Self-consistent Reionization Models: Observational Constraints

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Plan of the talk

- Background
- Formalism
  - Simple reionization models
  - Reionization of the inhomogeneous IGM
  - Self-consistent models
- Results
- Future work
Background

- Apparent discrepancy between Gunn-Peterson optical depths at $z \gtrsim 6$ and the first year WMAP results? White et al. (2003); Kogut et al. (2003)

- Explanation of the excess in the cosmic Near Infra Red Background observations requires Population III stars at $z > 9$ – what effect do they (and other sources) have on the reionization history? Salvaterra & Ferrara (2003)

- Require reionization models to deal with wide variety of spatial scales:
  - IGM inhomogeneities – sub-kpc
  - formation of (first) haloes with luminous sources – kpc
  - transfer of the ionizing radiation – tens of kpc
  - background radiation – Mpc
  - effect of QSOs – tens of Mpc

- Goal is to develop semi-analytical models with most of the essential physics incorporated
Simple models of reionization

Evolution of the volume filling factor of ionized regions:

\[
\frac{dQ_{\text{HII}}}{dt} = \frac{\dot{n}_{\text{ph}}}{n_H} - Q_{\text{HII}} C_{\text{HII}} \frac{n_e}{a^3} \alpha_R(T)
\]

Source term
\(\dot{n}_{\text{ph}}\): Rate of ionizing photons per unit volume

Recombination term
\(C_{\text{HII}} \equiv \langle n_{\text{HII}}^2 \rangle / \langle n_{\text{HII}} \rangle^2\): Clumping factor
\(\alpha_R(T)\): Recombination rate
Simple models of reionization

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\[ \dot{n}_{\text{ph}} = n_B N_{\text{ion}} \frac{dF_{\text{col}}}{dt} \]

Barkana & Loeb (2000)
Simple models of reionization

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\]

Evolution of the temperature

\[
\frac{dT}{dt} \approx -2H(z)T + \frac{2}{3k_{\text{boltz}} n_B} \frac{dE}{dt}
\]

Adiabatic cooling

Net heating rate per baryon

\[
\frac{dE}{dt} = \text{Photoheating} - \text{Recombination cooling} - \text{Compton cooling}
\]
Simple models of reionization

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Evolution of the ionization fraction

\[ \frac{dn_{\text{HII}}}{dt} = \text{Photoionization} - \text{Recombination} \]
Simple models of reionization

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\]

Ionizing flux is determined by the mean free path

\[
J_\nu \propto \lambda_\nu \dot{n}_{\text{ph}}
\]

Madau, Haardt & Rees (1999)
Reionization: Schematic Diagram

- Random density distribution

Just a sketch
Reionization: Schematic Diagram

- Random density distribution
- Sources of ionizing photons

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Reionization: Schematic Diagram

- Random density distribution
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- Ionized regions

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- Ionized regions
- Pre-overlap era

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- Approaching reionization

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- Reionization
- Post-overlap era

Just a sketch
Reionization of the inhomogeneous IGM

- **Post-overlap era**

\[
\frac{d[F_M(\Delta_{\text{HII}})]}{dt} = \frac{\dot{n}_{\text{ph}}(z)}{n_H} - R(\Delta_{\text{HII}}) \frac{n_e}{a^3} \alpha_R(T)
\]

**Clumping Factor:**

\[
R(\Delta_{\text{HII}}) = \int_{0}^{\Delta_{\text{HII}}} d\Delta \ \Delta^2 \ P(\Delta)
\]

Miralda-Escude, Haehnelt & Rees (2000)
Reionization of the inhomogeneous IGM

- Post-overlap era

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\frac{d[F_M(\Delta_{\text{HII}})]}{dt} = \frac{\dot{n}_{\text{ph}}(z)}{n_H} - R(\Delta_{\text{HII}}) \frac{n_e}{a^3} \alpha_R(T)
\]

- Pre-overlap era

\[
\frac{d[Q_{\text{HII}} F_M(\Delta_{\text{HII},\text{crit}})]}{dt} = \frac{\dot{n}_{\text{ph}}(z)}{n_H} - Q_{\text{HII}} R(\Delta_{\text{HII},\text{crit}}) \frac{n_e}{a^3} \alpha_R(T)
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Clumping Factor: 

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Miralda-Escude, Haehnelt & Rees (2000)
Reionization of the inhomogeneous IGM

- Post-overlap era
  \[
  \frac{d[F_M(\Delta_{\text{HII}})]}{dt} = \frac{\dot{n}_{\text{ph}}(z)}{n_H} - R(\Delta_{\text{HII}}) \frac{n_e}{a^3} \alpha_R(T)
  \]

- Pre-overlap era
  \[
  \frac{d[Q_{\text{HII}} F_M(\Delta_{\text{HII, crit}})]}{dt} = \frac{\dot{n}_{\text{ph}}(z)}{n_H} - Q_{\text{HII}} R(\Delta_{\text{HII, crit}}) \frac{n_e}{a^3} \alpha_R(T)
  \]

Mean free path determined by the fraction of ionized volume
Miralda-Escude, Haehnelt & Rees (2000)
Features of the model

