Witnessing the End of Cosmic Reionization

Ay211

Lecture is on http://www.astro.caltech.edu/~rse/ay211_reioniz.ppt
What is the Reionization Era?
A Schematic Outline of the Cosmic History

- The Big Bang
  The Universe filled with ionized gas

- The Universe becomes neutral and opaque
  The Dark Ages start

- Galaxies and Quasars begin to form
  The Reionization starts

- The Cosmic Renaissance
  The Dark Ages end

- Reionization complete, the Universe becomes transparent again

- Galaxies evolve

- The Solar System forms

- Today: Astronomers figure it all out!

S.G. Djorgovski et al. & Digital Media Center, Caltech
End of the Dark Ages:
Reionization of Hydrogen by First Star-forming Galaxies

Courtesy: Nick Gnedin
Clues to the End of Cosmic Reionization

- Evolution in the optical depth of Lyα absorption in high redshift QSOs (Fan et al AJ 131, 117, 2006; Fan et al ARAA 44, 415, 2006)

- Metals in the intergalactic medium (Songaila AJ 131, 24 2006; Ryan-Weber et al MN 395, 1476 2009)


- Rapid evolution in the Lyman alpha luminosity function 5.7 < z < 6.5 (Kashikawa et al Ap J 64, 7, 2006; Ouchi et al 2009 in prep)

These motivate us to search the era z > 7 for star forming sources

First results from WFC3/IR on Hubble Space Telescope
Gunn-Peterson Test

- The Normal Hydrogen Absorbers Forest (Reionization Complete)
- Ionized Bubbles in a Still Largely Neutral Universe
- Opaque Neutral Gas in the Earlier Universe (Before the Reionization)

Line of Sight to the Quasar

The Quasar

The Observed Spectrum:

Intensity

Wavelength or Redshift

Isolated Transmission Spikes Correspond to the Ionized Bubbles Along the Line of Sight

Dark Regions Correspond to the Still Opaque, Neutral Gas Along the Line of Sight

Becker et al AJ 122, 2850 (2001)
\[ \tau_{GP} = -\ln T \]

Do complete troughs mean reionization just ended at \( z=6.2 \)?

Or is it just natural thickening of the forest as we move to higher \( z \)?

Clue: as we approach end of reionization we expect abrupt change in optical depth \( \tau_{GP} \) with \( z \)

11 SDSS QSOs

Fan et al AJ 125, 1649 2003
SDSS QSOs (2006)

SDSS i-z colors in 6600 deg$^2$ used to locate 19 QSOs with 5.74<z<6.42

Combined analysis of Ly$\alpha,\beta,\gamma$ opacity used to verify $\tau_{GP}(z)$:

Wavelength ranges:

Ly$\alpha$: 1040 < $\lambda$ (Å) < (1216)
Ly$\beta$: 970 < $\lambda$ (Å) < (1040)
Ly$\gamma$: 949 < $\lambda$ (Å) < (970)

( ) - region affected by QSO ionization (proximity effect) excluded

Fan et al AJ 132, 117, 2006
Using Ly $\alpha$ & Ly $\beta$ together

Redshift

Ly$\beta$

Ly$\alpha$

cosmic variance

$z_{QSO}$

$z_{QSO}$
How GP effect works

\[ \tau_{GP} = \frac{\pi e^2}{m_e c} f_\alpha \lambda_\alpha H^{-1}(z) n_{HI} \]

\[ \tau_{GP}(z) = 1.8 \times 10^5 h^{-1} \Omega_m^{-1/2} \left( \frac{\Omega_b h^2}{0.02} \right) \left( \frac{1 + z}{7} \right)^{3/2} \left( \frac{n_{HI}}{n_H} \right) \]

- So even tiny neutral fraction \( x_{HI} \sim 10^{-4} \) gives a complete GP trough
- For reference \( x_{HI} \sim 10^{-5} \) at \( z \sim 0 \)
- But since \( \tau_{GP} \propto f_\lambda \), for same \( n_H \), \( \tau(\text{Ly}\beta) \), \( \tau(\text{Ly}\gamma) \) are <6.2, <17.9 smaller
- In practice, conversion from \( \tau \rightarrow n_{HI} \) depends on IGM clumpiness
- So absolute comparison of higher order Lyman lines more complicated than identifying relative trends in each
Empirical argument; discontinuity seen in both samples:

For $z < 5.5$ $\tau(\alpha) = 0.85[(1+z)/5]^{4.3}$ ; $\tau(\beta) = 0.38[(1+z)/5]^{4.3}$

