Radiation backgrounds from the first sources and the redshifted 21 cm line

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Overview

- 21 cm physics
- Atomic cascades and the Wouthysen-Field Effect
- Detecting the first stars through 21 cm fluctuations ($\text{Ly}_{\alpha}$)
- Inhomogeneous X-ray heating and gas temperature fluctuations (X-ray)
Ionization history

- **Gunn-Peterson Trough**
  - Becker et al. 2005
  - Universe ionized below $z \sim 6$, approaching neutral at higher $z$

- **WMAP3 measurement of $\tau \sim 0.09$** (down from $\tau \sim 0.17$)
  - Page et al. 2006
  - Integral constraint on ionization history
  - Better TE measurements + EE observations
Thermal history

• Ly\(\alpha\) forest

Hui & Haiman 2003

• IGM retains short term memory of heating - suggests \(z_R < 10\)
• Photoionization heating erases memory of thermal history before reionization

• CMB temperature

• Knowing \(T_{\text{CMB}} = 2.726\) K and assuming thermal coupling by Compton scattering followed by adiabatic expansion allows informed guess of high z temperature evolution
21 cm basics

- HI hyperfine structure

\[ \frac{n_1}{n_0} = 3 \exp(-h\nu_{21\text{cm}}/kT_s) \]

- Use CMB backlight to probe 21cm transition

- 3D tomography possible - angles + frequency

- 21 cm brightness temperature

\[ T_b = 27x_HI(1 + \delta_b) \left( \frac{T_S - T_\gamma}{T_S} \right) \left( \frac{1 + z}{10} \right)^{1/2} \text{ mK} \]

- 21 cm spin temperature

\[ T_s^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c} \]
Wouthysen-Field effect

Hyperfine structure of HI

\[ x_\alpha \propto J_\alpha \]

Effective for \( J_\alpha > 10^{-21} \text{erg/s/cm}^2/\text{Hz/sr} \)

Selection rules:

\[ \Delta F = 0, 1 \] (Not \( F=0 \rightarrow F=0 \))

Lyman \( \alpha \)

Field 1959
Higher Lyman series

• Two possible contributions
  - Direct pumping: Analogy of the W-F effect
  - Cascade: Excited state decays through cascade to generate Ly\(\alpha\)

• Direct pumping is suppressed by the possibility of conversion into lower energy photons
  - Ly \(\alpha\) scatters \(~10^6\) times before redshifting through resonance
  - Ly \(n\) scatters \(~1/P_{\text{abs}}\) \(\sim 10\) times before converting
    \(\Rightarrow\) Direct pumping is not significant

• Cascades end through generation of Ly \(\alpha\) or through a two photon decay
  - Use basic atomic physics to calculate fraction recycled into Ly \(\alpha\)
  - Discuss this process in the next few slides...

Pritchard & Furlanetto 2006

Hirata 2006
Lyman $\beta$

- Optically thick to Lyman series
  - Regenerate direct transitions to ground state
- Two photon decay from 2S state
- Decoupled from Lyman $\alpha$
- $f_{\text{recycle},\beta} = 0$

$A_{3p,2s} = 0.22 \times 10^8 \text{s}^{-1}$

$A_{3p,1s} = 1.64 \times 10^8 \text{s}^{-1}$

$A_{\gamma\gamma} = 8.2 \text{s}^{-1}$
Lyman $\gamma$

- Cascade via 3S and 3D levels allows production of Lyman $\alpha$
- $f_{\text{recycle},\gamma} = 0.26$
- Higher transitions $f_{\text{recycle},n} \sim 0.3$
Lyman alpha flux

- Stellar contribution

\[ J_C \]

\[ J_{I,*} \]

\[ \begin{array}{ccccccc}
\alpha & & & & & & \\
\beta & \gamma & \delta & \infty & \\
\hline
\text{No. Photons: (pop III)} & 2670 & & & & & \\
\text{f}_{\text{recycle}} : & 1.0 & & & & & \\
\text{Ly}\alpha \text{ Contribution:} & 2670 & & & & & \\
\text{Shell size @z = 20 (Mpc):} & 278 & & & & & \\
\end{array} \]

\[ \begin{array}{ccc}
965 & 451 & 810 \\
0 & 0.26 & 0.35 \\
0 & 118 & 268 \\
90 & 40 & 22 \\
\end{array} \]

- also a contribution from any X-rays...
X-rays and Lya production

\[ \sigma_{pi} \propto E^{-3} \]

\( X \)-ray

HI \rightarrow HII

photoionization

e\^-

collisional ionization

Ly\( \alpha \) excitation \( (f_\alpha \approx 0.8) \)

\[ J_{\alpha,X} = \frac{c \, \epsilon_{X,\alpha}}{4\pi \, h\nu_\alpha} \frac{1}{H\nu_\alpha} \]

