Cosmic Dawn:
The Quest for the First Stars & Galaxies

Richard Ellis, Caltech
Observable Cosmological History

1) Recombination

Robertson et al., *Nature*, 468, 49 (2010)
Observable Cosmological History

2) “Cosmic Dawn”

Robertson et al., *Nature*, 468, 49 (2010)
Observable Cosmological History

3) Reionization

Robertson et al., Nature, 468, 49 (2010)
4) Modern Cosmological History

Robertson et al., Nature, 468, 49 (2010)
The Grand Questions

• Cosmic Dawn: The First Metal-free Stars & Star Clusters:
  - When did they form?
  - How rapidly did later enriched generations form?
  - Visibility issues with James Webb Space Telescope

• Cosmic Reionization: The First Galaxies
  - When did reionization occur?
  - Were galaxies responsible for reionization?
  - What physical processes governed early assembly and IGM enrichment
  - How do we connect all this to \( z < 6 \) observations?

Recent review: *Nature* 468, 49 (2010)
Brant Robertson (CIT), Dan Stark (IoA), Jim Dunlop, Ross McLure (Edinburgh)

Collaborative material from:
Matt Schenker (Caltech) Masami Ouchi (Tokyo), Eiichi Egami (Arizona), Jean-Paul Kneib (Marseilles), Johan Richard (Lyon)
Cosmic Dawn: The First Stars

- Early protostars can cool via H\(_2\) which is easily dissociated by radiation (Dekel & Rees 1987)

  - pristene systems (H, He only)
  - very massive and compact (30 - 300 M\(_\odot\))
  - extraordinarily hot and luminous (10\(^6\) L\(_\odot\))
  - short-lived (~3 million years)

Questions: How long did this Pop III phase last? What governs the transition from Pop III to Pop II? What are the observational possibilities for detecting Pop III stars?
Pop III Stars are Hotter and Evolve Rapidly

$T_{\text{eff}}$ up to 100,000 K with much stronger/harder ionizing spectrum

Tumlinson & Shull (2000)
Evolution of First Stellar Systems & Halos

ENZO code (Bryan & Norman 1997, Wise & Abel 2011)

Wise et al astro-ph/1011.2632
Halo mass $M = 8 \times 10^7 \, M_\odot$
(no merger activity)

- Evolution of stellar metallicity is governed by *enriched outflow vs pristene inflow*

- Evolution is remarkably rapid (e.g. due to one PISN!)

- Near-instant enrichment to $[Z/H] \sim -3$; no low metallicity tail!

Wise et al astro-ph/1011.2632
James Webb Space Telescope
Nebular He II line widely discussed as possible probe of Pop III
- Transient feature – may disappear in short period (~ Myr)
- Also produced in WR stars so intense emission essential to detect

Schaerer 2002
Assumes single burst, \( f_{\text{gas}} \sim 0.01, f_{\text{SFR}}^Z \sim 0.1 \)

He 1640 only visible for low mass systems with top-heavy IMFs (Pop III.1)

Pawlik et al 2011 astro-ph/1011.0438
Number with S/N~10 in a 10 arcmin$^2$ field in $10^6$ s exposure

Counts very sensitive to presence of zero metallicity systems and top-heavy IMFs but depend also on duration of starburst ($<1$ to $10^3$ sources per pointing!)

Pawlik et al 2011 astro-ph/1011.0438
Cosmic Reionization: The First Galaxies

Did Galaxies Reionize the Universe?

- need enough star-forming galaxies to provide the necessary ionizing photons
- sustained population to overcome recombination
- means for ionizing photons to escape absorbing material within galaxies

What Physical Processes Govern the Emerging Mass and Luminosity Distribution?

- radiative/feedback determines what happens next

The Present Landscape

Indirect constraints on when reionization occurred:

• Optical depth to reionization, $\tau$, from the WMAP satellite
• Downturn in ionized carbon abundance at $z > 5$
• Stellar mass densities of $4 < z < 6$ galaxies: earlier star formation

Studies of Early Galaxies

• Two techniques: Lyman alpha emitters and Lyman break galaxies
• The HST WFC3 revolution: new galaxy candidates beyond $z \sim 7$
• Tracking Lyman $\alpha$ in distant galaxies spectroscopically
• Other related probes (QSOs, GRBs)

Challenges and prospects for the future
Data rejects instantaneous reionization at z~6-7

CMB does not pinpoint the responsible cosmic sources
Ionized Carbon Absorbers in High z QSOs

Use QSOs as background beacons to highlight absorbing clouds in the high z intergalactic medium.
Rapid Drop in Carbon Abundance beyond z~5?

