Lya Radiative Transfer through Outflowing Halo Models to Understand both the Observed Spectra and Surface Brightness Profiles of Lya Halos around High-z Star-forming Galaxies

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1st Korean Lyman Alpha Workshop
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Lya line

- HI 2p-1s transition, ~1216Å (UV)
- Sources of Lya = all mechanisms that generate the HI 2p state
  - Photo-ionisation
  - Collisional excitation
- Astrophysical Lya sources
  - Star-forming region (HII region)
  - Ionising background (lights from high energy sources in the Universe)
Observing Lya

• Prediction in 1967 by Partridge & Peebles

ARE YOUNG GALAXIES VISIBLE?

R. B. PARTRIDGE AND P. J. E. PEEBLES
Palmer Physical Laboratory, Princeton University
Received August 5, 1966; revised September 8, 1966

ABSTRACT

The purpose of this paper is to assess the general possibility of observing distant, newly formed galaxies. To this end a simple model of galaxy formation is introduced. According to the model galaxies should go through a phase of high luminosity in early stages of their evolution. The estimated luminosity for a galaxy resembling our own is $\sim 3 \times 10^{46}$ ergs/sec, roughly 700 times higher than the present luminosity. The bright phase would occur at an epoch of about $1.5 \times 10^{8}$ years, corresponding to a redshift between 10 and 30, depending on the cosmological model assumed.

The possibility of detecting individual young galaxies against the background of the night sky is discussed. Although the young galaxies would be numerous and would have sufficiently large angular diameters to be easily resolved, most of the radiation from the young galaxies would arrive at wavelengths of 1–3 $\mu$ where detection is difficult. However, it seems possible that the Lyman-$\alpha$ line might be detected if it is a strong feature of the spectra of young galaxies.

It is also shown how such an experiment might help us to distinguish between various cosmological models.
Observing Lya

- Prediction in 1967 by Partridge & Peebles
- First Lya emission detection in local Universe in 1981 by Meier & Terlevich
- First high-z Lya emission detection in 1998 by Cowie & Hu
Observing Lya

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Observing Lya is not easy?
Observing Lya
Observing Lya

• Full of neutral hydrogen atom in the ground state in the Universe
Observing Lya

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Dijkstra (2017)
Observing $\text{Ly}_\alpha$

- Full of neutral hydrogen atom in the ground state in the Universe

- $\text{Ly}_\alpha$ photons that are emitted through the transition $2p \rightarrow 1s$ will be absorbed immediately by another neutral hydrogen atom in the ground state, emitted, absorbed, emitted, absorbed, emitted, absorbed, … (a characteristic of resonance line)
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• Lya photons’ wavelength is shifted away from the central wavelength (depending on hydrogen atoms’ motion), and when the wavelength is far away from the central wavelength, Lya photons escape the system,
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Orsi et al. (2012)
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Observing Lya could be not easy, but this gives hint for the spatial & kinematic & chemical distributions of HI medium?
Observing Lya

LALA, LARS, MUSE, SILVERRUSH - many Lya surveys
Observing Lya

Stack of 92 galaxies

"a" MUSE galaxy

Steidel et al. (2011)

Leclercq et al. (2017)
Modeling Lya

• Radiative transfer calculation process

(1) Generate a Lya photon
   =assign frequency, position, and propagating direction

(2) Scatter that photon after traveling a certain optical depth
   =assign new frequency and new propagating direction

(3) Repeat (2) until that photon escapes the system

(4) Generate another Lya photon, and go to (2)
Modeling Lya

Verhamme et al. (2006)
Modeling Lya

- Shell model (e.g. Gronke et al. 2015)
  - Central source
  - Shell distribution for HI medium
  - Constant expanding velocity
  - Successful in reproducing various Lya spectra

Dijkstra(2017)
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Gronke et al. (2015)
Modeling Lya

- Clumpy-medium model (e.g. Dijkstra & Kramer 2012)
  - Central source
  - Clumpy clouds of HI
  - Momentum-driven wind (model I) + galaxy’s gravitational potential well (model IV)
- Can explain low-ionisation absorption lines and Lya SB (at larger radii).
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Our model

• Galaxy model (3D)
  • Instead of central source, modified Bessel function of 2nd kind with $n=0$ for Lya source distribution (exponential distribution in projected space)
  • Instead of uniform shell or halo distribution, exponential distribution for HI medium
  • Simplified “momentum-driven wind with galaxy gravity” model
Our model