Chen & Miralda-Escude 2006

Shull & van Steenberg 1985
Experimental efforts

LOFAR: Netherlands
Freq: 120-240 MHz
Baselines: 100m-100km

MWA: Australia
Freq: 80-300 MHz
Baselines: 10m-1.5km

PAST: China
Freq: 70-200 MHz

SKA: ???
Freq: 60 MHz-35 GHz
Baselines: 20m-3000km

\( f_{21\text{cm}} = 1.4 \text{ GHz} \)
Foregrounds

- Many foregrounds
  - Galactic synchrotron (especially polarized component)
  - Radio Frequency Interference (RFI)
    e.g. radio, cell phones, digital radio
  - Radio recombination lines
  - Radio point sources
- Foregrounds dwarf signal:
  foregrounds $T_{\text{sky}} \sim 1000$ s K vs 10 s mK signal
- Strong frequency dependence $T_{\text{sky}} \propto \nu^{-2.6}$
- Foreground removal exploits smoothness in frequency and spatial symmetries
The first sources

- HII
- Soft X-rays
- Hard X-rays
- Lyα

z = 15

Distances:
- 1000 Mpc
- 330 Mpc
- 5 Mpc
- 0.2 Mpc
Three main regimes for 21 cm signal
• Each probes different radiation field
Global history

\[ T_b = T_b(x_{\text{HI}}, T_K, J_\alpha, n_H) \]

\[
\frac{dT_K}{dt} = \text{Adiabatic expansion} + \text{X-ray heating} + \text{Compton heating}
\]

\[
\frac{dx_i}{dt} = \text{UV ionization} + \text{recombination}
\]

\[
\frac{dx_e}{dt} = \text{X-ray ionization} + \text{recombination}
\]

\[
J_\alpha = J_C + J_{I,*} + J_{I,X}
\]

- **Ly\(\alpha\) flux**
- **Sources:** Pop. II & Pop. III stars (UV+Lya)
- Starburst galaxies, SNR, mini-quasar (X-ray)
- **Source luminosity tracks star formation rate**
Thermal history

![Graph showing thermal history with labeled axes and regions: X-ray heating and adiabatic expansion.](graph.png)

**Legend:**
- $T_k$: Thick line
- $T_s$: Dotted line

**Regions:**
- $Z_T$
- $Z_h$
- $Z_\alpha$
- $Z_e$

**Labels:**
- Pop. II + Starbursts
- Pop. III + Starbursts
Ionization fluctuations relevant for $z<12$, not so important above that redshift. Furlanetto, Zaldarriaga, Hernquist 2004

We’ll restrict to fluctuations at $z>13$
# 21 cm fluctuations

<table>
<thead>
<tr>
<th>Baryon Density</th>
<th>Neutral fraction</th>
<th>Gas Temperature</th>
<th>W-F Coupling</th>
<th>Velocity gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta T_b = \beta \delta + \beta_x \delta x_{HI} + \beta_T \delta T_k + \beta_\alpha \delta_\alpha - \delta \partial_v$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Radiation background probed: UV, X-ray, Lyα

- In linear theory, peculiar velocities correlate with overdensities:
  \[ \delta_{d_r v_r}(k) = -\mu^2 \delta \]  
  
  - Bharadwaj & Ali 2004

- Anisotropy of velocity gradient term allows angular separation:
  \[ P_{T_b}(k) = \mu^4 P_{\mu^4} + \mu^2 P_{\mu^2} + P_{\mu^0} \]  
  
  - Barkana & Loeb 2005

- Initial observations will average over angle to improve S/N
21 cm fluctuations: z

\[ \delta T_b = \beta \delta + \beta_x \delta x_{HI} + \beta_T \delta T_k + \beta_\alpha \delta_\alpha - \delta_\partial \nu \]

- Exact form very model dependent
# 21 cm fluctuations: Lyα

<table>
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<tr>
<th>Density</th>
<th>Neutral fraction</th>
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<th>W-F Coupling</th>
<th>Velocity gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta T_b = \beta \delta + \beta_x \delta x_{HI}$</td>
<td>IGM still mostly neutral</td>
<td>negligible heating of IGM</td>
<td>Lya flux varies</td>
<td>$\beta_\alpha \delta_\alpha - \delta \partial \nu$</td>
</tr>
</tbody>
</table>

• Lyα fluctuations unimportant after coupling saturates ($x_\alpha >> 1$)

\[ \beta_\alpha \approx \frac{1}{1 + x_\alpha} \]

• Three contributions to Lyα flux:
  1. Stellar photons redshifting into Lyα resonance
  2. Stellar photons redshifting into higher Lyman resonances
  3. X-ray photoelectron excitation of HI

Chen & Miralda-Escude 2004  
Chen & Miralda-Escude 2006
Fluctuations from the first stars

