Probing the cosmic dark ages using the 21 cm line

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Particle Physics and Cosmology: The Fabric of Spacetime
Les Houches Summer School 2006
Overview

• 21 cm line as probe of the “Dark Ages”

• “Gastrophysics”
  ▪ First luminous sources
  ▪ IGM thermal history
  ▪ Reionization
    (reasonable soon)

• Cosmology
  ▪ Density power spectrum
  ▪ BBN - D/H
  ▪ Dark matter decay
    (more speculative)
21 cm basics

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

- **Use CMB backlight to probe 21cm transition**
  
  \[
  T_b = 27x_{\text{HI}}(1 + \delta_b) \left( \frac{T_S - T_\gamma}{T_S} \right) \left( \frac{1 + z}{10} \right)^{1/2} \text{ mK}
  \]

- **3D tomography possible - angles + frequency**

- **21 cm brightness temperature**

- **21 cm spin temperature**

- **Coupling mechanisms:**
  - Radiative transitions (CMB)
  - Collisions
  - Wouthysen-Field
Wouthysen-Field effect

Hyperfine structure of HI

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

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

\[ T_s \sim T_\alpha \sim T_k \]

W-F recoils

\[ n_F L_J \]

\[ 1_1S_{1/2} \]

\[ 1_0S_{1/2} \]

Field 1959

Lyman \( \alpha \)
Thermal History

The diagram illustrates the thermal history of the universe with key temperature markers and processes:

- **TS**: Temperature of the universe
- **Tk**: Temperature of the cosmic microwave background (CMB)
- **X-ray heating**: Heating process due to X-rays
- **Adiabatic cooling**: Cooling process without heat exchange
- **Thermal Coupling**: Process involving thermal exchange
- **Lya coupling**: Coupling process involving Lyα
- **Collisional coupling**: Coupling process involving collisions

The graph shows changes in temperature (T) over redshift (z), with phases of reionization and cosmic microwave background (CMB) depicted.
$\delta T_b \equiv \beta \delta + \beta_x \delta x_{HI} + \beta_T \delta T_k + \beta_\alpha \delta_\alpha - \delta_\partial \nu$

Cosmology  Reionization  X-ray sources  Ly$\alpha$ sources  Cosmology

Collisionally coupled regime

No 21 cm signal
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

Foregrounds are the big problem!
First Sources

\[ \Delta = \frac{k^3 P(k)}{2\pi^2} \]

Gas temperature fluctuations

Ly\(\alpha\) flux fluctuations

- trough if \(T_K < T_\gamma\): competition between density and temperature fluctuations
- Probe thermal history
- power spectrum sensitive to sources of Ly\(\alpha\) photons
- Probe first sources

Pritchard & Furlanetto 2005 + 2006
Reionization

- Main target of first experiments
  - $Z=12$

- HII regions grow around sources
- Characteristic size imprinted in 21 cm power spectrum
- Also get evolution of ionized fraction

Furlanetto, Sokasian, Hernquist 2003

Furlanetto, Oh, Briggs 2006
Density power spectrum

- 21 cm fluctuations probe density fluctuations
- Non-linear scale is smaller at high red-shift
- Smaller scales accessible than for galaxy surveys
- Independent cross-check on cosmological parameters
- Moderate gains on CMB constraints possible with SKA

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<-- Optimistic improve $n_s$ and $\Omega_\nu$ most

McQuinn et al. 2006
• Deuterium also has hyperfine structure
  \( \lambda_D = 91.6\text{cm} \)
  \( \lambda_H = 21.1\text{cm} \)

• Cross-correlate signal pixels at two wavelengths to extract D/H ratio
  \( \lambda_1 = \lambda_H (1+z) \)
  \( \lambda_2 = \lambda_D (1+z) \)
  \( = \lambda_1 \ast (\lambda_D / \lambda_H) \)

• Measure primordial D/H ratio to 1% level
• Technically challenging and well beyond currently proposed experiments
Dark matter decays

- Some dark matter candidates can decay during dark ages
  DM lifetime $\sim 10^{17}-10^{20}$ years \(\text{i.e. } \Gamma \ll H_0\)
  e.g. sterile neutrinos with $m\sim 2-4$ keV
  axinos with $m\sim 1-100$ GeV
- Energetic photons produced heat and ionize the IGM
- Detect resulting 21 cm fluctuations
- Constrain DM parameter space

Furlanetto, Oh, Pierpaoli 2006

- Also technically demanding and far in the future
Conclusions

• 21 cm signal contains an enormous wealth of information…
  … the trick is separating it all out
• Best region for doing cosmology is z>30, but also hardest to observe
• At z<30, “gastrophysics” tends to obscure cosmology but is interesting in its own right
• 21 cm should provide moderate gains in cosmological parameters in the next decade or so
• Very early days yet and still unclear what will and will not be possible
• Foregrounds are still a largely unresolved issue

Recent review: Furlanetto, Oh, Briggs (2006)
astro-ph/0608032