Line Formation of Lyα in Clumpy CGM and IGM

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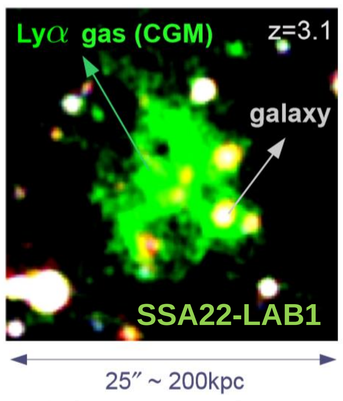
I. Abstract

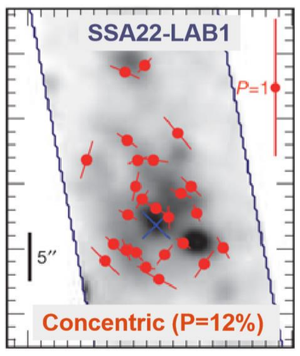
Lyα is one of the strongest spectral lines in emission line objects found in the early universe. Escape of Lyα is achieved after a large number of resonance and a moderate number of off-resonance scatterings in circumgalactic medium (CGM) and intergalactic medium (IGM). In Lyman alpha emitters (LAE) and Lyman alpha blobs (LAB), the spatial distribution of Lyα is significantly more extended than the continuum UV image, indicating the crucial role of scattering of Lyα. Assuming that the CGM and IGM are clumpy composed of a large number of spherical blobs, we develop a new grid-based Monte Carlo code to investigate the line profile of Lyα. In our simulation, we fully consider scattering processes of Lyα without employing the accelerating method, and each individual photon packet is traced until escape from the scattering region. Our preliminary result shows that most Lyα profiles exhibit weaker dips at the velocity center especially in the case of low covering factor, which is in high contrast with Neufeld (1990) results. We suggest that the reflection near the surface of clumpy blobs contributes significantly to the emergent Lyα.

II. Introduction

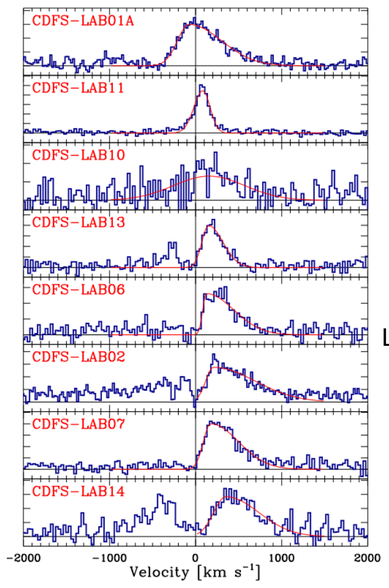
① Lyα Blob



Subaru Image of LAB1
Matsuda et al. 2014



Polarimetry of LAB1
Hayes et al. 2011

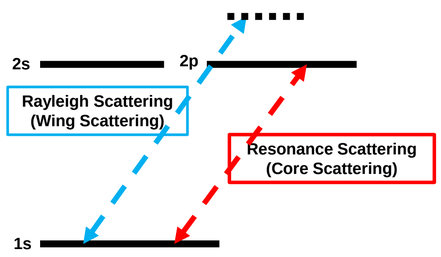


Lyα spectra of LAB
Yang et al. 2014

- Extended sources with a hundred kpc scale.
- Progenitors of proto-galaxy-groups?

- The origin of the extended Lyα emission in LAB is controversial.
- Lyα is polarized due to scattering with atomic hydrogen in LAB.
- The redshifted center of Lyα spectra is indicative of an expanding medium.

② Lyα Scattering

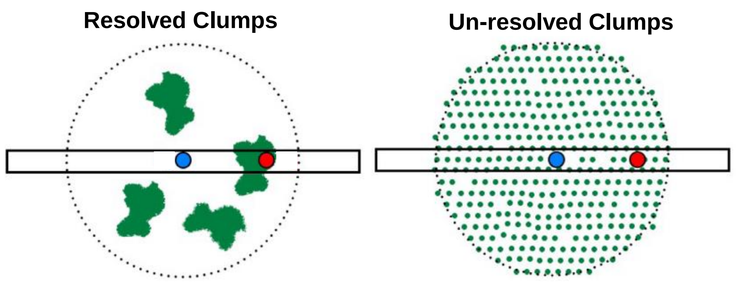


Hydrogen Energy Level

Lyα scattering with atomic hydrogen is classified into resonance (core) and Rayleigh (wing) scattering.

