Effects of Radiative Feedback on Reionization and the Local Universe

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Outline

• Introduction
• Ionizing Efficiency of First Galaxies
  – Star Formation Efficiency
  – Escape Fraction
  – Suppression of star formation by photoionization
  – Minimal Reionization Model
• Reionization and the Local Universe
  – “Missing Satellites” Problem
  – Satellite Abundance and Reionization Epoch
  – Environmental Dependence
• Summary
Reionization: The Standard Picture

- Reionization driven by ionizing radiation produced by stars
- First stars (Pop III) forming in minihalos were likely massive and efficient producers of ionizing radiation at z~15-30
- Pop III stars must have polluted IGM as minihalos (M<10^8 M_☉) merged into larger atomic cooling halos (M>10^8 M_☉)
- Eventually Pop II star forming galaxies dominate as reionization ends at z~6

Barkana & Loeb (2001)
Reionization: The Standard Picture

- Ionization is driven by exponential increase in dark matter halo collapsed fraction

\[ F_{\text{coll,II}}(z) = \frac{1}{\rho_0} \int_{M_{\text{II}}}^{M_{\text{la}}} dM \left( \frac{dn}{dM} \right) M \]

\[ F_{\text{coll,II}}(z) = \frac{1}{\rho_0} \int_{M_{\text{II}}}^{M_{\text{lb}}} dM \left( \frac{dn}{dM} \right) M \]

\[ F_{\text{coll,lb}}(z) = \frac{1}{\rho_0} \int_{M_{\text{lb}}}^{\infty} dM \left( \frac{dn}{dM} \right) M \]

Haiman & Holder (2003)
Complications

• Star formation efficiency vs. halo mass & environment (e.g. mergers vs. quiescent star formation)
• Escape fraction of ionizing radiation vs. halo mass & environment
• Effects of radiative feedback both internal and external
• Metal enrichment
• Evolving IMF
• Radiative transfer in the IGM
  – Clumping
  – Photoevaporation
  – Absorption systems
• Role of X-ray sources (e.g. binaries and quasars)
• Observations give global constraints (e.g. WMAP-tau), only probe brightest galaxies (LBGs and LAEs), or probe ionization state only at relatively late times (Lyman-alpha forest, z<6)
Complications

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Star Formation Efficiency of Early Galaxies

• Key parameter in predicting ionizing production rate for a given background cosmology

• Largely dependent on theoretical predictions (e.g. hydrodynamical simulations) due to extreme faintness

• Subject to several important physical effects:
  – Energy injection from supernovae and ionization heating
  – Metal enrichment history of the gas
Star Formation Efficiency of Early Galaxies

Finlator et al. (2011)
Star Formation Efficiency of Early Galaxies

Wise et al. (2012)
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Ionizing Escape Fraction

• Typically found to be low observationally -- less than ~5-10% at z<6 (e.g. Boutsia et al. 2011)

• Dependent on geometric effects -- whether stars can carve out “channels” of low-density gas out of which ionizing radiation can escape

• Simulations point to an increasing escape fraction with decreasing halo mass (Gnedin et al. 2008; Wise & Cen 2011; Yajima et al. 2011)
Ionizing Escape Fraction

Massive galaxies at $z=3$

Gnedin et al. (2008)
Ionizing Escape Fraction

Yajima et al. (2011)
Ionizing Escape Fraction

Wise & Cen (2009)
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Photoionization Heating

- Whether or not a dark matter halo can host star formation can depend on whether it is exposed to ionizing radiation.
- Low mass halos do not have sufficiently deep gravitational potentials to overcome the pressure of ionized gas.
- Suppression of star formation in low mass halos expected to be strongly inhomogeneous during reionization, due to the patchy build-up of the photoionizing UV background.
Photoionization Heating

Thoul & Weinberg (1996)
Photoionization Heating

\[ M_g (h^{-1} M_\odot) \]

\[ 10^{10} \]

\[ 10^9 \]

\[ 10^8 \]

\[ 10^7 \]

\[ 10^8 \]

\[ 10^9 \]

\[ 10^{10} \]

\[ 10^{11} \]

\[ 10 V_c (\text{km/s}) 50 \]

\[ z = 5 \]

Gnedin (2000)
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Minimal Reionization Model
(Alvarez, Finlator & Trenti 2012)

• We set out to find simplest reionization model that adheres to major current observational constraints:
  – WMAP electron scattering optical depth $\sim 0.09$
  – Gunn-Peterson trough in high-z QSOs
  – Low escape fraction for high-mass galaxies observed at $z<6$
  – UV Luminosity function of galaxies at $z \sim 6-8$
    (e.g. Trenti et al 2010; Bouwens et al. 2011)
  – Ionizing emissivity from Ly$\alpha$ forest and Lyman-limit system mean free path (Bolton & Haehnelt 2008; Songaila & Cowie 2010)
Minimal Reionization Model
(Alvarez, Finlator & Trenti 2012)

