The Epoch of Reionization: Galaxy Build-up in the First Billion Years

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Exploring the Reionization Epoch with HST

Here: Focus on Hubble’s Horizon and on Reionization by Galaxies
Are Galaxies Responsible for Cosmic Reionization?

WMAP predicts mean redshift of reionization at 10.6 
($\tau = 0.088 \pm 0.015$; Komatsu+ 2011)
The Ionizing Flux Density from Galaxies

\[ \phi(M_{1400}) \xrightarrow{\text{integrate}} \rho L_{1400} \langle N_{\gamma<912}/N_{\gamma 1400} \rangle \xrightarrow{f_{\text{esc,rel}}} \dot{N}_{\text{ion}} \]

- Faint contribution: Have to extrapolate to below detection limits
- With these steep faint-end slopes as observed: luminosity density completely dominated by faint galaxies

No problem to -17: Just integrate observed LF!
Correcting from Observed to Total LD

- Total: integrated down to $M = -10$
- Corrections change by almost an order of magnitude within currently allowed 1$\sigma$ range of faint-end slope
- Future effort: constrain this better!

Assume $\alpha = \text{const}$ and extrapolate LF trends
Inferred Reionization History

- A steep faint-end slope makes it easy for the galaxy population to complete reionization above $z>6$

- **But:** optical depth to electron scattering is below measured values from WMAP by $1.5\sigma$

Thomson optical depth of model: $\tau_e \sim \mathbf{0.066}$

WMAP measurement: $\tau_e \sim 0.088 \pm 0.015$

Even with somewhat optimistic assumptions:
- clumping factor = 3
- relative escape fraction = 20%

$z_{\text{reion}}$ (WMAP) $\sim 10.6$

$z_{\text{reion}} \sim 8$
Steepening in Faint-End Slope with Redshift?

Tentative evidence for steeper faint-end slopes at higher $z$

Thus: faint galaxies are consistent with being capable of driving reionization.

However: Need to better constrain this evolution!
The Horizon of the Hubble Space Telescope: Constraints on the z~10 galaxy population
Pushing Frontier to $z \sim 10$

- At $z \sim 9$: neutral IGM starts affecting $J_{125}$
- Can select $z > 9.5$ galaxies as J-dropouts based on red $J_{125}$-$H_{160}$ colors

- Very challenging:
  - $z \sim 10$ galaxies expected to be extremely faint
  - single band detections
  - low-z dusty galaxies can exhibit similar colors
Requirements on Data

- deep $J_{125}$ and $H_{160}$
- deeper data shortward of Ly$\alpha$ break

Non-detection required

Hubble Ultra Deep Field 2009–2010
Hubble Space Telescope • WFC3/IR

NASA, ESA, G. Illingworth (University of California, Santa Cruz),
R. Bouwens (University of California, Santa Cruz and Leiden University), and the HUDF09 Team
The $z \sim 10$ Candidate in the HUDF

- $z_{\text{phot}} = 10.4 \pm 0.4$
- Small ($\sim 10\%$) chance of being a low-$z$ contaminant
- Planned HST data might help to further strengthen the high-$z$ solution

- Very faint: $H_{\text{AB}} = 28.8 \pm 0.2$
- Small chance of being spurious:
  - It is detected at $\sim 6\sigma$
  - It is visible at $>2.5\sigma$ in 4 independent splits of the data
- Blue UV continuum: not detected in very deep IRAC data
**Extended z~10 Search**

- CDFS offers perfect data for z~10 search
- Large amount of public optical (ACS) and NIR (WFC3) data
  - HUDF09
  - ERS
  - CANDELS (Deep & Wide)
- Total of 160 arcmin$^2$
- Reach to 26.9 - 29.4 AB mag

Our first analysis included only these two fields: Bouwens et al., Nature, 2011

More than triple the search area both for bright and faint sources
Low-Redshift Contaminants

- 16 sources are found satisfying our HST selection criteria
- 15 out of these are dusty/evolved sources at intermediate redshift (z~2-4)
- These are identified by strong Spitzer IRAC detections (H_{160}-[3.6]>2)

**Therefore:** only our previous z~10 candidate from the HUDF found in full data

Such red intermediate redshift sources appear to have a peaked LF

**However:** Beware of z~10 selections without Spitzer coverage
Constraints on $z \sim 10$ LF

- Assume no evolution in galaxy population from $z \sim 8$ to $z \sim 10$: expect **25** $z \sim 10$ sources

- Extrapolate low-$z$ LF trends (c.f. Rychard's talk) to $z \sim 10$: expect to see **6** sources

- Even including cosmic variance: chance of finding one when expecting 6 is only ~6%

→ Accelerated evolution of UV LF detected at $\sim 2\sigma$
Constraints on $z \sim 10$ LF (II)

Three Wide Fields: limits are below $z \sim 8$

Three HUDF09 Fields: $z \sim 10$ limits are below extrapolation
Accelerated Evolution of the UV Luminosity

Rapid build-up of UV luminosity in galaxies within only 170 Myr

**But:** result is still uncertain (due to only 1 detection) needs confirmation with future deeper data (JWST!)
Summary

- The total flux density in ionizing photons is very sensitive to the faint-end slope. Given current uncertainties in the slope, deeper observations are absolutely necessary.

- The faint-end slopes measured at \( z \geq 6 \) are very steep and show weak trends to steepen towards high redshift. Therefore, galaxies below the current detection limits are consistent with being capable of reionizing the universe.

- Only 1 viable \( z \sim 10 \) candidate identified so far in current WFC3/IR data over CDFS. The upper limits on the \( z \sim 10 \) UV LF are significantly below extrapolation of observed trends.

- Indicates accelerated evolution of UV LF at \( M < -18 \) at \( z > 8 \), essentially at \( 2\sigma \), including cosmic variance. The 170 Myr from \( z \sim 10 \) to \( z \sim 8 \) appears to be a time of rapid change in the galaxy population.

- Need JWST to further constrain accelerated evolution. \( z > 8 \) is JWST territory.