	Resonance scattering	Rayleigh scattering
Transition	1s-2p (line center)	1s- near 2p (off center)
Phase Function	Weakly Anisotropic	Dipole
Polarization	Negligibly Polarized	Polarized
Free Path	Short	Long

③ Schematics of Clumpy Media in CGM

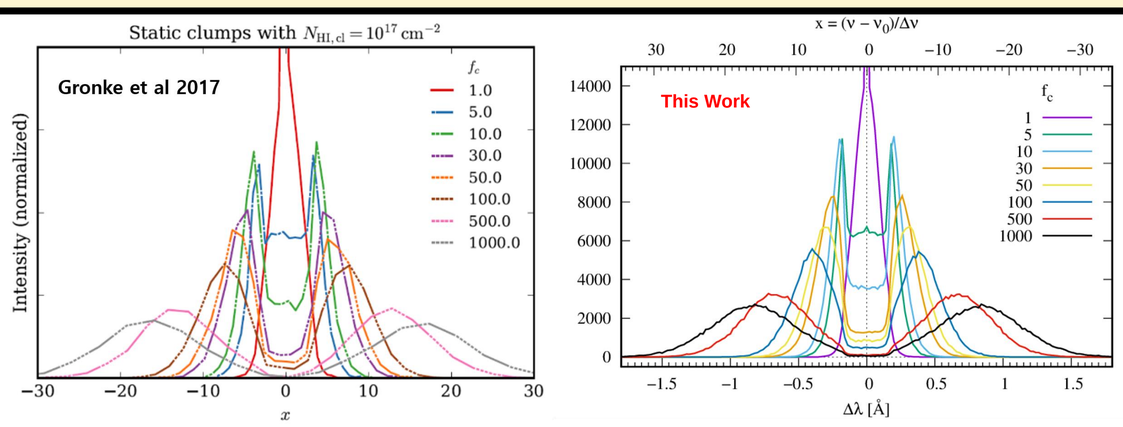


Schematic Illustration
Hennawi & Prochaskhar 2013

In the previous IGM and CGM studies, it is often assumed that the medium is composed of small clumps or clouds rather than continuous.

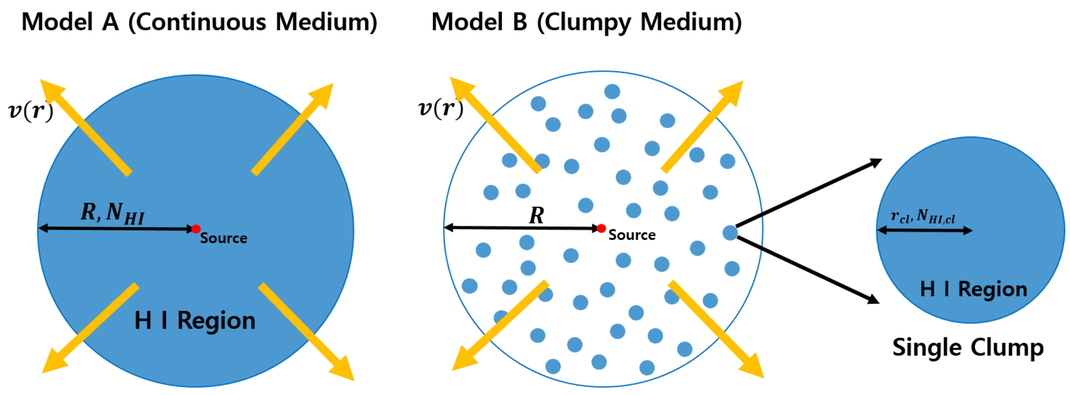
The clouds are in pressure equilibrium and virialized in the dark matter halo. Depending on the size and total column density, these clouds can be resolved or unresolved.
In this work, we explore a wide range of r_{cl} and the covering factor f_c (see IV. Geometry).

III. Code Check



The results of Gronke et al 2017 (Left) and our results (Right).