- Overdense region modifies observed flux from region $dV$
- Relate $\text{Ly}\alpha$ fluctuations to overdensities

$$\delta_{x,\alpha}(k) = W(k)\delta(k)$$

- $W(k)$ is a weighted average

$$W_\alpha = \sum_{i} W_{\alpha,i} \left( J_{\alpha,i} / J_\alpha \right)$$

Barkana & Loeb 2005
Determining the first sources

Sources

$J_{\alpha, \star}^\ast$ vs $J_{\alpha, X}$

Spectra

$\alpha_s$
Summary: Ly$\alpha$

- Including correct atomic physics is important for extracting astrophysical information from 21cm fluctuations
- Ly$\alpha$ fluctuations dominate 21 cm signal at high $z$
- Can be used to determine major source of Lya photons
- Intermediate scales give information on X-ray spectrum
- Constrain bias of sources at high $z$
- Probe early star formation
- Poisson fluctuations may also be interesting
21cm fluctuations: $T_K$

\[ \delta T_b = \beta \delta + \beta_x \delta x_{HI} + \beta_T \delta T_k + \beta_\alpha \delta_\alpha - \delta \partial v \]

- In contrast to the other coefficients $\beta_T$ can be negative

\[ \beta_T \approx \frac{T_\gamma}{T_K - T_\gamma} \]

- Sign of $\beta_T$ constrains IGM temperature

Pritchard & Furlanetto 2006
Temperature fluctuations

\[ T_B = \tau \left( \frac{T_S - T_\gamma}{1 + z} \right) \]

- **Temperature fluctuations**
  - \( T_S \sim T_K < T_\gamma \)
  - \( T_b < 0 \) (absorption)
  - Hotter region = weaker absorption
  - \( \beta_T < 0 \)

- **Temperature fluctuations**
  - \( T_S \sim T_K \sim T_\gamma \)
  - \( T_b \sim 0 \)
  - 21cm signal dominated by temperature fluctuations

- **Temperature fluctuations**
  - \( T_S \sim T_K > T_\gamma \)
  - \( T_b > 0 \) (emission)
  - Hotter region = stronger emission
  - \( \beta_T > 0 \)
X-ray heating

- X-rays provide dominant heating source in early universe (shocks possibly important very early on)
- X-ray heating usually assumed to be uniform as X-rays have long mean free path
  \[ \lambda_X \approx 4.9 \bar{x}_{HI}^{1/3} \left( \frac{1+z}{15} \right)^{-2} \left( \frac{E}{300 \text{ eV}} \right)^3 \text{ Mpc} \]
- Simplistic, fluctuations may lead to observable 21cm signal
  
  Fluctuations in \( J_X \) arise in same way as \( J_\alpha \)
  
  \[ \delta_T = g_T(k, z) \delta \]
Growth of fluctuations

\[
\frac{dg_T}{dz} = \left( \frac{g_T - 2/3}{1 + z} \right) \expansion - Q_X(z)\left[W_X(k) - g_T\right] - Q_C(z)g_T
\]

\begin{align*}
\text{X-rays} & \quad \text{Compton} \\
\text{Heating fluctuations} & \quad \text{Fractional heating per Hubble time at } z
\end{align*}
$T_K$ fluctuations

- Fluctuations in gas temperature can be substantial
- Uniform heating washes out fluctuation on small scales
- Inhomogeneous heating amplifies fluctuation on large scales
- Amplitude of fluctuations contains information about IGM thermal history
Indications of $T_K$

$$P_{T_b}(k) = \mu^4 P_{\mu^4} + \mu^2 P_{\mu^2} + P_{\mu^0}$$

- When $T_K < T_\gamma$ very different form from Ly$\alpha$
- $\Delta_{\mu^2}$ can be negative which is clear indication of $\beta_T < 0$ (trough)
- Existence of features will help constrain astrophysical parameters
• Sensitivity to $\alpha_s$ through peak amplitude and shape
• Also through position of trough
• Effect comes from fraction of soft X-rays
X-ray background?

- X-ray background at high z is poorly constrained
- Decreasing $f_X$ helps separate different fluctuations
- Also changes shape of Ly$\alpha$ power spectrum
- If heating is late might see temperature fluctuations with first 21 cm experiments
Summary: $T_K$

- Inhomogeneous X-ray heating leads to significant fluctuations in gas temperature
- Temperature fluctuations track heating rate fluctuations, but lag somewhat behind
- Gas temperature fluctuations contain information about the thermal evolution of the IGM before reionization
- $\beta_T < 0$ leads to interesting peak-trough structure
- Structure will assist astrophysical parameter estimation
- 21cm observations at high-z may constrain spectrum and luminosity of X-ray sources
Redshift slices: Ly$\alpha$

