Sources of Cosmic Reionization

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**SOURCE LIST**

- **Stars: Pop II and/or (massive) Pop III**
  
  *In what proportion?* (4, 30, 100) × $10^3$ phot/baryon into stars

- **Quasars**
  
  *Too rare, too late; key sources for HeII reionization*

- **Supernova explosions**
  
  *Filling factor too small; Compton-y limited*

- **Dark Matter: decays/annihilations**
  
  *Light particles (LDM, sterile neutrinos) can produce a* $\tau_e < 0.01$
  
  *Heavy particles (neutralinos, gravitinos) totally negligible*

- **Mini-quasars**
  
  *Limited by unresolved SXRB*
  
  *Only 3 phot/baryon in IGM in 10 Salpeter times*

- **Structure formation**
  
  *Important for HeII reionization, bremsstrahlung has $f_{esc} \approx 1!$*
REIONIZATION CHALLENGES

EXPERIMENTAL CONSTRAINTS

• Lyα Gunn-Peterson opacity
• Electron scattering optical depth
• Lyβ Gunn-Peterson opacity
• UV Background intensity
• Redshift evolution of Lyman Limit Systems
• IGM Temperature evolution
• IGM Metallicity
• Cosmic star formation history
• High-z galaxy counts
• Near Infrared Background
GLOBAL REIONIZATION MODELS

REIONIZATION HISTORY

Choudhury & AF 2005-2008

Electron sc. optical depth

Lyα G-P Optical depth

Counts

Lyβ G-P Optical depth

Temperature

Lyman Limit Systems

Counts

\[ \tau_e \]

\[ \tau_{\gamma} \]

\[ \rho_{\text{HI}} / h \]

\[ \Gamma_{\text{HI}} / 10^{-7} \text{erg}^{-1} \]

\[ T_e / 10^4 \]
HIGH-Z GALAXIES

SEARCH TECHNIQUES

DROP-OUTS

- Sharp drop in flux shortwards than Lya line
- Finding galaxy candidates at z>6 : using i, z, Y, J-drops.
- Contamination by stars and low-z ellipticals

LYMAN ALPHA EMITTERS

- Narrow band filters tuned on redshifted Lya line
- Few and narrow atmospheric clean windows
- Not all spectroscopically confirmed
CHEMICAL FEEDBACK

COSMIC POP III/POP II TRANSITION

Tornatore, AF & Schneider 2007

Fraction of Pop III forming sites

Total Metallicity

z=5

z=3

z=5

z=3

Pop III
Pop II

Pop II wave
CHEMICAL FEEDBACK

Tornatore, AF & Schneider 2007; Schneider+2008

STAR FORMATION RATES

\[ \langle Z \rangle_M \]

\[ M_\odot \text{yr}^{-1} \text{Mpc}^{-3} \]

\[ \frac{Z}{Z_\odot} \]

redshift

PopII

PopIII

(5Mpc)\(^3\)

(10Mpc)\(^3\)

(5Mpc, LR)\(^3\)
HIGH-Z GALAXIES

HIGH-Z LUMINOSITY FUNCTIONS

Simulations: Salvaterra+2010, submitted

Steep faint-end $\alpha \approx -2$
PROPERTIES

LYMAN ALPHA EMITTERS

• Halo masses $10^{10-12} \, M_\odot$
• SFR = 1-100 $M_\odot \, yr^{-1}$
• Ages > 40 – 400 Myr
• Lya LF evolves; UV LF does not in $z=5.7-6.6$
• Large EW (> 200Å) often observed
• Can be due to (a combination of):
  ✷ top-heavy IMF
  ✷ differential dust Lya/continuum extinction
  ✷ outflows //infall (also affecting line shape)
LAES IONIZING POWER

\begin{align*}
\log \left[ \frac{Q_{\text{LAE}}}{s^{-1} \text{Mpc}^{-3}} \right] &= 49.32 \\
\log \left[ \frac{Q_{\text{ion}}}{s^{-1} \text{Mpc}^{-3}} \right] &= 51.54 + \log C_{30}
\end{align*}

LAE contribute \( \approx 1\% \) of ionizing budget

PASSIVE TRACERS OF REIONIZATION?
DROPOUTS CONSTRAINTS

\[ \rho_{\text{SFR}} \approx 0.013 \, f_{\text{esc}}^{-1} \left( \frac{1 + z}{6} \right)^3 \left( \frac{\Omega_b \, h_{50}^2}{0.08} \right)^2 \, C_{30} \, M_\odot \, \text{yr}^{-1} \, \text{Mpc}^{-3} \]

Dwarf (fainter) galaxies required?
PERSISTING PUZZLES

Inoue+2008; Siana+2010

Reionization sources

\( f_{\text{esc}} \)

- Increases from \( z=0 \) to \( z=3 \)
- Increases for low mass objects
- Larger in LAEs than in LBGs
- Too many LCE for Salpeter IMF

\( z = 3.09 \)
REIONIZATION SOURCES

Choudhury & AF 2008

SMALL OR LARGE?

Searching for the reionization sources

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ABSTRACT

Using a reionization model simultaneously accounting for a number of experimental data sets, we investigate the nature and properties of reionization sources. Such model predicts that hydrogen reionization starts at \( z \approx 15 \), is initially driven by metal-free (PopIII) stars, and is 90\% complete by \( z \approx 8 \). We find that a fraction \( f_\gamma > 80\% \) of the ionizing power at \( z \geq 7 \) comes from haloes of mass \( M < 10^9 M_\odot \) predominantly harboring PopIII stars; a turnover to a PopII-dominated phase occurs shortly after, with this population, residing in \( M > 10^9 M_\odot \) haloes, yielding \( f_\gamma \approx 60\% \) at \( z = 6 \). Using Lyman-break broadband dropout techniques, \( J \)-band detection of sources contributing to 50\% (90\%) of the ionizing power at \( z \approx 7.5 \) requires to reach a magnitude \( J_{110,AB} = 31.2(31.7) \), where \( \sim 15(30) \) (PopIII) sources/arcmin\(^2\) are predicted. We conclude that \( z > 7 \) sources tentatively identified in broadband surveys are relatively massive (\( M \approx 10^9 M_\odot \)) and rare objects which are only marginally (\( \approx 1\% \)) adding to the reionization photon budget.
$f_\gamma > 80\%$ of the ionizing power from $M < 10^9 M_\odot$ halos
POSSIBLE SOURCE CANDIDATES

Salvadori & AF 2009

WHAT ARE THEY?

Willman+ 2006, Simon & Geha 2007

Ultra Faint Dwarf Spheroidals
POSSIBLE SOURCE CANDIDATES
Salvadori & AF 2009

ULTRA FAINT DSPHS: METALLICITY
UFs: MASS & FORMATION EPOCH

UF Dwarf Spheroidals
SUMMARY OF MAIN POINTS

- **Stars** dominate the reionization photon budget (mini-QSO/DM negligible contributors)
- Reionization started by metal-free stars at $z=20$; 90% complete at $z=8$
- Early reionization ($z > 7$) not in contrast with any experimental data
- $f_\gamma > 80\%$ of the ionizing power at $z > 7$ from halos of $M < 10^9 \, M_\odot$
- Current drop-out high-z candidates are not the reionization sources
- **LAEs** are passive tracers of reionization provided we break the dust-IGM HI degeneracy
- **Very/ Ultra faint** dwarfs are likely to be the dominant ionizing photons providers
- Ultra Faints are the oldest dSphs ($z > 8.5$) left-overs of $H_2$ cooling mini-halos