THE HYDRODYNAMIC FEEDBACK OF COSMIC REIONIZATION ON SMALL-SCALE STRUCTURES & ITS IMPACT ON PHOTON CONSUMPTION DURING THE EPOCH OF REIONIZATION

Speaker: Hyunbae Park
Post-doctoral researcher @ Korea Astronomy and Space science Institute (KASI)

Collaborators:
Paul R. Shapiro (UT Austin), Jun-Hwan Choi, Naoki Yoshida (U. of Tokyo), Shingo Hirano, Kyungjin Ahn (Chosun Univ.)
Recombination from Small-scale Structures during the Epoch of Reionization

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1-1) Photon Consumption during the Epoch of Reionization

Ionizing photons are consumed to ionize
(1) H in neutral region.
(2) recombined H in ionized region.
1-2) Recombination and ionization photon budget

We believe galaxies and quasars have reionized the universe.
1-2) Recombination and ionization photon budget

- # of UV photons produced > # of UV photons Consumed

In order to confirm that, we need to account for the UV photons that ionized the universe.
Observed galaxies do not account for them needed photons yet. Most of the photons are thought to have come from faint galaxies beyond the current detection limit.
Recombination is another important factor in accounting for the reionization.

Need for Precise Modeling of Recombination

1) Ionizing Photon Budget

\[
\text{# of UV photons} > \text{# of hydrogen} \times (1 + N_{\text{rec}})
\]

(? \approx 1 - 3)
What is so tricky about recombination rate?

\( \mathcal{R} \propto n_e n_{\text{HII}} (\propto \rho^2) \)

In fully ionized gas, the recombination rate goes nearly as the density squared.
What is so tricky about recombination rate?

In large-scale simulations, the spatial resolution is limited for sub-Mpc scales.
Recombination & Clumping Factor

\[ \langle R \rangle_V \propto \langle \rho^2 \rangle_V \neq \langle \rho \rangle_V^2 \]

Square of average does not equal to average of square!

\[ \langle \rho^2 \rangle = \langle \rho \rangle^2 = 1 \quad \text{and} \quad \langle \rho^2 \rangle = 2, \quad \langle \rho \rangle^2 = 1 \]

\[ C \equiv \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} = \frac{\text{(Actual)}}{\text{(Approximate)}} \]

\[ C = 1 \quad \text{and} \quad C = 2 \]

Neglecting density distribution within a volume underestimates the recombination rate by clumping factor, C.
To obtain an accurate recombination rate, we need to model clumping factor within a cell.
To do so, we shall simulate “small-scale structures” in such cells.
Requirement for Simulation
1) Hydrodynamics

Photo-ionization of gas increases the temperature from \(~100\) K to \(~10000\) K, leading to expansion of gas.

Hydrodynamics is required to simulate the expansion.

We use the GADGET-3 code for that.
 Requirement for Simulation
2) Shielding of UV Radiation

Gas in minihalos can hold against the ionizing background radiation up to \(~100\) Myr (Shapiro et al. 2004; Iliev et al. 2005).

Thus, we need to delay the ionization of that gas in a realistic way.
Most gas will be ionized immediately except dense gas in minihalos that will be able to shield against the external background.
Physics to include

(2) Self-shielding of minihalos

1) Search for neutral particles within 200 physical pc.
2) Attenuate radiation using neutral column densities in 6 directions.
   (+x, -x, +y, -y, +z, -z)
Physics to include
(2) Self-shielding of minihalos

1) Search for neutral particles within 200 physical pc. This uses the pre-constructed tree structure for gravity solver.
2) Attenuate radiation using neutral column densities in 6 directions. (+x, -x, +y, -y, +z, -z)
Simulation Setup (1)
Basic

Code: GADGET-3

Simulation Volume: 200 kpc/h in a side

Resolution: $M_{DM} = 51 \, M_{\odot} \ (N = 256^3)$

Ionizing Radiation:
Shielded Isotropic External Background
We are targeting the majority of cells that are ionized externally by galaxies forming in usually dense regions.
Result: Simulation Overview
Result: Clumping Factor

Standard case: $J_{21} = 1, \ z_i = 10$

High clumping factor early and low clumping factor later. (Park et al. 2016)
Clumping Factor at Early Time

Clumping Factor

Supersonic 1-fronts

$\Delta t$ (Myr)

[Graph showing clumping factor over time]

[Images showing cell structures]
Clumping Factor at Late Time

\[
\begin{align*}
\text{Clumping Factor} &
\end{align*}
\]

\[
\begin{align*}
\Delta t \text{ (Myr)} &
\end{align*}
\]

Hydrodynamic feedback
Result: Extra Photon Consumption due to Small-scale Structures

Initially high clumping factor results in extra photon consumption. (Park et al. 2016)
Result: Extra Photon Consumption due to Small-scale Structures

\[ N_{\text{add}}^{\text{rec}} = 0.32 \]

(Park et al. 2016)
For different $J_{21}$’s and $z_i$’s

Higher recombination for lower $z_i$ and higher $J_{21}$. 
Result:
Accumulated Recombination

\[ N_{\text{rec}}^{\text{add}} = 0.32 \times [J_{21}]^{0.12} \left( \frac{1 + z_i}{11} \right)^{-1.7} \]

(\text{Park et al. 2016})
Extending the result to Mpc scale

We run 4 more simulations with sub-cubes of a 800 kpc/h box that the mean density contrasts are $\delta = -0.52, -0.26, 0.24, & 0.59$. 

$J_{21} = 1$  
$z_i = 10$
$C$ for varying $\delta$

\[ \frac{N_{\text{rec}}^{\text{add}}}{100} = 0.32 \times [J_{21}]^{0.12} \left( \frac{1 + z_i}{11} \right)^{-1.7} \left[ 1 + \frac{\delta}{2.5} \right] \]
Ionization photon budget for a 800 kpc/h-Box

\[ N_{\text{rec}}^{\text{add}} = 0.32 \times [J_{21}]^{0.12} \left( \frac{1 + z_i}{11} \right)^{-1.7} [1 + \bar{\delta}]^{2.5} \]

\( J_{21} = 1 \)
\( z_i = 10 \)

\[ \langle N_{\text{rec}}^{\text{add}} \rangle_{800 \text{ kpc}/h} = \frac{1}{64} \sum_{i} [1 + \bar{\delta}_i] N_{\text{rec},i} = \frac{1}{64} \sum_{i} 0.32[1 + \bar{\delta}_i]^{3.5} = 0.67 \]
Conclusion

Ionization photon budget per H for reionization

\[ = \\
\]

1 for ionizing an H atom first time

+ 

1 - 3 for extra due to recombination in large-scale structure

+ 

0.67 < for yet another extra due to recombination in small-scale structure
Thank you!