The Quest for Cosmic Dawn

Richard Ellis (UCL)
1. Early reionisation (WMAP)

- Tantalizing fading (0.5 m3) seen in the LF of Ly α emitters over a small redshift interval 5.7 < z < 6.6 (150 Myr)
- Does this mark the end of reionization corresponding to an increase in XHI (e.g. XHI ~0.6 at z~7)?

Optical depth to scattering:
\[ \tau = 0.17 \pm 0.08 \text{ (WMAP1, 2003)} \]
\[ \tau = 0.09 \pm 0.03 \text{ (WMAP3, 2007)} \]
\[ \tau = 0.087 \pm 0.017 \text{ (WMAP5, 2009)} \]

2. Lyα LF 5.7<z<6.5

3. WFC3 revolution began

4. Great anticipation of JWST (launch 2014) and TMT/ELT (2018) 😐
Receding Horizons: The Most Distant Object

The Current Frontier

 Courtesy: Dan Mortlock
Since Hubble UDF, HST has undertaken wider field comparably deep campaigns (CANDELS) plus a series through lensing clusters (CLASH, Frontier Fields, RELICS).

Impressive but only 28 galaxies z>7 and 6 galaxies z>8 are spectroscopically confirmed.
The Holy Grail: Locating the First Galaxies?

A commonly promoted idea for isolating first generation systems has been to search for chemically pristine examples.
Rapid (<60 Myr) SN Enrichment in Early Mini-Halos

Identifying rare pristene (Pop III) galaxies will be very hard
More practical to tie cosmic dawn to onset of reionisation

Planck Indicates Late and Fast Reionisation

CMB polarisation probes foreground Thomson scattering from the start of reionisation to the present epoch. Optical depth of scattering $\tau$ constrains the mean redshift $<z>$ and (model dependent) duration of reionisation.

Planck (2019) find $\tau = 0.0506 \pm 0.009$ corresponding to $<z> \sim 8.0$

Models indicate reionisation began at $z \sim 10$-12 and ended at 6.
Depending on their ionising output, galaxy demographics from HST matches Planck’s optical depth with reionisation from $12 < z < 6$ suggests galaxies reionised universe provided their ionising capability is similar to that seen in $z \sim 3$ Lyα emitters.

We find $\log \xi_{\text{ion}} \sim 25.5$ cgs
$< f_{\text{esc}} > \sim 10\%$

Ionising Spectrum of z~3 Lyα Emitters

\( \xi_{\text{ion}} = \) Intrinsic Lyman continuum flux per unit UV luminosity

\( \text{O32} = [\text{O III}] 5007 / [\text{O II}] 3727 \)

Lyman alpha emitters (leakers/non-leakers) are metal-poor, dust-free & promising analogues of z>7 galaxies with harder radiation fields than Lyman break galaxies (grey)

**Escape Fraction of z~3 Lyα Emitters**

HST LyC imaging of z~3 LAEs: 30% have $f_{\text{esc}} \sim 15$-65% and correlation with O32

Stack of the rest reveals no signal ($f_{\text{esc}} < 0.3\%$)

No spectral difference between leakers/non-leakers; dichotomy due to viewing angle

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**F336W**  
**Lyα**  
**F160W**

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**$f_{\text{esc}}$ vs O32**

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Fletcher, RSE et al (2018)  
Nakajima, RSE et al (2019)
The End of Cosmic Reionisation

Consistent views from Planck, Gunn-Peterson test and Lyman α fractions?

Challenges:
(1) Hard to convert \( x(\text{Ly}α) \) into \( x(\text{HI}) \)
(2) Scatter in GP \( \tau_{\text{eff}} \) – origin unclear
(3) No good data beyond \( z \approx 7 \)

The probes confirm reionisation ended at \( z \approx 6 \) but give little additional evidence

Even so, some papers interpret this trend in terms of sources of reionisation
**Robertson et al (2015)** – classic paper assumed all galaxies have equal ionising capabilities regardless of luminosity and redshift

**Finkelstein et al (2019)** – redshift-dependent contribution; feeble galaxies contribute more early on, hence extended reionisation history

**Naidu et al (2019)** – contribution is dominated by massive galaxies which form later and hence provide better fit to fast/late evolution of neutral fraction
Cosmic Dawn: The Beginning of Reionisation

Planck Consortium 2016: Surprisingly bold statement!

The distributions of the two parameters, \( z_{\text{end}} \) and \( z_{\text{beg}} \), are plotted in Fig. 12. With the redshift-asymmetric parameterization, we obtain \( z_{\text{beg}} = 10.4^{+1.9}_{-1.6} \) (imposing the prior on \( z_{\text{end}} \)), which disfavours any major contribution to the ionized fraction from sources that could form as early as \( z \gtrsim 15 \).

Later modeling within \( \Lambda \)CDM framework suggests otherwise...

Greig & Mesinger (2016)
Cosmic Dawn @ \( z \sim 15-20 \)?

An absorption profile centred at 78 megahertz in the sky-averaged spectrum

Judd D. Bowman\(^1\), Alan E. E. Rogers\(^2\), Raul A. Monsalve\(^{1,3,4}\), Thomas J. Mozdzen\(^1\) & Nivedita Mahesh\(^1\)

Wouthuysen-Field coupling of 21cm spin temperature and Lyman alpha radiation from first sources produces 21cm absorption of CMB

EDGES experiment (Bowman et al 2018) claims surprisingly deep 21cm absorption over \( 15 < z < 20 \)
Declining Luminosity Density to $z > 10$

Data from deep fields (UDF, CANDELS) and lensing clusters (CLASH, Frontier Fields)

- reasonable agreement but seriously sample-limited at $z > 9$
- contentious issue – is there a sharper decline at $z > 8$?

