Star-Forming Galaxies at $z>5$ & Reionization

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"Lyman break technique" - sharp drop in flux at $\lambda$ below Ly-\(\alpha\). Steidel et al. have $>1000$ $z\sim3$ objects, "drop" in U-band.
HUBBLE SPACE TELESCOPE
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Pushing to higher redshift- Finding Lyman break galaxies at $z \sim 6$ : using $i$-drops.
Using HST/ACS GOODS data - CDFS & HDFN, 5 epochs B,v,i',z'

Bunker et al. (2003) MNRAS
HST WFC3
RECENT EXCITEMENT - 100 orbits of HST with WFC3 in 3 near-IR filters on Hubble Ultra Deep Field. Galaxies at $z=7-9$! Data first taken in August-Sept. 2009. 4 papers immediately (Bouwens et al., Bunker et al., McLure et al., Oesch et al.) and 7 more since. 2 large HST surveys (Illingworth UDF + WFC3 team - O’Connell)
By selecting on rest-frame UV, get inventory of ionizing photons from star formation. Stanway, Bunker & McMahon (2003 MNRAS) selected z-drops $5.6 < z < 7$ - but large luminosity bias to lower $z$. Contamination by stars and low-$z$ ellipticals.
Latest results:
Wilkins et al.
(2010) MNRAS
ArXiv:
1002.4866

We studied 3 deep fields (each 5 sq. arcmin) and a larger 40 sq. arcmin field in GOODS-South to search for 7<z<10 galaxies. Found 44
I-drops in the Chandra Deep Field South with HST/ACS
Elizabeth Stanway, Andrew Bunker, Richard McMahon
2003 (MNRAS)
Brightest HUDF Y-drop
Found in Sept 2009:
YD3 in Bunker et al
UDFy-31835539 in
Bouwens et al.;
#1721 in McLure et al.

In late 2009, Nature paper
Lehnert et al. claiming
spectroscopic confirmation
of Ly-alpha at $z=8.55$
with SINFONI-IFU on VLT.
No evidence of Ly-alpha at $z=8.55$ in 5-hour VLT/XSHOOTER and 11-hour Subaru/MOIRCS spectrum. Also, the deep HST/WFC3 Y-band encompasses Ly-alpha, should be detected at $\sim 4\sigma$ but is undetected.
Looking at the UDF (going 10x deeper, \(z'=26 \rightarrow 28.5\) mag)

\[
\log_{10}(\rho_{\text{SFR}} / h_{70} M_\odot \text{yr}^{-1} \text{Mpc}^{-3})
\]

\[
\begin{align*}
\text{No Extinction} \\
\text{Bunker, Stanway, Ellis & McMahon 2004 MNRAS} \\
\text{SFR}\geq 1.5M_\odot \text{yr}^{-1}
\end{align*}
\]
- **UDF enables us to identify even fainter galaxies at these times** (end of dark ages)
- **We were first to analyse & publish 50 high redshift galaxies in the UDF**
- **Confirms our previous work: much LESS star formation than in more recent past**
After era probed by WMAP the Universe enters the so-called “dark ages” prior to formation of first stars. Hydrogen is then re-ionized by the newly-formed stars. When did this happen? What did it?
Reionization

At high redshift, the Lyman-\(\alpha\) forest can absorb most of the flux below \(\lambda_{\text{rest}}=1216\text{\AA}\). Indications from \(z>6.3\) SDSS QSOs that Universe many be optically thick (Fan et al. 2001; Becker et al. 2001). BUT confusing messaged from WMAP CMB - reionization at \(z\sim11\)? (Dunkley et al. 2010).
Probing the dark ages
reionization and distant galaxies

- Universe at z~6 was very different from z~3: would predict 6x as many bright star forming galaxies at z~6 than we see!

- Reionization: the UDF data has star formation at z=6 which is 3x less than that required!

So how does Universe reionize?

- Different physics of star formation early on? (masses of stars)
- Undiscovered fainter sources (forming globular clusters?)
- Star formation at even earlier times?
An increasing problem for reionization: requires steep faint-end slope ($\alpha < -1.7$), large contribution from unobserved faint galaxies, high escape fraction ($f_{\text{esc}} > 0.5$) and very smooth IGM (low clumping, $C \sim 5$)

Wilkins et al. (2010) MNRAS
The Luminosity Function at $z \sim 7$
Evolution of luminosity function
(note $M^*$ is correlated with $\phi^*$)

Wilkins et al. (2011)
UV Spectral Slopes at $z > 6$ : $f_\nu \propto \lambda^{-\beta}$

Stanway, McMahon & Bunker (2005) - found very blue colours for i-drops in NICMOS UDF
Also now seen in z-drops with WFC3 (Bouwens et al. 2011, Dunlop et al. 2011, Wilkins et al. 2011)
- From Wilkins et al. (2011) MNRAS
- Weak dependence of beta evolution on luminosity
- Careful on filters - the Lyman-alpha break will redden intrinsic colours
Spitzer – IRAC (3.6-8.0 microns)
30 Myr constant SFR with E(B-V) = 0.1
- No reddening
- 0.2 solar metallicity
JAMES WEBB SPACE TELESCOPE – successor to Hubble (2014+)
Conclusions

- Have found star-forming galaxies at $z=6-10$ (Lyman breaks), and spectroscopic confirmation at $z\sim 6$
- However, $z>7$ number counts from HST/WFC3 imply the newly-discovered galaxies would struggle to reionize
- Many of these have very blue rest-UV spectral slopes
- High escape fraction/Steep faint end slope/low metallicity/smooth IGM?
- JWST spectroscopy should resolve many questions