Data for $z > 5.5$ is inconsistent: $\propto (1+z)^{10.9+}$

Dispersion increases likewise: $\sigma(\tau)$ from $0.3 \rightarrow 0.6$

This is the fundamental justification for the end of reionization
Fan et al (2006): Combining the higher order Lyman lines on an absolute scale is hard

For a log-normal P there is no apparent discontinuity.
Is there really a break at $z \sim 5.5$?
Summary of the G-P Issues

Optical depth \( \tau \) is not very sensitive to ionized fraction

Key issue is rate of change in \( \tau(z) \): this distinguishes reionization (overlapping HII regions) from thickening in forest: do we see a break in trends as we approach \( z>6 \)?

Geometry important: knowing UV background can we directly infer sizes of Stromgren spheres at various \( z \)?

Line of sight fluctuations and statistics of `dark gaps’ contains information on topology of late stages

Are some lines of sight at \( z>6 \) still consistent with large neutral fraction?
Metallicity of the Intergalactic Medium

CIV forest is already present at z=4.5

Keck II + ESI 12 hrs

Ubiquity of CIV in many sight-lines to z~5 indicates earlier SF

Songaila & Cowie (AJ 123, 2183, 2002)
CIV was detected in the Ly$\alpha$ forest in 1995 with $N$(CIV)/$N$(HI)~$10^{-2}$ - $10^{-3}$

CIV is seen in even the weakest Ly$\alpha$ systems (Ellison et al AJ 120, 1175, 2000)

How did it get there? These are low column density HI systems

Suggestive of ubiquitous enrichment from early times
Puzzle: why does CIV abundance change so little during period of intense SF activity – presumably ionization changes?

CIV Absorbers in High z QSOs

IR spectra of 10 QSOs with “absorption distance” $X(z>5) \sim 25$ to log $n_{\text{CIV}} \sim 14.2$

Complementary deeper search with $X \sim 11$ to log $n_{\text{CIV}} \sim 13.4$ (Becker et al 2009)

Rapid drop in $\Omega_{\text{CIV}}$ from $z=4.5$ to $z=6$

$\times 3.5$ drop in $\Omega_{\text{CIV}}$ (4$\sigma$) over 300 Myr ($4.7 < z < 5.8$)

- Suggests rapid enrichment since $z\sim9$ (c.f. Oppenheimer et al. vzw model)
- Caveats: ionization changes, blending (c.f. Becker et al.), cosmic variance
- If absorbers representative: $Z_{\text{IGM}}(z\sim6) \sim 10^{-4} Z_\odot$ (depends on ionization)
- Puzzle: implies too few escaping photons ($6<z<9$) to keep IGM ionized
Progress in Microwave Background Studies
Polarization in WMAP Data

CMB polarization from scattering by foreground electrons at reionization
Data rejects instantaneous reionization at $z \sim 6-7$, suggests process is extended $6 < z < 20$
CMB studies do not pinpoint the responsible cosmic sources  

Dunkley et al (2009)

Power law $\Lambda$CDM
$\tau = 0.17 \pm 0.08$ (WMAP1, 2003)
$\tau = 0.09 \pm 0.03$ (WMAP3, 2007)
$\tau = 0.087 \pm 0.017$ (WMAP5, 2009)

Instantaneous reionization

Instantaneous reionization
Eyles et al (2005): to produce this mass required $5-30 \, M_\odot \, \text{yr}^{-1}$ since $z \sim 7-10$ comparable to the ongoing SFR $(6-20 \, M_\odot \, \text{yr}^{-1})$ so should see earlier examples if unobscured.
Balmer Break Galaxies

$t = 50$ Myr
$t = 100$ Myr
$t = 300$ Myr
$t = 500$ Myr
$t = 600$ Myr
$t = 800$ Myr

$z = 7$
Stellar Mass Densities @ z~5-6

Extend earlier work to attempt to conduct census of stellar mass in v- and i-drop samples. This is much harder because:

- relies largely on photometric redshifts; contamination by foreground sources will bias mass density upwards
- typically 50% of faint sources are confused in IRAC data; scale up mass densities proportionally using isolated IRAC sources
- stellar populations may be diverse & different to those at low z: opportunity for big errors by taking conventional approximations
- drop-out target selection focuses only on active SF sources, so mass estimates likely will be lower limits

Dunlop et al (MN 376, 1054, 2007): K<23.5 GOODS-S massive gals
Eyles et al (MN 374, 91, 2007): z~6 GOODS I-drops

What does assembled mass imply for SF before z~6?
Assembled Stellar Mass at $z \sim 5-6$

Integrated stellar mass density at $z \sim 5-6$:

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

Now turn the argument around:

Instead of checking that mass is consistent with past SF we can ask:

What does accumulated stellar mass imply for earlier SF & reionization?

