Exploring the High-Redshift Universe with HST

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The Reionization Epoch with HST

Here: Focus on Reionization by Galaxies and on Hubble’s Horizon
Installation of WFC3 on HST

- 6.5x larger field-of-view than previous NIR camera (NICMOS)
- 3-4x more sensitive than before
- 2x higher spatial resolution

→ ~40x more efficient to explore the high-redshift universe
Progress on z>6.5 Samples with WFC3/IR

NICMOS: 12 galaxies (10 years of observations)

WFC3/IR: 20 galaxies (1st week of observations)

WFC3/IR: >100 galaxies (2 years of data)
WFC3/IR’s Resolution => Structure/Sizes

Oesch et al. 2010b
Evolution of UV LF to $z \sim 8$

Main Evolution: only in $M^*$ (0.33 mag per unit $z$)

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

\[ \phi(M_{1400}) \rightarrow \rho L_{1400} \rightarrow \dot{N}_{ion}^{int} \rightarrow \dot{N}_{ion} \]

integrate

\[ \langle N_\gamma < 912 / N_\gamma 1400 \rangle \]

\[ f_{esc, rel} \]


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 problems to -17: Just integrate observed LF!
Where is the Faint-End Cutoff?

- Halos with $T=10^{4-5}$ K are affected by UV background
- Halos below $T=10^4$ K can only cool in H$_2$

**ICLF model**

$L \sim M_h^{1.3}$

$10^4$ K halos host $M_{AB} = -10$ galaxies

Trenti et al. 2011

**Lower luminosity cut-off in the range: $M_{AB} = -10$ to -13 (but see also M. Kuhlen’s talk!)**
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 faint (undetected) 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: $\tau_e \sim 0.066$

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

Additional assumptions:

- clumping factor = 3
- relative escape fraction = 20%
Tentative evidence for steeper faint-end slopes at higher $z$ (also seen in many simulations/theoretical models)

Required optical depths can be achieved since $\tau_e$ very sensitive to changes in faint end slope

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

**However:** Need to better constrain evolution of faint end slope with redshift!
The Horizon of the Hubble Space Telescope: Constraints on the z~10 Galaxy Population
Pushing the Frontier to $z \approx 10$

- At $z \approx 8$: 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:
  - $z \approx 10$ galaxies expected to be extremely faint
  - single band detections
  - low-$z$ dusty galaxies can exhibit similar colors
Requirements on Data

deep $J_{125}$ and $H_{160}$

deep data shortward of Ly$\alpha$ break

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

STScI-PRC11-05
The $z \approx 10$ Candidate in the HUDF

- Very faint: $H_{AB} = 28.8 \pm 0.2$
- 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

$z_{\text{phot}} = 10.4 \pm 0.4$

Small ($<\sim 10\%$) chance of being a low-$z$ contaminant

Planned HST data might help to further strengthen the high-$z$ solution
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~10 LF

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

- Extrapolate low-z LF trends (c.f. Garth’s talk) to z~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 ~2σ
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 $z > 8$, at $2\sigma$ significance, 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.