- Near-IR spectra of z > 6 QSOs reveal CIV abundance (Ryan-Weber et al, Simcoe et al)
- Sudden decline over 300 Myr in $\Omega_{\text{CIV}}(z)$

Sudden drop could arise from rapid abundance rise due to early enrichment of galaxy halos or ionization changes?
High Redshift Star Forming Galaxies

**Lyman break galaxies (LBGs):**
Rest-frame UV continuum discontinuity

**Lyman alpha emitters (LAEs):**
Located via narrow band imaging

- Typical intrinsic spectrum of massive star
- After passing through interstellar gas

![Graphs and images related to Lyman break galaxies and Lyman alpha emitters.](image-url)
Star formation density of LBGs

Monotonically declining population to $z \sim 6$ and beyond

Drop of $\times 8$ in UV luminosity density $2 < z < 6$

Appealing indicator: but `observed SF' may be misleading guide

Spitzer Revolution: Stellar Masses & Ages

A modest 85cm cooled telescope can see the most distant known objects and provide crucial data on their **assembled stellar masses and ages**

SMB03-1: \( z_{\text{spec}}=5.83 \) IRAC(3.6\( \mu \text{m} \))=24.2 (AB)

stellar mass = \( 3.4 \times 10^{10} \, \text{M}_\odot \)    age > 100 Myr

Eyles et al (2005): to produce this mass since \( z \sim 10 \) required 5-30 \( \text{M}_\odot \, \text{yr}^{-1} \) comparable to the ongoing SFR (6-20 \( \text{M}_\odot \, \text{yr}^{-1} \)) so should see earlier examples if unobscured
Age is degenerate with star formation history but can infer time-averaged star formation rate and compare this with actual on-going star formation rate.

Key concern: do nebular emission lines contaminate the IRAC bands?
Stellar Mass Density

Stellar mass density at $z \sim 5-6$ implies significant past SF in low luminosity galaxies: perhaps sufficient for reionization?

$M_*(z) = \int_{z=5}^{z=10} \rho_*(z) dV(z)$

Stark et al 2007, 2009; Labbé et al 2009ab, Gonzalez et al 2010
Panoramic imaging with Subaru using narrow-band filters has been used to locate high redshift Lyα emitters (LAEs). As much as 7% of the total output of a young galaxy can be in this single emission line (so very efficient for survey work).
Lyman α Emitters: How it Works

- Selection made in narrow z interval c.f. LBGs
- Spectroscopic confirmation often incomplete
Direct imaging through a narrow band filter with Subaru found 2 candidate z~7 galaxies

One was spectroscopically confirmed at z=6.96

Lyman $\alpha$ as a probe of the Dark Ages

• Lyman $\alpha$ line is weakened by neutral hydrogen and thus a valuable tracer of its presence.

• Neutral hydrogen in `Dark Ages’ acts as fog obscuring the line emission from young galaxies.

• A sudden drop in the visibility of line emitting galaxies may indicate we are entering the Dark Ages!
A Rapid Drop in Lyα Emitters from 5.7<z<6.6?

• 1 deg² SXDS field with 608 photometric and 121 spectroscopic Lyα emitters

• Tantalizing fading (0.₃ m) seen in the LF of Lyα 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 $x_{\text{HI}}$ (e.g. $x_{\text{HI}}$ ~0.6 at z~7)?