If mass density at $z \sim 5-6$ is greater than can be accounted for by previous SF history, options include:

- extinction: star formed but dust is present
- intrinsically faint contributors: lensing may find them
- upturn in SFH before $z \sim 10$

Stellar Mass Functions $4 < z < 6$ (Stark et al 2009)

- 2443 B-drops, 506 V-drops, 137 i-drops in ACS GOODS N/S
- 35% sufficiently isolated with Spitzer/IRAC for robust photometry
- Deep K imaging from ISAAC (Cesarsky), MOIRCS (Bundy)
- Low z contaminants identified (morphology, MIPS)
- Masses and ages using CB07, testing effect of TP-AGB stars
- Individual measures to $M \sim 10^{9.5} M_\odot$; stacked properties for fainter sources
Examples across the full range of data

High mass/bright

mass = 2.3 \times 10^{10} \, M_\odot
age = 290 \, Myr

Low mass/faint

mass = 4.8 \times 10^{9} \, M_\odot
age = 320 \, Myr

Stacked data

mass = 1.7 \times 10^{8} \, M_\odot
age \approx 50 \, Myr
Stellar Mass Density

- Factor ×5 growth in mass density over 4 < z < 6:
  \[ M_{\text{UV}} < -20: \]
  \[ z\sim4: \rho_\star = 1.1 \times 10^7 \, M_\odot \, \text{Mpc}^{-3} \]
  \[ z\sim5: \rho_\star = 4.0 \times 10^6 \, M_\odot \, \text{Mpc}^{-3} \]
  \[ z\sim6: \rho_\star = 2.0 \times 10^6 \, M_\odot \, \text{Mpc}^{-3} \]
- Substantial mass in place at z~5 suggesting vigorous activity >300 Myr earlier (z > 7)

Extrapolation to \( M_{\text{UV}} < -10 \)
\[ z\sim5: \rho_\star = 10^7 \, M_\odot \, \text{Mpc}^{-3} \]

\[
M_\star(z) = \int_{z=5}^{z=10} \rho_\star(z) \, dV(z)
\]

Hard to reconcile this mass with observed decline in luminous LBGs

High Redshift Star Forming Galaxies

Lyman break galaxies:
Rest-frame UV continuum discontinuity

Lyman alpha emitters:
Located via narrow band imaging
Extending Lyman break technique to high z

Traditional dropout technique poorly-suited for z~6 galaxies:

- significant contamination (cool stars, z~2 passive galaxies)
- spectroscopic verification impractical below ~few L*

i-drop volumes: UDF (2.6 \(10^4\)), GOODS-N/S (5.10^5), Subaru (10^6) Mpc^3

flux limits: UDF z’ < 28.5+, GOODS z’ < 25.6, Subaru z’ < 25.4
Declining star formation density of LBGs

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

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

1.2 mag dimming in characteristic luminosity $L^*$

Reddy & Steidel (2009)
Bouwens et al (2009)
Narrow band filters & z=7 barrier

$z(\text{L} \alpha) = 4.7 \quad 5.7 \quad 6.6 \quad 6.9$

Requires panoramic imaging as $\Delta z$ range is small: restricted to $z < 7$
Candidate Selection & Removal of Interlopers

Hu et al (2003) $z=5.7$ survey

Keck spectra

bb-nb (Subaru)
LBGs vs LAEs: Very Different Evolution

- Lyman break (continuum): clear decline in abundance over 3<z<6, especially for luminous examples
- Lyman alpha (line) emitters: no significant change
- Suggests early galaxies dominated by Lyman alpha emission
Lyman $\alpha$ emitters as probes of reionization

Efficient: < 6-7% of young galaxy light may emerge in Ly$\alpha$ depending on IMF, metallicity etc.

- Ly$\alpha$ damping wing is absorbed by HI and thus valuable tracer of its presence.
- In weaker systems, it may be a sensitive probe of reionisation

Santos (2004)
A Rapid Drop in Lyα Emitters from 5.7<z<6.6?

- 1 deg$^2$ SXDS field with 608 photometric and 121 spectroscopic Lyα emitters
- Contrast with LBGs: no evolution 3<z<5.7!
- Tantalizing fading (0.\text{m}3) 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$_{\text{HI}}$?

