Galaxy Formation and Cosmic Reionization

Stuart Wyithe
(University of Melbourne)
Reionization: Basic Questions

- What were the sources? (stars or quasars)
- When did it occur? (6<z<15)
- What was the topology? (smooth or patchy)
- Where did it start? (outside-in or inside-out)
- Was it regulated by feedback? (radiative or chemical)
Reionization: Things (think) We Know

- ΛCDM cosmology plus hierarchical structure formation
- The first sources appeared in halos above the Jeans mass \([H_2 \text{ cooling in } 3\sigma \text{ peaks (}10^6 M_\odot\text{) at } z=30]\)
- Photo-ionization provided the ionization mechanism, as evidenced by the Ly\(\alpha\) forrest
- Stars rather than quasars provided the ionizing photons, at 6<z<20
Observations of the End of Reionization
Constraining Reionization From Quasar Spectra

- The GP troughs imply a rapid increase in the neutral fraction at $z \approx 6$

Model Fits Imply Reionization at $z \sim 6$

- Reionization by Pop-II stars with evolution regulated by structure formation yields observed evolution of the ionizing background

---

Gnedin & Fan (2006)
CMB Photons Scatter off Free Electrons in the Reionized Universe

- The optical depth $\tau_{es}$ to Thomson scattering is

\[
\tau_{es} = \int_0^{1000} dz \frac{cdt}{dz} \sigma_T n_H^0 \left[ 1 - x_{HI}(z) \right] (1 + z)^3
\]

- $\tau_{es}$ is sensitive to early reionization

- Correlation function consistent with $\tau_{es} \sim 0.06--0.12$ ⇒ an early reionization at $10 < z < 15$. (Spergel et al. 2006)
The Evolution of the Ly$\alpha$ Luminosity Function Provides No Evidence For or Against Reionization at $z=6$

Dijkstra et al. (2007)
Shimasaku et al. (2006)
Kashikawa et al. (2006)
Iye et al. (2006)

theoretical value
Galaxies at the End of Reionization

- Star-formation rate at $z \sim 6$ consistent with the completion of reionization at $z \sim 6$
- HUDF sees galaxies down to $\sim 10^{10}M_\odot$

Bouwens and Illingworth (2006)
Bouwens et al. (2006)
• Models based on structure formation, with $f_{\text{star}} f_{\text{esc}}$ a free parameter. Existing data readily reproduced

• Reionization is dominated by low mass galaxies, and occurs rapidly. Models are currently under-constrained
Patchy Reionization and Suppression of Galaxy Formation in a Heated IGM
$\tau_{\text{eff}}$ Shows Spatial Variation in the Ionizing Background

\[
\tau_{\text{eff}} = -\ln\left(\exp\{-\tau\}\right)
\]

\[
\tau = A \frac{\Delta^2}{J}
\]

- Important length scales: Ionizing photon mfp and absorption path length ($\Delta z = 0.15$)

Fan et al. (2006)
Simulation of Fluctuating Density

- Halo mass: $10^9 - 10^{10} M_\odot$
- $10^{10} - 10^{11} M_\odot$
- $10^{11} M_\odot$

Absorption path-length $\delta > 0$
Variation in $\tau_{\text{eff}}$ Due to Density Fluctuations

- Simulations of the scatter in $\tau_{\text{eff}}$ find values that are similar to, but smaller than observed.

Variation in $\tau_{\text{eff}}$ Due to Density Fluctuations
Lidz et al. (2006)

Observed scatter

\[ \tau_{\text{eff}} \]

\[ z \]

Lidz et al. (2006)
Fluctuations in Ionizing Background

- All galaxies contribute to the ionizing background radiation
- Fluctuations in the ionizing background probe the minimum galaxy mass
- Fluctuations dominated by Poisson noise and cosmic variance in formation times
Formation with $M < 10^{10} M_\odot$ is Suppressed Following Reionization

- Evidence for radiative feedback on formation of low mass galaxies at $z < 5.7$
- Constraints less restrictive at higher $z$ - hint of the start of suppression at $z \sim 6$

Wyithe & Loeb (2006)
The Future: Redshifted 21cm Observations of Neutral Hydrogen
Neutral hydrogen at $z \sim 6$ could be detected at frequencies near 200MHz:

$$\Delta T_b \approx (23\text{mK}) x_{\text{HI}}$$

Several low-frequency arrays under construction including LOFAR, PAST, and the MWA-LFD

Topology of Reionization is Sensitive to the Source Population

Each panel would subtend the same solid angle as the moon.

McQuinn et al. 2007
Reionization should leave a distinct mark on the power-spectrum of spatial fluctuations in 21cm emission.

Reionization topology is encoded in the power-spectrum of 21cm intensity.

McQuinn, Zahn, Hernquist, & Furlanetto (2006)

- Reionization should leave a distinct mark on the power-spectrum of spatial fluctuations in 21cm emission.
The MWA-LFD Aims to Detect the End of Reionization in 21cm Emission

Uncertainty due to thermal and cosmic sample variance (360 hours, 8 MHz bandwidth)

Non-Gaussian 21cm Fluctuations

- Galaxy bias leads to non-Gaussianity of fluctuations, and non-monotonic variation of fluctuations with ionization and redshift

Wyithe & Morales (2007)
Second and Third Moments of 21cm Fluctuations Probe Galaxy Formation

Wytche & Morales (2007)
Cross-Correlation of Fluctuations With Galaxies Directly Probes the Sources of Reionization

(Wyithe & Loeb 2007; Furlanetto & Lidz 2007)

• Galaxy bias correlates galaxies, ionization with dense regions => negative cross-correlation
Conclusions

• Models of the reionisation history can accommodate current observations within a $\Lambda$CDM cosmology, but these are very under constrained.

• Low frequency arrays will provide a powerful tool to probe galaxy formation in the pre-reionisation era.

Photo: D. Barnes