High Redshift Star Forming Galaxies

Lyman break galaxies (LBGs):
Rest-frame UV continuum discontinuity

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Located via narrow band imaging

**Typical intrinsic spectrum of massive star**

After passing through interstellar gas
Keck Spectroscopic Survey of $4 < z < 7$ LBGs

- B, V, i’, z drops in GOODS/UDF from Stark et al (09) ACS/IRAC catalog
- 8-16 hr exposures with DEIMOS to $m_{AB} = 26.5$ (emission lines to $m_{AB} \approx 27.5$)
- Keck/DEIMOS: 361 B + 141 V + 45 I + 17 z-drops = 564 spectra
- VLT/FORS2 retro-selected + same criteria: 195 spectra (Vanzella et al)

Sample Keck Spectra (R~2500)

$m=24.15, z=4.01$

$m=26.4, z=5.19$

$m=25.9, z=4.35$

$m=27.4, z=3.87$

$m=26.4, z=3.74$

$m=26.3, z=5.45$

Stark et al (2010) MN 408, 1628
We see a rising visibility with redshift to z~6
Suggests should be straightforward to detect emission in z > 7 sources

Boosting the signal with gravitational lenses
Gravitationally Lensed Galaxies: Record Breakers (1991-2008)

- Cl2244-02 (z=2.237); Mellier et al 1991
- A2218 #384 (z=2.515); Ebbels et al 1996
- MS1512 cB58 (z=2.72); Yee et al 1996, Seitz et al 1998
- A2390 (z=4.05); Frye et al 1998, Pellò et al 1999
- MS1358+62 (z=4.92); Franx et al 1997
- A2218 (z=5.7); Ellis et al 2001
- A370 (z=6.56); Hu et al 2002
- A2218 (z~6.8); Kneib et al 2005
- A1689 (z~7.6); Bradley et al 2008
Critical line discoveries in Abell 2218

RSE et al 2001, Kneib et al 2004

\[ z \approx 6.8 \]

\[ z \approx 5.6 \]
Deciphering past history of z~6.8 lensed LBG

Multiply-imaged z=6.8 galaxy in cluster Abell 2218; magnification ×25

Star formation rate = 2.6 M⊙yr⁻¹  Stellar mass ~ 5-10 10⁸ M⊙

Balmer break gives age = 100 – 450 million yrs, so formed at 9 < z_F < 12

This is already a well-established system 800 Myrs after Big Bang

Egami et al (2005)
Hubble Ultradeep Field
Progress with WFC3

$\lambda\lambda 850 - 1170$nm

$2.1 \times 2.3$ arcmin  0.13 arcsec pixel$^{-1}$

Hubble WFC3 High z Stampede

WFC3/IR: 850 - 1170nm
2.1 × 2.3 arcmin field of view
0.13 arcsec pixel\(^{-1}\)
10 times survey power of NIC3

UDF 4.7 arcmin\(^2\)
60 orbits in YJH
Reaches m\(_{AB}\)~29 (5σ)

2009 Sep – Dec articles

Bouwens et al 0909.1803
Oesch et al 0909.1806
Bunker et al 0909.2255
McLure et al 0909.2437
Bouwens et al 0910.0001
Yan et al 0910.0077
Labbé et al 0910.0838
Bunker et al 0910.1098
Labbé et al 0911.1365
Finkelstein et al 0912.1338
z > 7 candidates from WFC3 UDF campaign

3 IR filters c.f. 2 leads to more secure photometric redshifts and reliable UV continuum slopes

Spectra of 26 WFC3 selected LBGs 6.3<z_{\text{photo}}<8

Keck NIRSPEC/LRIS-R spectra of 19 z>6.3 WFC3-IR LBGs from UDF, ERS, lensing clusters

Plus 7 Hawk-I/WFC3-IR FORS-2 spectra from Fontana et al (2010)

Luminosity distribution c.f. 5<z<6 sample

**z~6 emitters**

New z > 6.3 emitters

SuddenDeclinein\ \text{Ly}\alpha\ \text{Fraction}\ \text{in}\ \text{LBGs}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{sudden_decline_lya_fraction_lbg}
\caption{Sudden decline in \text{Ly}\alpha\ fraction in LBGs.}
\end{figure}

z~7 QSOs!

