Simulations of galaxy formation and reionization

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Outline

1. Simulating the epoch of reionization
2. The Aurora radiation hydrodynamical simulations
3. Semi-analytic models of the epoch of reionization based on the EAGLE simulation
Some questions about the epoch of reionisation

- When did reionisation end?
- How long did it last?
- What is the topology of the HII regions?
- What types of sources are responsible?
- What are the main photon sinks?
- How many photons/baryon are required?
- What is the impact of reionisation on:
  - Galaxy formation
  - Galaxy evolution
  - The intergalactic medium
Simulations of the epoch of reionisation

- Reionisation is by definition a radiative transfer problem
- Radiative feedback:
  - Negative: floor on $T_{\text{vir}}$ of galaxy halo
  - Negative: dissociation of molecules
  - Positive: Pressure smoothing reduces recombination rate
- Reionisation is thus a radiation-hydrodynamics problem
Simulations of the epoch of reionisation

- Mass of objects quenched by
  - photo-heating: $\sim 10^8 \, M_\odot \rightarrow 25 \, \text{cMpc box for } 1000^3 \text{ particles and 100 particles per halo}$
  - Photo-dissociation: $\sim 10^5 \, M_\odot \rightarrow 3 \, \text{cMpc box for } 1000^3 \text{ particles and 100 particles per halo}$

- To begin to resolve the cold ISM phase, we need particle mass $<< 10^3 \, M_\odot \rightarrow 1 \, \text{cMpc box for } 1000^3 \text{ particles}$

- Consequences:
  - Cannot do radiation-hydrodynamics for simulation volumes appropriate for 21cm experiments
  - Cannot accurately predict efficiency of stellar feedback
    - Need to calibrate (to observed luminosity function)
  - Cannot accurately predict escape fraction
    - Need to calibrate (to reionisation history)
Simulations of the epoch of reionisation

Cannot predict from first principles
• Galaxy mass and SFR functions
• Reionisation history
Simulations of the epoch of reionisation

- Most reionisation simulations:
  - Post-process dark matter simulations
  - Use a radiative transfer method that is not spatially adaptive → extremely poor resolution, e.g. $500^3$ in 100 cMpc box gives cell size of 200 ckpc
  - Group sources
    - Use radiative transfer with and accuracy that is limited and that cannot be controlled

- Most radiative transfer simulations similar to semi-numerical methods, which have therefore not yet been tested
Spatially adaptive radiation-hydrodynamical simulations of galaxy formation during cosmological reionization

Andreas H. Pawlik\textsuperscript{1*}, Joop Schaye\textsuperscript{2}, Claudio Dalla Vecchia\textsuperscript{3,4} 2015, MNRAS, 451, 1586

The Aurora radiation-hydrodynamical simulations of reionization: calibration and first results.

Andreas H. Pawlik\textsuperscript{1*}, Alireza Rahmati\textsuperscript{2}, Joop Schaye\textsuperscript{3}, Myoungwon Jeon\textsuperscript{4}, Claudio Dalla Vecchia\textsuperscript{5,6} 2016, MNRAS, submitted (arXiv:1603.00034)
The Aurora project

• Spatially adaptive, accurate radiation hydrodynamics with TRAPHIC (Pawlik & JS ‘08, ‘11)
• Cosmological simulations, box size up to 100 Mpc
• Up to $2 \times 10^{24} \text{}^3$ particles, equivalent to $\sim 26,000^3$ uniform grid
• Highest resolution $\sim 1 \text{ kpc}$ comoving, $\sim 3 \times 10^5 \text{ M}_\odot$
• For each resolution and box size:
  o Subgrid stellar feedback calibrated to $z=7$ SFR function
  o Subgrid escape fraction calibrated to achieve reionization at $z = 8.3$
• Supernova feedback and photoheating individually turned on and off
The Aurora project