![SFR Density Evolution Graph]

- $> 0.3 \, M_\odot/yr$
- $z \sim 10$ Combined HST Fields
  
  HUDF+GOODS (Oesch+13/14)
  Ishigaki+17
  McLeod+16
  Bouwens+16

**Cosmic Dawn?**

McLeod et al (2016)

Oesch et al (2017)
Probing Cosmic Dawn Indirectly?

Current facilities cannot observe sources beyond $z \sim 11$

Over 1000 $z > 7$ HST candidates, but only $\sim 28$ spectroscopically confirmed

Can we estimate their ages and earlier star formation histories?

Salmon et al 2018
Earlier workers noted the IRAC 4.5µm excess which, given photometric redshift uncertainties, could arise from nebular [O III] 5007 emission or a Balmer break due to starlight – an age indicator!

The interpretation of the so-called IRAC excess in MACS1149_JD1 depends critically on its redshift!

Beyond a redshift $z=9.0$, [O III] moves out of the IRAC 4.5μm band.

Courtesy: Guido Roberts-Borsani
MACS1149_JD1: $z=9.1096$ is $>200$ Myr old

Spectroscopic confirmation from ALMA/VLT demonstrates IRAC excess is due to starlight not nebular emission. Balmer break provides a valuable age indicator.

To reproduce Balmer break, UV SED/[O III] 88 μm & dust continuum upper limit, most of rest-frame optical light is due to $\sim10^9 \text{ M}_\odot$ of stars 290 Myr old $\Rightarrow $ $z_F \sim 15 \pm 2$

Hashimoto, Laporte, RSE et al (2018)
Spectra of More Balmer Break Candidates….

Keck 6hrs: Lyα @ z=8.78 (6σ)

GN-z10-3 has Lyα at z=8.78. Although IRAC excess could be due to [O III], a young stellar population is ruled out by prominent F160W flux: 
Age ~ 290 Myr z_F~15

Keck 6hrs: possible Lyα z>9 (marginal)

VLT 10hrs: in progress (Aug/Sep)

Laporte, Meyer, RSE in prep
Revisiting the Origin of the IRAC Excess

Many luminous $7 < z < 9$ galaxies have a strong excess in the 4.5μm Spitzer IRAC band.

4 such objects (H$\sim25$) located in CANDELS fields; all spectroscopically-confirmed

How sure are we that this excess arises solely from [O III]/H$\beta$ emission given we see similar excess at $z > 9$ where these lines are redshifted beyond the band?

Perhaps surprisingly, a Balmer break SED (MACS1149_JD1 with no lines) can, within the observational uncertainties, also explain the IRAC excess colours for 7.5<z<9.0 spectroscopically confirmed sources with IRAC data!

NB: Not implying [O III] does not contribute but rather than the ages and stellar masses of these sources may be underestimated.

Roberts-Borsani, Laporte, RSE in prep
Atacama Large Millimetre Array (2015 - )

ALMA interferometer with up to 15 km baselines has Hubble resolution for tracing early dust
Dust at $z=8.38$

ALMA Band 7 ~1mm dust at $z=8.38$

If early dust grains were formed mostly in SNe, the mass could provide a crude estimate of earlier chemical enrichment and star formation.

Redshift with ALMA ([O III])

Stellar mass $2 \times 10^9 M_\odot$

SFR $\sim 20 M_\odot$ yr$^{-1}$

Dust mass $\sim 6 \times 10^6 M_\odot$

Laporte, RSE et al (2017)
Three Dust Detections at $z > 7.5$

- $T_{dust}$ leading to large mass uncertainties
- Past SF history (uniform/rising/declining with time?)
- Amount of dust ejected or not detected (nonetheless a valuable lower limit)
- Continued dust production via sputtering in ISM?
Probing Cosmic Dawn: The Latest

Although highly uncertain, using dust masses and stellar ages we get a first glimpse of evidence for earlier star formation to redshifts $z \sim 11-15$. 

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Age of Universe

500 400 300 200 Myr
Direct Detection of Progenitors?

Predicted early evolution of the UV brightness of MACS1149_JD1 according to the best SED fit at z=9.1 compared to imaging limits with NIRCAM (10σ 20 mins) and spectroscopic limits with NIRSpec (10σ 3 hours).
Summary

• Good progress in determining the demographics of star-forming galaxies to z~10 from deep fields and via lensing clusters

• Census (numbers, LFs) can be made consistent with Planck optical depth if ionising radiation is hard and escape fractions are ~10% as suggested in metal-poor analogues: Lyman alpha emitters at z~3

• The most distant spectroscopically-confirmed z>8 sources with metal lines, dust continua and Balmer breaks point to star formation as early as z~15

• In the best studied cases the prospects are good for directly studying the earlier phases of activity with JWST
How uncertain is the age, e.g. as a function of assumed SF histories?

- Unable to reproduce the Balmer break with constant or rising SFHs

Do the stellar population diagnostics come from same spatial location?

- Hard to convincingly determine due to low IRAC resolution
- Velocity offset between Lyα and [O III] 88μm may imply two components

Could IRAC ch2 excess be due to extremely intense Hβ/[O III] 4959A?

- Only for very young SF; intense [O II] would produce `inverted Balmer break’

Is JD1 an outlier in terms of structure formation?

- Most models predict rising SFHs over 8<z<15 and lower stellar masses
- Katz et al (2019) can reproduce the basic properties in hydro simulations