IV. Geometry

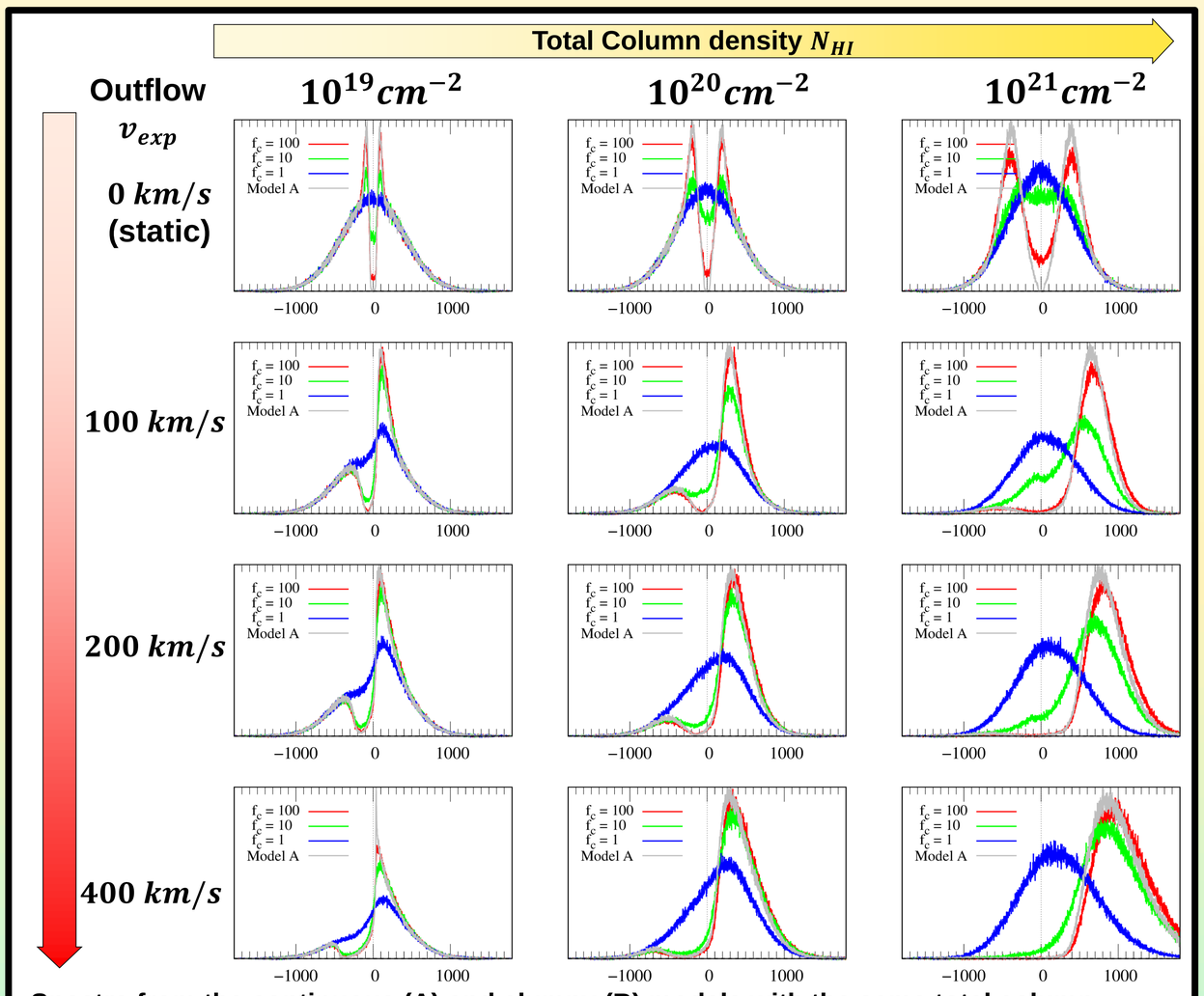


- We consider two spherical models (Models A and B) with the same Lyα point source (AGN or a star-forming galaxy) and the same total column density N_{HI} and the halo radius $R = 100\ kpc$. (The total column density N_{HI} is defined as $R\ n_{HI}$ in Model A and $f_c N_{HI,cl}$ in Model B.)
- Model A is a continuous medium with uniform density.
- Model B is composed of a large number of clumps with a uniform density and distribution.

In Model B, we consider
the clump radius $r_{cl} = 100$ pc (un-resolved cloud at $z \sim 2$) and a range of the clump column densities $N_{HI,cl} = 10^{17-21} cm^{-2}$ and covering factors $f_c = 1 - 100$.
(f_c represents the number of clumps in the line of sight directly toward the center)

In Models A and B, we assume a Hubble-type outflow velocity given by $v(r) = v_{exp}\frac{r}{R}$ and Gaussian emission profile with a width of $400\ km/s$ ($FWHM \sim 1000\ km/s$) similar to those of type-II AGNs.

V. Results



Spectra from the continuous (A) and clumpy (B) models with the same total column density N_{HI} and outflow velocity v_{exp}.
The line colors represent covering factor $f_c = N_{HI}/N_{HI,cl}$.

- **The spectra for high covering factors $f_c \sim 100$ are similar to those from the continuous Model.**
- The difference between clumpy and continuous medium models (e.g., green vs gray) becomes larger as the total column density N_{HI} increases.
- The peaks of Lyα tend to get red-shifted as the medium is expanding.
  The positions of the Lyα peaks depend on N_{HI} and weakly on expanding velocity v_{exp}.
- **In clumpy media, low covering factors ($f_c \sim 1$) can produce single-peaked Lyα profiles at $v_{sys} = 0$ despite the presence of outflows.**
- The formation of single-peak profiles is due to very low probability of deep penetration into the inside of clumps while traveling between clumps.

Reference & Contact

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F. Arrigoni Battaia et al. 2015, ApJ, 809, 163
M. Gronke et al. 2016, ApJL, 833, L26
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M. Hayes et al. 2011, Natur, 476, 304
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Summary and Future Work

- The results from the clumpy models (B) converge to that for the continuous model case (A) as the covering factor f_c increases.
- In the case of low covering factors and high column densities of clumps, **the scattering on the surface of the clumps dominate while Lyα photons propagate through the medium.**
- We will include turbulence / random motions of each clumps in the simulation.
- We will compute the surface brightness and polarization profiles for clumpy models.
- We will compare our scattering-only models with observations (surface brightness, velocity profiles and polarizations).

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