Pawlik, Rahmati, JS+ (2016)
Evolution of the SFR function

Pawlik, Rahmati, JS+ (2016)
Cosmic star formation history

\[ \rho_{SFR} \left[ M_\odot \text{yr}^{-1} \text{cm}^{-3} \right] \]

- SFR > 0.2 \( M_\odot \text{yr}^{-1} \)
- Total

\[ Z \]

Pawlik, Rahmati, JS+ (2016)
Reionization history

Pawlik, Rahmati, JS+ (2016)
Effects of supernovae and photoheating

$z = 7$

Pawlik, JS & Dalla Vecchia (2015)
Reionisation history: Feedback and resolution

Winds reduce SFR, but increase escape fraction

Pawlik, JS & Dalla Vecchia (2015)
Clumping factor: Effect of feedback

Pawlik, JS & Dalla Vecchia (2015)
• Models that are consistent with the observed low photo-ionisation rate at z < 6 and the low escape fractions at z~0 require the escape fraction to increase with z (e.g. Khaire+ ‘16, Gnedin+ ‘16, Pricë+ ‘16, Faisst ‘16)

• Escape fractions should only know about local galaxy properties, not redshift

• Galactic winds open channels through which photons escape (e.g. Razoumov & Sommer-Larsen ’06, Gnedin+ ‘08, Wise & Cen ‘09, Yajima+ ‘11, Traino+ ‘15, Ma+ ‘15, Pawlik+ ‘15, ’16)

• Galactic winds observed for SFR surface densities greater than 0.1 M⊙ yr⁻¹ kpc⁻² (e.g. Heckman ‘01, ‘02)

• Ansatz: Escape fraction is 0 (0.2) if the local SFR surface density is below (above) the critical value 0.1 M⊙ yr⁻¹ kpc⁻²
EAGLE:
• Volumes of 25 - 100 Mpc and zooms
• Up to 7 billion particles
• Includes feedback from stars and AGN
• Winds develop naturally without predetermined mass loading or velocity
• Feedback calibrated to match $z \sim 0$ galaxy mass function and sizes
• Many different models, spin offs
• Galaxy data publicly available
SFR surface density vs UV luminosity

Sharma+ (2016a)
Predicted luminosity-weighted mean escape fractions

$\log_{10} \dot{M}_* (M_\odot \, \text{yr}^{-1})$

$\log_{10} L_{1500} \, (\text{erg s}^{-1} \, \text{Hz}^{-1})$

Sharma+ (2016a)
Reionisation history

This work: $f_{\text{esc}}(\dot{\Sigma}_*)$

Constant $f_{\text{esc}} = 0.2$

$f_{\text{esc}} \propto (1 + z)^{3.4} \text{ (HM12)}$

Sharma+ (2016b)
Electron scattering optical depth

This work, $f_{\text{esc}}(\Sigma_*)$
Constant $f_{\text{esc}} = 0.2$
$f_{\text{esc}} \propto (1 + z)^{3.4}$ (HM12)

PLANCK 2016

Sharma+ (2016b)
Evolution of the photo-ionisation rate

![Graph showing the evolution of the photo-ionisation rate with redshift. The graph includes lines for different models: This work, constant $f_{\text{esc}} = 0.2$, and $f_{\text{esc}} \propto (1 + z)^{3.4}$ (HM12). The graph also includes data points for quasars, galaxies, and the total.](image)

Sharma+ (2016b)
Detectable fraction of cumulative ionizing emissivity

\[ f_\gamma(>z) \]

- detected
- undetected

HST
JWST
(30 hours)

sharma+ (2016b)
Conclusions

• Cosmological radiative transfer simulations cannot predict the star formation history, escape fraction, and reionization history
• Need observations to calibrate stellar feedback and subgrid escape fraction (for each resolution; factor of ~2 adjustments)
• Photoheating has both negative and positive effects on reionization
• Spatially adaptive simulations are starting to capture the effects of photoheating
• Galactic winds increase the escape fraction
• Galactic winds more prominent for higher SFR surface densities, naturally results in increase of mean escape fraction with redshift, as required by observations