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UV Luminosity Function

Oesch et al. (2012)
UV Luminosity Function

Oesch et al. (2012)
Abundance Matching

Kuhlen & Faucher-Giguere (2012)
Abundance Matching

Kuhlen & Faucher-Giguere (2012)
Abundance Matching

ICLF model

HUDF

$L \sim M_h^{1.3}$

Trenti et al. (2010)
Abundance Matching

Trenti et al. (2010)
Minimal Reionization Model
*(Alvarez, Finlator & Trenti 2012)*

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Emissivity from Ly$\alpha$ Forest

Bolton & Haehnelt (2007)
Emissivity from Lyα Forest

Songaila & Cowie (2010)
Emissivity from Ly$\alpha$ Forest

Flux and mean free path measurements can be combined to obtain ionizing photon emissivity

\[ \dot{n}_\gamma \propto \frac{\Gamma_{-12}}{\lambda_{\text{mfp}}} \]

Bolton & Haehnelt (2007)

Songaila & Cowie (2010)
Minimal Reionization Model

\[ \dot{x} = \frac{\dot{n}_\gamma}{n_0} - \frac{x}{\langle t_{\text{rec}} \rangle} \]

\[ \dot{n}_\gamma = f_{\text{esc},1} f_\gamma \dot{\rho}_*,1 + f_{\text{esc},2} f_\gamma \dot{\rho}_*,2 \]

\[ \dot{\rho}_* = \rho_0 \frac{\Omega_b}{\Omega_m} \left[ (1 - x) \epsilon_*,1 \dot{f}_1 + \epsilon_*,2 \dot{f}_2 \right] \]
Minimal Reionization Model

\[ \dot{x} = \frac{\dot{n}_\gamma}{n_0} - \frac{x}{\langle t_{\text{rec}} \rangle} \]

\[ \dot{n}_\gamma = f_{\text{esc},1} f_\gamma \rho_{*,1} + f_{\text{esc},2} f_\gamma \dot{\rho}_{*,2} \]

Use standard clumping factor of \( \approx 3 \) at \( z=6 \), declining to high redshift (e.g. Pawlik et al. 2011)
Minimal Reionization Model

Motivated by simulations, we use a two-component model, with two different escape fractions for low and high mass halos. High-mass halo escape fraction is fixed to be 0.05, while low-mass halo escape fraction was varied so as to obtain $\tau_{es} = 0.086$.
Minimal Reionization Model

\[ \dot{x} = \frac{\dot{n}_\gamma}{n_0} - \frac{x}{\langle t_{\text{rec}} \rangle} \]

\[ \dot{n}_\gamma = f_{\text{esc},1} f_\gamma \dot{\rho}*,1 + f_{\text{esc},2} f_\gamma \dot{\rho}*,2 \]

\[ M_1 = 10^8 M_\odot \quad f_{\text{esc},1} = 0.8 \]

\[ M_2 = 2 \times 10^9 M_\odot \quad f_{\text{esc},2} = 0.05 \]
We include the effect of suppression of low-mass halos by only allowing star formation to occur in halos with mass $M_1 < M_h < M_2$ if located in neutral regions, assuming they are distributed uniformly in space.

$$\dot{x} = \frac{n_{\gamma}}{n_0} - \frac{x}{\langle t_{\text{rec}} \rangle}$$

$$\dot{\rho}_* = \rho_0 \frac{\Omega_b}{\Omega_m} \left[ (1-x)\epsilon_{*,1} \dot{f}_1 + \epsilon_{*,2} \dot{f}_2 \right]$$
Minimal Reionization Model

\[ \dot{x} = \frac{n_\gamma}{n_0} - \frac{x}{\langle t_{\text{rec}} \rangle} \]