Follow-up photometry of ULAS J1120+0641:

\[ F_{\lambda,i} = (0.1 \pm 0.4) \times 10^{-17} \text{ W m}^{-2} \text{ } \mu\text{m}^{-1}; \lambda_{\text{AB}} \gtrsim 25 \]
\[ F_{\lambda,z} = (0.6 \pm 0.2) \times 10^{-17} \text{ W m}^{-2} \text{ } \mu\text{m}^{-1}; \lambda_{\text{AB}} \sim 24 \]
\[ F_{\lambda,Y} = (8.1 \pm 0.4) \times 10^{-17} \text{ W m}^{-2} \text{ } \mu\text{m}^{-1}; \lambda_{\text{AB}} = 10.3 \]
\[ F_{\lambda,J} = (6.0 \pm 0.4) \times 10^{-17} \text{ W m}^{-2} \text{ } \mu\text{m}^{-1}; \lambda_{\text{AB}} = 20.2 \]

Mortlock et al (2011)

UKIDSS

8500 A

VISTA

Venemans et al (in prep)
Further Evidence: Damping Wing in z=7.085 QSO?

Fit both near-zone radius & damping wing to red side of Lyα
Suggests $x_{\text{HI}} > 0.1$ at $z \sim 7$
A proximate DLA is an alternative explanation but unlikely

Bolton et al (2011)
Gamma Ray Bursts

$\log N_{\text{HI}} \sim 21.3$

GRB050904
$z=6.295$

Subaru
FOCAS 4.0 hr exposure

$x_{\text{HI}} < 0.6$

How Does Cosmic Reionization Occur?

Ionization Fraction Evolution

\[ \frac{dQ_{\text{HII}}}{dt} = \frac{1}{\langle n_{\text{HII}} \rangle} \frac{dn_{\text{ion}}}{dt} - Q_{\text{HII}} C_{\text{HII}} \frac{\langle n_{\text{HII}} \rangle}{a^3} \alpha_B(T) \]

Comoving H density

Scale factor

Case B recombination coefficient

Ionizing Photon Density

\[ \frac{dn_{\text{ion}}}{dt} = f_{\text{esc}} \zeta Q \rho_{\text{SFR}} \]

Escape fraction

Ionizing photon production rate

Comoving star formation rate density

Recombination Time

\[ t_{\text{rec}} = \left[ (1 + 2 \chi_{\text{He}}) \langle n_{\text{HII}} \rangle \alpha_B(T) C_{\text{HII}} \right]^{-1} \]

Helium fraction

Clumping Factor

\[ C_{\text{HII}} \equiv \frac{\langle n_{\text{HII}}^2 \rangle}{\langle n_{\text{HII}} \rangle^2} \]

\( \sim 1-6 \) (Pawlik et al. 2009)

Robertson et al (2010)

Madau et al. 1998, Bolton & Haehnelt 2007
Requirements for Reionization by Galaxies

3 basic requirements to test hypothesis:

• A sustained output from star-forming galaxies over 7<z<10 (continuity in SF trends over Δt~300 Myr)
• A steep faint end slope ensuring high fraction of UV photons arises from abundant sub-luminous sources (α < -1.8), i.e. ρ_{SFR}
• A good understanding of the stellar populations, for example: is there a increased number of massive stars at high z such as might be expected in very metal poor young systems? i.e. ζ_Q
• A high escape fraction of ionizing photons f_{esc}

Prospects for resolving ambiguities in next 2-3 years is promising via

- first UDF campaign (Cy 18, Illingworth 105W, 125W, 160W)
- shallower CANDELS MCT campaign (Faber/Ferguson)
- deeper targeted UDF campaign (Cy 19, Ellis, 105W, 140W, 160W)
Sustained Output from SF Galaxies $3 < z < 10$

66 $z \sim 7$ and 47 $z \sim 8$ candidates in deep HUDF + parallel fields (AB~29, 4 arcmin$^2$) & shallower ERS area (AB~27.5, 40 arcmin$^2$)

Bouwens et al astro-ph/1006.4360
An aside: $z \sim 10$? Bouwens et al vs Yan et al

Bouwens et al 0912.4263
Yan et al 0910.0027

Bunker et al: no convincing J-drop candidates to $H \sim 28.5$
Yan et al: 20 J-drops to $H \sim 29$
Bouwens et al: 3 J-drops to $H \sim 29$

One band detections and not a single candidate in common!
Steep Luminosity Functions @ z~7

Utilizing deep + shallow WFC3/IR plus Subaru

Steep faint end slope: low star formers <1 M☉ yr⁻¹ dominant

Ouchi et al 2009 Ap J 706, 1136; Bouwens et al astro-ph/1006.4360 plus many earlier papers (Oesch, Bunker, McLure…) also poster by Yan
Robertson et al (2010): some tensions even assuming $f_{\text{esc}} = 0.2$, $C_{\text{HII}} = 2$
Constraining Early Star Formation from GRBs

$N(<z)$ for 152 GRBs (plus dark sample) matches integral of SFH $0<z<4$ (best fit for low metallicity sources following $z$-dependent MMR). Allows us to interpret rate of GRBs with $z>6$. 

