The First (and last) Billion Years of Star Formation in the Universe

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Star Formation Through Cosmic Time, August 13-17, 2007
THE DARK AGES of the Universe

Astronomers are trying to fill in the blank pages in our photo album of the infant universe

By Abraham Loeb

When I look up into the sky at night, I often wonder whether we humans are too preoccupied with ourselves. There is much more to the universe than meets the eye on earth. As an astrophysicist I have the privilege of being paid to think about it, and it puts things in perspective for me. There are things that I would otherwise be bothered by—my own death, for example. Everyone will die sometime, but when I see the universe as a whole, it gives me a sense of longevity. I do not care so much about myself as I would otherwise, because of the big picture.

Cosmologists are addressing some of the fundamental questions that people attempted to resolve over the centuries through philosophical thinking, but we are doing so based on systematic observation and a quantitative methodology. Perhaps the greatest triumph of the past century has been a model of the universe that is supported by a large body of data. The value of such a model to our society is sometimes underrated. When I open the daily newspaper as part of my morning routine, I often see lengthy descriptions of conflicts between people about borders, possessions or liberties. Today’s news is often forgotten a few days later. But when one opens ancient texts that have appealed to a broad audience over a longer period of time, such as the Bible, what does one often find in the opening chapter? A discussion of how the constituents of the universe—light, stars, life—were created. Although humans are often caught up with mundane problems, they are curious about the big picture. As citizens of the universe we cannot help but wonder how the first sources of light formed, how life came into existence and whether we are alone as intelligent beings in this vast space. Astronomers in the 21st century are uniquely positioned to answer these big questions.

What makes modern cosmology an empirical science is that we are literally able to peer into the past. When you look at your image reflected off a mirror one meter
On small scales the universe is clumpy

- Early times
- Intermediate times
- Late times

Density perturbation

Mean Density

Bound Object

Void
Silk damping of small-scale fluctuations in the baryon-photon fluid prior to cosmic recombination implies that galaxies could not have formed in our Universe without dark matter!
The First Dark Matter Objects in the Universe

Smallest dark matter clumps:
~0.1 Jupiter mass

\[ M_{\text{cut}} = \frac{4\pi}{3} \left( \frac{\pi}{k_{\text{cut}}} \right)^3 \Omega_M \rho_{\text{crit}} \]
\[ \approx 10^{-4} \left( \frac{T_d}{10 \text{ MeV}} \right)^{-3} M_\odot, \]

Loeb & Zaldarriaga, astro-ph/0504112

Diemand, Moore & Stadel
astro-ph/0501589
Emergence of the First Star Clusters

molecular hydrogen in Jeans mass objects

(\( \phi \ 10^5 M_\odot \))

Yoshida et al. 2003
Observing the Cosmic Hydrogen
Hydrogen

excitation rate = (atomic collisions) + (radiative coupling to CMB)

Couple $T_S$ to $T_k$
Couples $T_S$ to $T_{\text{spin}}$

$21\text{cm} = (1:4\text{GHz})^{\frac{1}{3}}$

Spin Temperature

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp f \approx \frac{0.068K}{T_S}g$$

$(g_1=g_0) = 3$

Predicted by Van de Hulst in 1944; Observed by Ewen & Purcell in 1951 at Harvard
Sources of 21cm fluctuations

Density inhomogeneties (Loeb & Zaldarriaga 04) and peculiar velocities (Barkana & Loeb 04)
Ionized bubbles (Madau, Meiksin & Rees 1997; Furlanetto et al. 2004; Gnedin & Shaver 2003)
Emision from mini-halos (Iliev, Shapiro, et al. 2002)
Fluctuations in Lya flux, and gas temperature (Barkana & Loeb 2004)
In the beginning of the Dark Ages, electrically neutral hydrogen gas filled the universe. As stars formed, they ionized the regions immediately around them, creating bubbles here and there. Eventually these bubbles merged together, and intergalactic gas became entirely ionized.
**21 cm Absorption by Hydrogen Prior to Structure Formation**

\[ T_b = \hat{\mu} \frac{T_s - T_i}{1+z} \]

\[ T_b = 28\text{mK} \frac{a_{1+z}}{10} \frac{a_{1=2}}{T_s} \]

