The physics of reionization

Benoît Semelin (Observatoire de Paris)
Ilian Iliev (University of Sussex)

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Basic physics of the reionization process

The physics of reionization is ruled by:

- The radiative transfer equation for UV radiation
- The local ionization equation
- The local energy equation

Two meaningful quantities:

- Ionizing photon mean free path:

  \[ l = \frac{1}{\sigma(\nu)n_H} = 2. \left( \frac{E}{E_0} \right)^3 \left( \frac{10}{1+z} \right)^2 \text{ ckpc} \]

  \[ l \sim 2 \text{ kpc in UV} \quad l \sim 1 \text{ Gpc in X-ray} \]

- Hydrogen recombination time:

  \[ t_{\text{rec}} = \frac{1}{\alpha(T)n_H} = 240 \left( \frac{10}{1+z} \right)^3 \left( \frac{\bar{\rho}(z)}{\rho} \right)^3 \text{ Myr} \]

  ➢ The bulk of the IGM requires only \( \sim 1 \) photon / atom
  ➢ Moderate overdensities act as photon sinks
Ionization in the IGM

Ionization by UV photons:

Short mfp $\Rightarrow$ Sharp I-front $\Rightarrow$ “ionized bubbles”

I-front velocity $> 1000$ km.s$^{-1}$
Sound velocity $< 10$ km.s$^{-1}$

$\Rightarrow$ Extreme weak R-type shock
$\Rightarrow$ negligible response from the gas

Ionization by X-rays:

Long mfp $\Rightarrow$ diffuse ionization with fluctuations

Main consequence: heating by secondary electron.

✓ Probably does not kill 21cm absorption (Santos et al. 2008, Pritchard & Loeb 2008, Baek et al. 2010, and more)

✓ Soft and hard X-ray leave different signatures (Fialkov et al. 2014, Pacucci et al. 2014)
Ionization in the IGM

Baek et al. 2010

UV only

UV + X-ray

Mesinger et al. 2013

Temperature ($T_K$)

1 10 100 $10^3$ $10^4$
Escape of ionizing photons from primordial galaxies

The amount of ionizing photon available for reionization is set by:

1. Source formation efficiency
2. Number of photon produced by source atoms (e.g. IMF)
3. Ionizing photons escape faction $f_{\text{esc}}(M, Z, ...)$

All three unknown at high $z$!

Small scale coupled (RT+dynamics) simulations attempt to constrain those quantities

Greif et al. (2011)  Wise et al. (2014)
Small and dense structures (minihalos):

- Act as photon sink (Iliev et al. 2005)
- Slow down ionization fronts (Ciardi et al. 2006)

Often treated with sub-grid recipe in numerical simulations:

- Using a clumping factor : $C(\rho, \Gamma) = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2}$ (e. g., Emberson et al. 2013)
- Including a self-shielding prescription (e.g. Finlator et al. 2012, Sobacchi et al. 2014)
- Including suppression by photo-evaporation (Shapiro et al. 2004, Ciardi et al. 2006)

A fully self-consistent treatment remains a challenge!
Conclusions

- The production of photons is not well constrained
- The propagation of I-front in diffuse IGM is comparatively simple
- The recombinations in galaxies and mini-halos are a crucial, difficult-to-model factor.