Robertson & Ellis (astro-ph/1109.0990)
A Gamma Ray Burst Version?

High number of \( z > 6 \) GRBs implies more SF than HST has seen and matches WMAP \( \tau \) but seriously overproduces Spitzer measured stellar mass.

Robertson & Ellis (astro-ph/1109.0990)
What could make up the photon shortfall?

- Some component of WMAP $\tau$ (~0.02?) may come from first generation of massive stars; not all has to arise in $7<z<10$ galaxies
- Steeper than observed faint end slope of LF?
- Exotic stellar populations (e.g. top heavy IMF)?

Failing this, we’d have to consider a second source of reionizing photons
Future Prospects

• HST + WFC3:
  - Deeper UDF campaign will probe fainter sources and clarify UV slope

• Continued improvement in 4<z<7 spectroscopic surveys:
  much to learn about demographics of LBGs/LAEs including spatial mapping of populations (Subaru PFS + Keck DEIMOS)

• Multi-slit IR spectrographs for following existing and other z>7 candidates
  - MOSFIRE on Keck (2012A)

• JWST (2018??) and..not too far off..(2020)..TMT

LOTS TO LOOK FORWARD TO!
Projected LFs @ $z \sim 7-8$ with New HST campaign

- Very steep LFs ($\alpha \sim -2$) necessary to close reionization budget
- Statement is highly dependent on assumed $f_{\text{esc}}$
- Current uncertainty in faint end slope $\Delta \alpha \sim 0.2-0.3$ (Bouwens, McLure)
- New UDF program (128 orbits) will provide improved faint end constraints
Cryogenic Multi-slit IR spectrograph
6.1 x 3.1 arcmin spectroscopic field
\(\lambda\lambda 0.97 - 2.45\) microns
R \(\sim 3300\) for 0.7 arcsec slit
45 slits via configurable slit unit
(\(<5\)mins)
Subaru Wide Field Instrumentation

2400 fiber positioning system

FoV of HSC

FoV of Suprime

FoV of PFS

FoV of FOCAS

TMT/WFOS

DEIMOS

VIMOS

~1.5 deg

1.7 m

500 mm
AO impacts JWST-TMT Synergy

TMT with AO will have better resolution than JWST (*not a dream: Keck AO has better resolution than HST*)
– together with large aperture significantly changes space-ground synergy

First sources & cosmic reionization:
– TMT is key to locating more abundant, fainter, smaller sources (AO gives ×10-100 gain over JWST depending on angular size).
– JWST probes to higher z in mid-IR

Lensed galaxies at z ~6
Unlensed sizes ~ 150pc or < 30mas!
James Webb Space Telescope

Assembled Flight Instrument

NIRSPEC
Simulated NIRSPEC spectra

AB=27 z=8 enabling full nebular/stellar decontamination and gas phase metallicities

AB=29 z=10 (current UDF limit)
Conclusions & Future Prospects

- Exciting time in the study of z>7 galaxies with HST, Spitzer and large telescopes still in the vanguard
- Dramatic progress with deep IRAC observations: from a couple of z~6 detections in 2005 now to comprehensive measures of the stellar mass density over 4<z<7
- WFC3 has led to rapid progress:
  - continuity of SF trends over 300 Myr
  - dominant fraction of sub-luminous galaxies
- Rapid decline in visibility of Lyman α over 6.5<z<8 suggests neutral era begins in this redshift range
- Many uncertainties but good prospects for improved data which will address possible deficiency of galaxies as source of reionizing photons
- Key role of future large telescopes in exploiting adaptive optics and efficient multi-object spectrographs in concert with JWST and large samples of 7<z<10 which can still be delivered by HST