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*Observed wavelength=21cm (1+z) → 3D tomography (slicing the universe in redshift)*

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**Fluctuations in 21cm brightness are sourced by fluctuations in gas density**
Number of independent patches:
\[ \phi \ 10^{16} \ \frac{l_{\max}}{10^6} \frac{\bar{E}}{\Delta \nu} \]

while Silk damping limits the primary CMB anisotropies to only \( \phi \ 10^7 \)

Noise due to foreground sky brightness:

\[ N_\nu \sim 0.4 \text{ mK} \left( \frac{I_\nu}{5 \times 10^5 \text{ Jy sr}^{-1}} \right) \left( \frac{l_{\min}}{35} \right) \left( \frac{5000}{l_{\max}} \right) \left( \frac{0.016}{f_{\text{cover}}} \right) \]
\[ \times \left( \frac{1 \text{ year}}{t_0} \right)^{1/2} \left( \frac{\Delta \nu}{\nu} \right)^{-1/2} \left( \frac{50 \text{ MHz}}{\nu} \right)^{5/2} \]
21cm Tomography of Ionized Bubbles During Reionization is like *Slicing Swiss Cheese*.

Observed wavelength $\leftrightarrow$ distance

$21\text{cm } \lambda \ (1 + z)$
Zahn et al. 2006

\[ Z = 8.16 \]

\[ Z = 7.68 \]

\[ Z = 6.89 \]

21cm Brightness

\[ \log_{10}(\delta I) \text{ (mK)} \]

Mellema et al. 2006
Experiments

*MWA (Mileura Wide-Field Array)
MIT/ATNF/CfA

*LOFAR (Low-frequency Array)
Netherlands

*21CMA (formerly known as PAST)
China

*PAPER
UCB/NRAO

*GMRT (Giant Meterwave Radio Telescope)
India/CITA/Pittsburg

*SKA (Square Kilometer Array)
International
**Mileura Wide-Field Array**: mapping cosmic hydrogen through its 21cm emission

- 4mx4m tiles of 16 dipole antennae, 80-300MHz
- 500 antenna tiles with total collecting area 8000 sq.m. at 150MHz across a 1.5km area; few arcmin resolution
Primary challenge: foregrounds

- Terrestrial: radio broadcasting
- Galactic synchrotron emission
- Extragalactic: radio sources

(Di-Matteo et al. 2004)

Although the sky brightness (>10K) is much larger than the 21cm signal (<10mK), the foregrounds have a smooth frequency dependence while the signal fluctuates rapidly across small shifts in frequency (=redshift). Preliminary estimates indicate that the 21cm signal is detectable with the forthcoming generation of low-frequency arrays

**Power-Spectrum Sensitivity**

Isotropic power spectrum sensitivity, in logarithmic bins with $\Delta k = k/2$, for several experimental configurations. In each panel, the thin solid and dashed curves show estimates of the signal with and without reionization. The thick solid, dashed, and dot-dashed curves show error estimates for 1000 hour observations over 6 MHz with the SKA, MWA, and LOFAR, respectively. Each assumes perfect foreground removal. The dotted curve in the middle panel assumes a flat antenna distribution for the MWA. From *McQuinn et al. 2006*

\[
T_{\text{sky}} \sim 180 \left( \frac{\nu}{180 \text{ MHz}} \right)^{-2.6} \text{ K}
\]

\[
\Delta T^N_{\text{int}} \sim 2 \text{ mK} \left( \frac{A_{\text{tot}}}{10^5 \text{ m}^2} \right) \left( \frac{10^{10}}{\Delta \theta} \right)^2 \left( \frac{1 + z}{10} \right)^{4.6} \left( \frac{\text{MHz}}{\Delta \nu} \right) \left( \frac{100 \text{ hr}}{t_{\text{int}}} \right)^{1/2}
\]
Observing the Stars
Hubble Ultra Deep Field (HUDF)