- Model parameters
  - Spatially and frequency-wise uniform source distribution
  - HI medium temperature of $10^4$K
  - HI medium distribution ($r_{\text{scale}}$)
  - HI medium optical depth ($\tau_0$)
  - HI medium velocity field ($r_{\text{peak}}, V_{\text{peak}}, \Delta V$)
- Zero metallicity (dust free)
Our model

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  • Spatially and frequency-wise uniform source distribution
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• Zero metallicity (dust free)
Our model

- Simulation parameters’ grid
  - $r_{\text{scale}}$: 0.1, 0.2, 0.3, 0.4, 0.5 ($r_{\text{max}}$)
  - $r_{\text{peak}}$: 0.1, 0.2, 0.4, 0.4, 0.5 ($r_{\text{max}}$)
  - $V_{\text{peak}}$: 100, 200, 300, 400 (km/s)
  - $\Delta V$: +50, 0, -50, -100, -150, -200 (km/s)
  - $\log \tau_0$: 6, 6.3, 6.6, 6.9, 7.2, 7.5

LaRT fortran, mpi code by K. Seon
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LaRT
fortran,
mpi code
by K. Seon

3600 cases!
$10^6$ photons/each case
Our model

- Outputs (for each photon)
  - Initial position ($r_i$)
  - Initial frequency ($\nu_i$)
  - Cumulative HI optical depth ($\tau^*$)
  - Cumulative HI column density ($N_{\text{HI}}^*$)
  - Final position ($r_f$)
  - Final frequency ($\nu_f$)
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post-processing source distribution (spatial, frequency) and destruction by dust
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post-processing
source distribution
(spatial, frequency)
and destruction by dust

photon weight = 
$r_i ^2 K_0 (r_i/r_{\text{source, scale}}) 
\times \text{Voigt} (\nu_i; T) 
\times \exp (-\tau_d ^*)$

\[ \tau_d ^* = \frac{Z/Z_\odot \sigma_d (Z_\odot)}{N_{\text{HI}}^* (1-A)} \]
Our model

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Post-processing source distribution (spatial, frequency) and destruction by dust.
Can our model explain MUSE observations?
\[-\ln \mathcal{L} = \sum_i \frac{(O_{sp,i} - M_{sp,i})^2}{E_{sp,i}^2} + \sum_i \frac{(O_{SBP,i} - M_{SBP,i})^2}{E_{SBP,i}^2}\]
$L$

$r_{\text{peak}}$

$V_{\text{peak}}$

$\Delta V$

$\log \tau_0$

$Z/Z_\odot$

$z$

$L_{\text{tot}}$

$r_{\text{scale}}$

$r_{\text{peak}}$

$V_{\text{peak}}$

$\Delta V$

$\log \tau_0$

$Z/Z_\odot$

$z$
\( \mathcal{L} \), \( r_{\text{peak}} \), \( V_{\text{peak}} \), \( \Delta V \), \( \log \tau_0 \), \( Z/Z_\odot \), \( \mathcal{L}_{\text{sp}}, \mathcal{L}_{\text{SBP}} \)
Best-fit

Spectrum best-fit

SBP best-fit
$r_{\text{peak}}$, $V_{\text{peak}}$, $\Delta V$, $\log T_0$, $Z/Z_\odot$, $z$, $r_{\text{scale}}$, $L$, $L_{\text{tot}}$
#547
## Best-fit results

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How each parameter affects spectrum and SBP?
$\log \tau_0$

MUSE#1185
Rule of thumb?

- More scatterings, more offset and broader spectrum, and less steep SBP.
$V_{\text{peak}}$
Rule of thumb?

• More scatterings, more offset and broader spectrum, and less steep SBP.

• Larger medium velocity, broader spectrum.
$r_{\text{scale}}$

MUSE#82
Rule of thumb?

• More scatterings, more offset and broader spectrum, and less steep SBP.

• Larger medium velocity, broader spectrum.

• The position of (last) scattering affects SBP, and velocity there affects spectrum peak position.
$Z/Z_\odot$
Summary

• Our galaxy model - not the famous shell model - could reproduce simultaneously the spectra and SBPs of the MUSE high-z star forming galaxies.

• Spectrum and SBP could be complementary in determining most of the parameters in our model (except metallicity and redshift).

• To explain both red-peaked spectra and extended SBP, the expanding velocity of the HI medium should not expand forever ($\Delta V \leq 0$), and HI medium distribution itself should be much more extended than source distribution ($r_{\text{scale}} \sim 10^{-44} r_{\text{source, scale}}$).

• Redshift can be determined to the 3rd decimal place.