\alpha$ emitting galaxies

Ly$\alpha$ haloes

Intensity of light

Colour (wavelength) of light/Å
“Perturbative approach” to cosmological Lyα transfer

Cosmological Lyα radiative transfer equation

\[
\frac{1}{c} \frac{\partial I_v}{\partial t} + n \cdot \nabla I_v - \frac{H + n \cdot \nabla v \cdot n}{c} v \frac{\partial I_v}{\partial v} + \frac{3H}{c} I_v = -\sigma_\alpha n_{H_1} \varphi_v I_v + \sigma_\alpha n_{H_1} \int R(v, v') I_v(v') dv' + \varepsilon_v
\]

Schematic purpose only

Idea: perturbatively expand Lyα RT equation w.r.t the number of scatterings
“Perturbative approach” to cosmological Lyα transfer

\[ \tau_{\text{eff}}(\nu_e, r_\perp) = \int dN_{\text{HI}} \frac{\partial^2 N}{\partial N_{\text{HI}} \partial z} \left| \frac{dz}{dr} \right| \int d\nu_\parallel \frac{1 + \xi_\nu(\nu_\parallel, r_\perp)}{aH} \left[ 1 - e^{-\tau(\nu_e | \nu_\parallel, N_{\text{HI}})} \right] \]

‘zeroth-order’ expansion + remormalized small-scale:
Lyα line profile = affected by both ISM & CGM/IGM

\[ \langle \tau_\alpha \rangle = \int e^{-\tau_{\text{eff}}^{\text{Ly}\alpha}(\nu_e)} \langle \Phi^{\text{ISM}}_\alpha(\nu_e) \rangle d\nu_e \]

‘Single-scattering’ approximation (first order expansion)
Lyα haloes = mostly CGM/IGM

\[ \langle \varepsilon_\alpha(r) \rangle = \frac{1 + \xi(r)}{4\pi r^2} \int dN_{\text{HI}} \frac{\partial^2 N}{\partial N_{\text{HI}} \partial z} \left| \frac{dz}{dr} \right| \int \frac{dv_{12}}{\sqrt{2\pi \sigma^2_{12}(r)}} \mathcal{L}_\alpha(v_{12}, N_{\text{HI}}) \exp \left[ -\frac{(v_{12} - \langle v_{12}(r) \rangle)^2}{2\sigma^2_{12}(r)} \right] \]
Calibrating the model of CGM&IGM around galaxies with Ly$\alpha$ absorption data

Ansatz:
Self-similar clustering between gas and galaxies
Cosmological inflow
2D optical depth maps: model vs observation

cf. median pixel HI optical depth map (Turner+14)

See also LBG-Lyα forest cross-correlation function (Bielby+16)
Implication of the galaxy-Lyα forest clustering: the impact of CGM/IGM on Lyα line profile

~80% of Lyα flux is attenuated by the CGM/IGM around galaxies
Enhanced attenuation of Lyα even at z~3 (also Laursen+11, Rudie+12)
... with a testable prediction: higher order Lyman series attenuation in galaxy spectra

VIMOS Ultra Deep Field
Thomas+14, Le Févre+14
Connection to Ly$\alpha$ haloes

Galaxy-Ly$\alpha$ forest clustering + Ly$\alpha$ scattering =  \textbf{‘power-law’ Ly$\alpha$ halo}

\[
\langle SB_{\alpha}(r_\perp) \rangle / \left[ \text{erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2} \right] \approx 1.1 \times 10^{-17} \left( \frac{\langle L_{\alpha} \rangle}{3.7 \times 10^{43} \text{ erg s}^{-1}} \right) \left( \frac{r_\perp}{10 \text{ pkpc}} \right)^{-2.4}
\]
Connection to Ly$\alpha$ haloes

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$$\langle SB_\alpha(r_\perp) \rangle / [\text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}] \approx 1.1 \times 10^{-17} \left( \frac{\langle L_\alpha \rangle}{3.7 \times 10^{43} \text{erg s}^{-1}} \right) \left( \frac{r_\perp}{10 \text{ pkpc}} \right)^{-2.4}$$
Ly$\alpha$ lines and haloes as a function of CGM/IGM environment

Higher suppression Ly$\alpha$ flux in spectra & stronger Ly$\alpha$ haloes in a region of higher Ly$\alpha$ absorption
Implication to reionization

Impact of the absorbers (UV background) around Ly$\alpha$ emitting galaxies to the IGM transmission

$$\tau_\alpha = \tau_{\text{bubble}} + \tau_{\text{absorber}}$$

$$\langle \tau_\alpha (T_{HI} = 2 \times 10^{-13} \text{ s}^{-1}) \rangle \approx 0.81$$

$$\langle \tau_\alpha (T_{HI} = 1 \times 10^{-12} \text{ s}^{-1}) \rangle \approx 0.81$$
Implication to reionization

Impact of the absorbers (UV background) around Ly$\alpha$-emitting galaxies to the IGM transmission

\[ \tau_{\alpha} = \tau_{\text{bubble}} + \tau_{\text{absorber}} \]

\[ \langle T_\alpha(\Gamma_{\text{HI}} = 2 \times 10^{-13} s^{-1}) \rangle \approx 0.81 \]

KK+16

\[ \langle f_{H I} \rangle_N = 0.387 \]

KK+16

Redshift

Momose+14

Schenker+14
Implication to cosmology

Power-law Ly\(\alpha\) emission tail of Ly\(\alpha\) haloes may contribute more than often-assumed exponential profile to the large-scale Ly\(\alpha\) emission clustering.
Spectroscopic galaxy survey in 4<z<7 QSO fields

→ Direct map of galaxies & IGM at the end of reionzation
Spectroscopic survey of dropout galaxies in z>6 QSO fields

Spectroscopic survey of Ly\(\alpha\) emitting galaxies in QSO fields

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z>6
Spectroscopic survey of dropout galaxies in $z>6$ QSO fields

Expectation from a hydrodynamical, radiative transfer simulation of reionization (KK+16)

Galaxy-transmission spike correlation has two contributions
1. UV background fluctuations
2. density fluctuations

KK+ in prep
Spectroscopic survey of dropout galaxies in $z>6$ QSO fields

Spectroscopic i-dropouts + QSO ESI spectra (provided by Anna-Christina Eilers)

SDSS J1030+0524 QSO field $z_{\text{QSO}}=6.31$

Spatial distribution of Ly$\alpha$ emitting galaxies + transmission spikes/Gunn-Peterson troughs

Can we estimate the ionising capability of galaxies to the IGM at the end of reionization?
Spectroscopic survey of dropout galaxies in z>6 QSO fields

Can we estimate the impact of QSOs on the IGM at the end of reionization? i.e. contribution of luminous galaxies in reionization
Near-future landscape

HII bubble

neutral H

ionized HII

Loeb 06

2<z<4

HETDEX+BOSS Lyα forests

2<z<7

Subaru/HSC QSOs+ follow-up PFS

3<z<7+

Spectroscopic Galaxy Survey in Deep QSO/GRB fields using MUSE, KCWI or JWST?
Galaxy-Ly$\alpha$ forest clustering data implies

1: CGM/IGM attenuates $\sim$80% of Ly$\alpha$ emission line at z$\sim$3
2: Power-law emission tail at the outskirt of Ly$\alpha$ haloes
Using Ly\alpha in emission and absorption together, spectroscopic galaxy survey in z>5-6 QSO fields gives a direct map of galaxies & IGM at the reionization era.

— A single message —

Let's go for it!
Should be fun!