- Mirror diameter: 6.5 meter
- Material: beryllium
- 18 segments
- Wavelength coverage: 0.6-28 micron
- L2 orbit

Launch date: 2013
Extremely Large Telescopes (20-40 meters)

- GMT=Seven mirrors, each 8.4m in diameter
- TMT, EELT – segmented 20-40m aperture
Cross-correlation between 21cm brightness and galaxy density

Figure 4. Left: 21cm brightness temperature as a function of $\delta_{\text{gal}}$. Two values of galaxy mass are assumed for a clumping of $C = 10$, $M = 10^{10} M_\odot$ (solid line) and $M = 10^{12} M_\odot$ (dashed line). The dot-dashed line shows $C = 2$ with $M = 10^{10} M_\odot$. Right: The cross-correlation function $\xi_{\text{gal}} = \langle \delta_{\text{gal}}(T - \langle T \rangle) \rangle$ for the IGM smoothed on various angular scales ($\theta$). The function is presented assuming $C = 10$ for masses of $M = 10^{10} M_\odot$ (solid line) and $M = 10^{12} M_\odot$ (dashed line). The dot-dashed line represents $C = 2$ with $M = 10^{10} M_\odot$. The lines show power-laws of slope $d(\log \xi_{\text{gal}})/d(\log \theta) = -1$, $-2$ and $-3$. The upper and lower rows correspond to observations at $z = 6.57$ and $z = 8$ respectively.
The Correlation Between Unresolved Star Formation and 21cm Emission During the Reionization Epoch

Figure 4. Signal to noise ratios as a function of angle. In each panel six cases are shown, corresponding to Lyα surveys with areas of $A = 10$ and 100 square degrees using a 2m telescope and a 1 hour integration; combined with low-frequency arrays of collecting area corresponding to 1, 10 and 100 LFDs with an integration time 1000 hours. The left-hand panels correspond to space based (i.e. no sky-glow, but including zodiacal light), and the right-hand panels to ground based near-IR observations (i.e. including sky glow). The value of $f_{\text{lat}}$ is listed in each case. Note the assumed values for $f_{\text{lat}}$ are an order of magnitude lower for ground based observations.
Figure 2. Top panels show the projection of \( \xi_1 \) in the survey volume. In the white regions the projection is fully ionized and in black it is neutral. The left, middle, and right panels are for \( z = 8.2 \) (\( \xi_1 = 0.3 \)), \( z = 7.7 \) (\( \xi_1 = 0.5 \)), and \( z = 7.3 \) (\( \xi_1 = 0.7 \)). The middle and bottom rows are the intrinsic and observed Lya emitters maps, respectively, for \( f_E = 0.25 \) and assuming that we can observe unobscured emitters with \( m \exp(-\gamma_m(m_0)) > 7 \times 10^{19} M_\odot \). (Note that \( L_{\text{int},E} \propto m \)). The observed distribution of emitters is modulated by the location of the HII regions (compare bottom panels with corresponding top panels). Each panel is 94 Mpc across (or 0.6 degrees on the sky), roughly the area of the current Subaru Deep Field (SDF) at \( z = 6.6 \) (Kashikawa et al. 2006). The depth of each panel is \( \Delta \lambda = 110 \) \( \AA \), which matches the FWHM of the Subaru 9210 \( \AA \) narrow band filter. The number densities of Lya emitters for the panels in the middle row are few times larger than the number density in the SDF photometric sample of \( z = 6.6 \) LAEs.
From the Subaru Deep Field at $z=6.6$

$x_\text{HI} < 0.5_{\alpha=2}$

But subject to uncertainties due to detailed radiative transfer effects: see Dijkstra et al., arXiv:astro-ph/0701667