Star formation efficiency fixed to be same in both halo mass ranges - low mass halos no more efficient at forming stars. Ionizing photon per stellar mass obtained using Salpeter IMF with $[\text{Fe/H}] = -2$

\[ \dot{\rho}_* = \rho_0 \frac{\Omega_b}{\Omega_m} \left[ (1 - x)\epsilon_{*,1} f_1 + \epsilon_{*,2} f_2 \right] \]
Minimal Reionization Model

\[ \dot{x} = \frac{n_\gamma}{n_0} - \frac{x}{\langle t_{\text{rec}} \rangle} \]

\[
M_1 = 10^8 M_\odot \\
M_2 = 2 \times 10^9 M_\odot \\
\epsilon_{*,1} = \epsilon_{*,2} = 0.03
\]

\[
\dot{\rho}_* = \rho_0 \frac{\Omega_b}{\Omega_m} \left[ (1-x)\epsilon_{*,1} f_1 + \epsilon_{*,2} f_2 \right]
\]
Low mass halos contribute more ionizing photons at high redshift, while higher mass halos ‘take over’ at low redshift.
Satisfies emissivity constraints from $\text{Ly}\alpha$ forest determination of ionization rate (Bolton & Haehnelt 2007) and mean free path (Songaila & Cowie 2010)
Matches the star formation rate density predicted by extrapolation of UV luminosity function for large halos using the abundance matching method of Trenti et al. (2010)
Escape fraction decreases with time as star formation in low-mass halos is suppressed.
Qualitatively the same behaviour as in reionization model of Haardt & Madau (2012)
Summary

• Our model matches
  – Relatively low emissivity of ionizing photons at end of reionization
  – Relatively high Thomson scattering optical depth of ~0.09 reported by WMAP
  – Rapid decline in star formation rate density in high mass halos towards high redshift predicted from abundance matching LBGs

• No need to invoke Pop III stars or star formation in minihalos -- we use standard Salpeter IMF and Pop II metallicity and only atomic cooling halos

• Rapid increase in escape fraction required by Haardt & Madau (2012) and Kuhlen & Faucher-Giguere (2012) naturally explained by suppression of star formation in low-mass halos possessing high escape fractions
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Reionization and the Local Universe

MA, Busha, Wechsler & Abel (2009)
Busha, MA, Wechsler, Abel, & Strigari (2010)
Li, MA, Wecshler & Abel (2012)
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Missing Satellites “Problem”

\[ N(\gtrsim V_{\text{circ}}) \]

- \( \Lambda \text{CDM satellites} \)
- Local Group dwarfs
- Luminous satellites

\( V_{\text{circ}} \) (km/s)

Kravtsov et al. (2004)
Missing Satellites “Problem”

- Below a given mass, some satellite halos of the local group have been inhibited from forming long-lived stars.
- Many more of these satellite halos are predicted to form in CDM than are actually observed.

*Strigari et al. (2008)*

![Image showing a graph with mass and luminosity on logarithmic scales, with various satellite halos plotted.]
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Milky Way mass halos could have been reionized at $12 < z < 6$, even for a given global reionization history.

We used publicly available Via Lactea 2 data to track $\sim 6,000$ subhalos back to the reionization epoch.

We then assumed a given reionization epoch $z_{\text{reion}}$ and assumed star formation was shut off if halos were below a mass $M_{\text{thresh}}$. 
Satellite Abundance and Reionization History

Busha et al. (2010)
Results

Busha et al. (2010)
Results

• Strong dependence on $z_{\text{reion}}$ is at odds with previous results (i.e. Somerville 2002; Kravtsov et al. 2004)

• They used very smooth dependence of star formation rate by applying $f_{\text{gas}}$ from Gnedin (2000)

• However, that was measurement of total gas fraction, including hot gas

• In reality, such gas in low mass halos is completely ionized and cannot form stars
\[ f_{\text{gas}}(M, z) = \frac{f_{\text{baryon}}}{[1 + 0.26 M_f(z)/M]^3} \]

\[ f_{\text{cold gas}} \]

Busha et al. (2010)
Results

• To show this, we used star formation rate

\[ SFR = \begin{cases} \epsilon \left( f_{\text{cold gas}} \frac{M_{DM}}{M_\odot} \right)^\alpha & \text{if } M_{DM} > M_t, \ z > z_{\text{reion}} \\ 0 & \text{otherwise} \end{cases} \]

for a model with gradual and instantaneous suppression of star formation and tracked stellar luminosity using Bruzual & Charlot (2003) stellar population synthesis code with lowest possible metallicity
Results

Busha et al. (2010)
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Fast Reionization Simulations

• A technique for producing 3D evolving ionization field without doing radiative transfer
• Based on Furlanetto, Zaldarriaga, & Hernquist (2004) model
• Only requires linear Gaussian random density field as is usually produced for cosmological N-body simulations
• Smooth around each point and calculate collapsed fraction according to
  \[ f_{\text{coll}}(t) = \text{erfc} \left[ \frac{\delta_c(t) - \delta_m}{\sqrt{2 [\sigma^2_{\text{min}} - \sigma^2(m)]}} \right] \]
• Point is ionized if \( \zeta f_{\text{coll}} > 1 \) is met for any smoothing scale
Coupling N-body and Reionization Simulations

- Couple reionization and N-body simulations in
  - 1 Gpc/h box with $1120^3$ particles (Alvarez et al. 2009)
  - 420 Mpc/h box with $1400^3$ particles (Li et al. 2012)
- Halos identified at $z=0$
- For each halo, we trace back all the particles to find the redshift at which they were reionized
- This method allows easy determination of the size of the region that reionized a given point and the reionization history of every halo in the volume
$M_{\text{HALO}} = \frac{4\pi \rho_0 R_{\text{LAG}}^3}{3}$

$R_{\text{LAG}}$ is the radius of the halo mass at mean density.