- Self-consistent treatment for the evolution of ionized regions and thermal history.
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- Follow evolution of neutral, HII and HeIII regions simultaneously. Treat the IGM as a multi-phase medium.
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- Inhomogeneous IGM density distribution: lognormal model
  Found to be a reasonable approximation for the low-density IGM at $2 < z < 6$
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- Three sources of ionizing radiation:
  1. PopIII stars: early redshifts, high mass, low metallicity
     Required to match the excess in NIRB
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- Three sources of ionizing radiation:
  1. PopIII stars: early redshifts, high mass, low metallicity
  2. PopII stars: normal stars, transition from PopIII at $z \gtrsim 9$
     Press-Schechter and Sasaki formalism to calculate the formation rate and survival time of dark matter haloes.
     Model for SFR: peaking around the dynamical time of the halo, decreasing exponentially thereafter.
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  3. Quasars: significant at $z \lesssim 6$

  Model based on the empirical $v_c - M_{BH}$ relation; Wyithe & Loeb (2002); Mahmood et al. (2003)
Features of the model

- Self-consistent treatment for the evolution of ionized regions and thermal history.
- Follow evolution of neutral, HII and HeIII regions simultaneously. Treat the IGM as a multi-phase medium.
- Inhomogeneous IGM density distribution: lognormal model
- Three sources of ionizing radiation:
  1. PopIII stars: early redshifts, high mass, low metallicity
  2. PopII stars: normal stars, transition from PopIII at $z \gtrsim 9$
  3. Quasars: significant at $z \lesssim 6$
- Radiative feedback suppressing star formation in low-mass haloes
  Lower limit of the mass function
  - set by molecular cooling in neutral regions
  - set by photoionization temperature in the ionized regions
Free parameters

- Star forming efficiencies ($\epsilon_*$) and escape fractions ($f_{\text{esc}}$) for PopII and PopIII stars
- Transition redshift ($z_{\text{trans}}$) for PopIII $\longrightarrow$ PopII

Check the effects of varying the parameters, and try to constrain by matching with observations.
Free parameters

- Star forming efficiencies ($\epsilon_*$) and escape fractions ($f_{\text{esc}}$) for PopII and PopIII stars
- Transition redshift ($z_{\text{trans}}$) for PopIII $\rightarrow$ PopII

Use a model with “fiducial” values of parameters.

- $\epsilon_*,\text{III} \sim 0.5\%$ (NIRB studies)
- $f_{\text{esc},\text{III}} \sim 1$ (Whalen et al. (2004))
- $\epsilon_*,\text{II} \sim 10\%$ (Low-$z$ SFR)
- $f_{\text{esc},\text{II}} \sim 2\%$ (uncertain)
- $z_{\text{trans}} \approx 10$ (NIRB studies)

Check the effects of varying the parameters, and try to constrain by matching with observations.
Results: Reionization History

Volume filling factor

![Graph showing the volume filling factor over redshift (z) for HII and HeIII]
Results: Reionization History

Volume filling factor

SFR

Graphs showing the volume filling factor and SFR as functions of redshift (z).
Results: Reionization History

Volume filling factor

SFR

Photoionization rate for HI

Photoionization rate for HeII
Results: Reionization History

Volume filling factor

$\Delta_i$

[HII, HeIII]

$z$

[10, 20]

[0, 1]

[0, 0.5]
Results: Reionization History

Volume filling factor

Clumping factor

Δ_i

H II
He III
Results: Reionization History

Volume filling factor

Clumping factor

Mean free path
Results: Reionization History

Volume filling factor

Neutral fraction
Results: Comparison with Observations

Volume filling factor

Mean free path

Lyman limit systems

Lyman limit system data points from Storrie-Lombardi et al. (1994)
Results: Comparison with Observations

Volume filling factor

GP optical depth

GP optical depth data from Songaila (2004)
Results: Comparison with Observations

Volume filling factor

GP optical depth

Temperature

$T_0$ data from Schaye et al. (1999)

$\gamma = 1$

$\gamma = 1.7$

$\gamma = 2.4$
Results: Comparison with Observations

Volume filling factor

Electron scattering optical depth

TE cross $^z$ power spectrum (WMAP) data from Kogut et al. (2003)
Results: Possible variations

- $0.15\% < \epsilon_{*,\text{III}} < 2\%$ from WMAP data.
- $f_{\text{esc,II}} < 10\%$ from GP optical depth at $2 \lesssim z \lesssim 6$.
- Different feedback models: Higher feedback at high redshifts can suppress the growth of HeIII regions and can delay or prohibit the (first) HeII reionization.
- Reduced power on small scales by suppressing cooling in minihaloes ($T_{\text{vir}} < 10^4$ K):
  - require higher $\epsilon_{*,\text{III}}$ to match WMAP data
  - the effect of feedback is less severe
Results: Summary

- H-reionization at $z \approx 14$.
- Double HeII-reionization at $z \approx 12$ (PopIII-induced) and at $z \approx 3.5$ (QSO-induced). Recombination at $z \lesssim z_{\text{trans}}$.
- Observations of $T_0$: consistent with HII regions at $z \gtrsim 3.5$ and with HeIII regions at $z \lesssim 3.5$.
- About 0.2% of total stars need to be PopIII in order to explain the WMAP data and to achieve the H-reionization at high redshifts.
Future Studies

- Detailed look into the Gunn-Peterson optical depths around $z \approx 6$ using line-of-sight realizations.
- Implications on future CMB polarization and 21cm observations.
- Incorporate evolution of the IGM metallicity?