$z=19-20$

• Pure Ly$\alpha$ fluctuations
Redshift slices: Ly$\alpha$/T

$z=17-18$

- Growing $T$ fluctuations lead first to dip in $\Delta T_b$ then to double peak structure

- Double peak requires $T$ and Ly$\alpha$ fluctuations to have different scale dependence
Redshift slices: $T$

$z=15-16$

- $T$ fluctuations dominate over Ly$\alpha$
- Clear peak-trough structure visible
- $\Delta \mu^2 < 0$ on large scales indicates $T_K < T_\gamma$
Redshift slices: $T/\delta$

$z=13-14$

- After $T_K > T_\gamma$, the trough disappears.
- As heating continues, $T$ fluctuations die out.
- $X_i$ fluctuations will start to become important at lower $z$. 
Observations

- Need SKA to probe these brightness fluctuations

- Observe scales $k=0.025-3 \text{ Mpc}^{-1}$

- Easily distinguish two models

- Probably won’t see trough :(
Conclusions

• 21 cm fluctuations potentially contain much information about the first sources
  - Bias
  - X-ray background
  - X-ray source spectrum
  - IGM temperature evolution
  - Star formation rate
• Lyα and X-ray backgrounds may be probed by future 21 cm observations
• Foregrounds pose a challenging problem at high z
• SKA needed to observe the fluctuations described here

For more details see astro-ph/0607234 & astro-ph/0508381
The end
Calculation

- Model star formation to calculate X-ray flux variation ([Barkana & Loeb 2005](#))
- Convert X-ray flux to temperature perturbations ([Shull & Van Steenberg 1985](#))
- Calculate resulting 21cm $T_b$ signal
- Compare with temperature variation from overdense regions e.g. from photo-ionization equilibrium ([Nasser 2005](#))

$$
\delta T_b = \beta \delta + \beta_T \delta T_k + \frac{x_\alpha}{\tilde{x}_{tot}} \delta x_\alpha + \delta x_{HI} - \delta d_r v_r
$$

- Density
- Gas Temperature
- W-F Coupling
- Neutral fraction
- Velocity gradient

- Density + x-ray
- Ly$\alpha$ coupling saturated
- IGM still mostly neutral
21cm Fluctuations: $x_i$

\[ \delta T_b = \beta \delta + \beta_T \delta T_k + \beta_\alpha \delta x_\alpha + \beta_x \delta x_{HI} - \delta_d r v_r \]

- Density
- Gas Temperature
- W-F Coupling
- Neutral fraction
- Velocity gradient

$T_K >> T_\gamma$
$T_b$ temperature independent

- Coupling saturated
- HII regions fill >10% of IGM volume

• In contrast to the other $\beta$, $\beta_T$ can be negative

Furlanetto, Zaldarriaga, Hernquist 2004
• HII regions imprint “knee” on characteristic scales

Fig. 18. Rms variation in the 21 cm brightness temperature as a function of wavenumber at several different stages of reionization, ignoring peculiar velocities. All the curves assume $z = 10$. They have $\bar{x}_i = 0.13$ (dotted curve), $\bar{x}_i = 0.36$ (dash–dotted curve), $\bar{x}_i = 0.48$ (short dashed curve), $\bar{x}_i = 0.69$ (long-dashed curve), and $\bar{x}_i = 0.78$ (solid curve). Following [253, 311].
Sources

- **Stars:** Pop. II, very massive Pop. III

- **X-ray sources:** starburst galaxies, SNR, mini-quasars
  Power law spectra chosen to explore sensible range
  \[ \hat{\epsilon}_X(\nu) \propto \nu^{-\alpha_X-1} \]

- **Link source luminosity to star formation rate**
  \[ \hat{\epsilon}_X(z, \nu) = \hat{\epsilon}_X(\nu) \left( \frac{\text{SFRD}}{M_\odot \text{yr}^{-1} \text{Mpc}^{-3}} \right) \]

- **Star formation rate from collapse fraction**
  \[ \text{SFRD} = \bar{\rho}_b^0(z) f_* \frac{d}{dt} f_{\text{coll}}(z) \]

- **Two main models:**
  A) Pop. II + starburst galaxies
  B) Pop. III + starburst galaxies
X-ray source spectra

- Sensitivity to $\alpha_s$ through peak amplitude and shape
- Also through position of trough (sign change in $\Delta \mu^2$)
- Effect comes from fraction of soft X-rays
Poisson fluctuations

• Fluctuations independent of density perturbations
• Small number statistics
• Different regions see some of the same sources though at different times in their evolution

\[ P_{un-\delta}(k) \equiv P_{\mu^0} - \frac{P_{\mu^2}}{4P_{\mu^4}} = \left( \frac{x_{\alpha}}{\bar{x}_{tot}} \right)^2 \left( P_{\alpha} - \frac{P_{\delta-\alpha}^2}{P_{\delta}} \right) \]

Barkana & Loeb 2004