**Figure 10.** Angular correlation function of emitters at $z=6.6$, assuming that observed emitters reside in halos with $m_{\text{exp}}(\tau_\alpha(\nu_0)) > 7 \times 10^{10} M_{\odot}$. The curves in the top panel are calculated in the same volume and with the same number of emitters, 58, as the SDF photometric sample. The bottom two panels are in a volume a slightly larger volume than the upcoming 1 sq. deg. Subaru/XMM-Newton Deep Survey (SXDS), with 250 emitters in the middle panel and with 190 in the bottom one. The thick error bars owe to shot noise, and the thin one to shot noise plus cosmic variance. To calculate these errors, we conservatively assume $F_\text{e} = 0.25$ in the top two panels ($F_\text{e} = 0$ in the bottom panel). Current surveys can potentially distinguish an ionized universe (the curves labeled “intrinsic”) from a universe with $x_\text{HI} \lesssim 0.5$. 

**Figure 4.** The observed Lyα line from $z=5.7$ galaxies in a reionized IGM for a range of different models. The upper right corner of each panel shows the model-parameter that is varied. Top Left: $M_\alpha = 10^6 M_{\odot}$/yr (black), $M_\alpha = 10^7 M_{\odot}$/yr (grey) and $M_\alpha = 10^8 M_{\odot}$/yr (red). Top Right: $\sigma_\alpha = 1.0_{\text{low}}$ (black), $\sigma_\alpha = 0.7_{\text{low}}$ (red) and $\sigma_\alpha = 1.0_{\text{low}}$ (grey). Lower Left: Variation of the ionizing background: 3 ionizing background (dotted), $\Gamma_{\text{B1}}$(black), $\Gamma_{\text{B2}}$(grey) and $\Gamma_{\text{B3}}$ (red). Lower Right: Impact of galaxies peculiar velocity: $v_{\text{pec}} = 0.25$ (black), $v_{\text{pec}} = 0.5_{\alpha=2}$ (red) and $v_{\text{pec}} = 0.5_{\alpha=2}$ (grey). For each model the total transmission, $T_\alpha$, and the skewness of the line, $S_\alpha$, are shown.
The Imprint of Reionization on Galaxy Clustering

Inhomogeneous photo-ionization heating to $\varnothing \ 10^4 K$ modulates the minimum mass of galaxies on scales of tens of comoving Mpc

Because of the modulation in the minimum galaxy mass, gas is converted into stars later in overdense regions (reionized earlier)  

Wyithe & Loeb, arXiv: 0706.3744
Implications for the Cosmic Reionization from the Optical Afterglow Spectrum of the Gamma-Ray Burst 050904 at $z = 6.3^*$

Tomonori Totani, Nobuyuki Kawai, George Kosugi, Kentaro Aoki, Toru Yamada, Masanori Iye, Kenji Ohta, and Takashi Hattori
Enough about the past…
what does the future hold?
All galaxies beyond a redshift of $z=1.8$ are already outside our horizon (no cell phone communication to $z>1.8$!). (Loeb 2001)
How many galaxies will reside within our event horizon in 100 billion years?

Answer: one surrounded by vacuum

The merger product of the Andromeda and Milky-Way
The Forthcoming Collision Between the Milky-Way and Andromeda

- The merger product is the only cosmological object that will be observable to future astronomers in 100 billion years
- Collision will occur during the lifetime of the sun,
- The night sky will change
- Simulated with an N-body/hydrodynamic code (Cox & Loeb 2007)
- *The only paper of mine that has a chance of being cited in five billion years...*
The Future Collision between the Milky Way and Andromeda Galaxies
The Last Billion Years of Star Formation in the Visible Universe

Figure 9. The cumulative star-formation rate during the merger of the Milky Way and Andromeda compared to the star formation for models of the Milky Way and Andromeda evolved in isolation.
Summary

• 21cm brightness fluctuations are expected to be anti-correlated with infrared galaxies during reionization.

• Lya galaxies should show excess clustering due to a neutral IGM (but subject to radiative transfer effects in the infall region around them).

• Light from unresolved Lya galaxies should also be anti-correlated with 21cm fluctuations but its detection is challenging.

• Reionization leaves an imprint on the clustering of star-forming galaxies at intermediate redshifts. This compromises the use of galaxy surveys for precision cosmology (e.g. inflation, acoustic oscillations/dark energy).