Ouchi et al (2009)
Summary (z < 7)

- WMAP polarization data rules out instantaneous reionization at late times (z~6-7); expect extended phase with sources distributed over 7<z<20
- Rapid rise in CIV abundance over 4.5<z<6 supports prompt enrichment since z~9
- Drop in Ly $\alpha$ LF over 5.7<z<6.6 may indicate modest increase in neutral fraction to z~7 or perhaps other obscuration
- Assembled stellar mass at z~5 indicative of much earlier SF
- Detailed studies of individual z~7 sources present a diverse set:
  - LBGs with Balmer breaks indicative of activity since z~10
  - LAEs seen during active (perhaps primeval) phases
- No single epoch of formation but mix of continually-forming systems

Upshot: expect abundant population of SF sources z>7 but they may be sub-luminous/obscured (and perhaps not emit Ly $\alpha$)
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 (5\(\sigma\))

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
Labbe et al 0910.0838
Bunker et al 0910.1098
z > 7 candidates from WFC3 UDF campaign

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

McLure et al (2009)
But beware.. uncertain redshifts still an issue.

\( z \quad Y \quad J \quad H \)

1678: \( z_{\text{est}} = 7.05 \ (6.60 - 7.40) \)

1107: \( z_{\text{est}} = 7.60 \ (7.30 - 7.90) \)
WFC3 Progress – I: z~7 Luminosity Function

- 10-16 z-band dropouts to $Y_{AB} \sim 28.5$ corresponding to $6.5 < z < 7.5$
- Towards a reliable faint end slope: low star formers $\sim 1 \; M_\odot \; yr^{-1}$ dominant
- Abundance decline of $\sim \times 2$ since $z=6$

Oesch et al, Bunker et al 2009
IRAC Detections of Luminous Galaxies @ z~7

11 objects in GOODS/UDF
M<10^{10} M_\odot ages <400 Myr

SF that produced these galaxies likely insufficient for reionization

Gonzalez et al 2009
WFC3 Progress – II: Stellar Mass Density @ z~7

- To complete mass density at z~7 need to probe much fainter
- UDF z~7 candidates only detected in stacked IRAC data (N=12)
- Highly uncertain but estimate $M \sim 10^9 M_\odot$ and ages > 100 Myr
- Warm mission should improve constraints significantly

Labbé et al 2009
Stellar mass density at z\~5-6 (and with greater uncertainty at z\~7) implies past SF in low luminosity galaxies may be sufficient for reionization, especially if escape fraction of photons is $>0.2$.

Stark et al 2007, 2009; Labbéd et al 2009
Unusually Blue UV Continua?

$z \sim 7$ WFC3 data provides Y+J+H data and thus the first reasonable estimate of the slope $\beta$ of the stellar continuum where $f(\lambda) \propto \lambda^\beta$: remarkably steep values $\beta \rightarrow -3$

Bouwens et al 2009

Bunker et al 2009
- Can reproduce $\beta > -2.5$ with dust-free young stars with $Z \sim 0.1 Z_\odot$
- To reproduce $\beta \sim -3$ need very low metallicities, extremely young bursts or top-heavy IMF with implied high escape fraction
- If verified, strengthens case for reionization from low L galaxies
Summary

• Discussed various independent & indirect probes of cosmic reionization suggestive of star formation in interval 6<z<12

• The HI troughs in SDSS QSOs - the arguments rely on a subtle change in properties below and above z~5.5

• Decline of CIV to z~6 in deep intergalactic space - they can only have got there from a rapid early period of SF z > 6

• WMAP polarization from electron scattering - not as precise a pointer to the redshift of activity as reported

• The remarkable amount of assembled mass at z~5 - perhaps the best pointer to much SF z > 5

• Puzzling decline in abundance of Lyman alpha emitters 5.7<z<6.6

• Initial results from WFC3/IR – much cosmic variance and other uncertainties but suggestive of steep UV slopes from Pop III stars
Discussion Topics

1. How reliable is claim that QSO spectra indicate the neutral era ended just before z~6?

*Consider tests other than Gunn-Peterson: Fan et al ARAA 44, 415 (2006)*

2. Lyman alpha as a tracer of reionization

*Santos MNRAS 349, 1137 (2004)*


3. First results from WFC3/IR

*Steep continuum slopes: Bunker et al 0909.2253; Bouwens et al 0910.0001*

*Models of Pop III spectra: Schaerer A&A 397, 527 2003 & refs therein*