H II Region size when halo’s comoving position was ionized.

**EXTERNAL REIONIZATION**

**INTERNAL REIONIZATION**
Bubble size distribution

Alvarez et al. (2009)
Bubble size distribution

Alvarez et al. (2009)
Bubble size distribution

Alvarez et al. (2009)
Bubble size distribution

\[ \frac{dN}{d\ln R} / \frac{dN}{d\ln M} \text{ (normalized)} \]

\[ R_{\text{bubble}} [\text{Mpc}] \]

11.5 < \log M_{\text{vir}} < 12.5
12.5 < \log M_{\text{vir}} < 13.5
13.5 < \log M_{\text{vir}} < 14.5
14.5 < \log M_{\text{vir}} < 15.5

Alvarez et al. (2009)
Bubble size distribution

Alvarez et al. (2009)
Halo Reionization Histories

\[ 11.75 < \log \frac{M_h}{M_\odot} < 12.25 \]

\[ \bar{x}(z) \]

--- global

Li et al. (2012)
Halo Reionization Histories

$12.25 < \log \frac{M_h}{M_\odot} < 12.75$

Li et al. (2012)
Halo Reionization Histories

\[ 12.75 < \log \frac{M_h}{M_\odot} < 13.25 \]

Li et al. (2012)
Halo Reionization Histories

13.75 < log $M_h/M_\odot$ < 14.25

Li et al. (2012)
Halo Reionization Histories

14.25 < \log \frac{M_h}{M_\odot} < 14.75

Li et al. (2012)
Halo Reionization Histories

$14.75 < \log M_h/M_\odot < 15.25$

Li et al. (2012)
Halo Reionization Redshifts

\[ 11.75 < \log \frac{M_h}{M_\odot} < 12.25 \]

\( z_{\text{reion}, 50\%} \) (in \( z=0 \) halos)

\( z_{\text{reion}, 50\%} \) (global)

Li et al. (2012)
Halo Reionization Redshifts

$12.25 < \log \frac{M_h}{M_\odot} < 12.75$

$L_1 \text{ et al. (2012)}$
Halo Reionization Redshifts

$12.75 < \log M_h / M_\odot < 13.25$

$z_{\text{reion}}, 50\%$ (in $z=0$ halos)

$z_{\text{reion}}, 50\%$ (global)

Li et al. (2012)
Halo Reionization Redshifts

$13.25 < \log M_h/M_\odot < 13.75$

Li et al. (2012)
Halo Reionization Redshifts

$13.75 < \log \frac{M_h}{M_\odot} < 14.25$

- - - $z_{\text{reion}}$, 50% (global)

$z_{\text{reion}}$, 50% (in $z=0$ halos)

$\propto \frac{dN}{dz}$

Li et al. (2012)
Halo Reionization Redshifts

$14.25 < \log M_h / M_\odot < 14.75$

$z_{\text{reion, 50\%}}$ (in $z=0$ halos)

$z_{\text{reion, 50\%}}$ (global)

Li et al. (2012)
Halo Reionization Redshifts

$14.75 < \log M_{h}/M_{\odot} < 15.25$

- - - $z_{\text{reion}}, 50\%$ (global)
  - $z_{\text{reion}}, 50\%$ (in $z=0$ halos)
Halo Reionization Redshifts

Li et al. (2012)
Dependence on Environment

\[ \Delta t_{\text{reion}} = 2.2 \text{ Myr} \]

\[ \Delta t_{\text{reion}} = 279.8 \text{ Myr} \]

\[ \Delta t_{\text{reion}} = 3.8 \text{ Myr} \]

\[ \Delta t_{\text{reion}} = 278.9 \text{ Myr} \]

Li et al. (2012)
Dependence on Environment

Li et al. (2012)
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• Effect of Radiative Feedback on the Local Universe
  – Timing of reionization in local environment strongly affects number of satellites when radiative feedback is assumed to be sudden
  – High mass halos at z=0 (i.e. clusters) were ionized internally, while lower mass halos (i.e. galaxies) could have been ionized either externally or internally depending on environment
  – Halos in high-density regions were ionized mostly externally and much faster than halos in low-density regions