Measuring the IGM thermal state with wavelets

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Outline

- *Physics of IGM*
  - Previous measurements of thermal state at $z \sim 2--3$
  - What are wavelets?
  - How we applied wavelets

- Results
  - Comparison with recent work

- Future work
Lyman alpha series

\[ \frac{1}{\lambda} = R \left( \frac{1}{1^2} - \frac{1}{n^2} \right) \]

For Lyman $\alpha \ \ n = 2$

\[ L_{\text{Ly} \alpha} \approx 1215 \ \text{Å} \]
Temperature & IGM structure

★ Thermal broadening:
  smoothing absorption along the line of sight through the thermal motion of the gas

★ Jeans smoothing:
  smoothing the physical distribution of the gas in three dimensions through pressure support
Natural profile and doppler broadening

\[ \sigma_\nu = \left( \frac{\pi e^2}{m_e c} \right) \left[ \frac{1}{4\pi \varepsilon_0} \right] f_{lu} \frac{(\Gamma_{ul}/4\pi^2)}{(\nu - \nu_{lu})^2 + (\Gamma_{ul}/4\pi)^2} \]

\[ f_{\nu}(\nu_i) = \sqrt{\frac{m}{2\pi kT}} \exp \left[ -\frac{mv_i^2}{2kT} \right] \]
Voigt profile

\[ b = \sqrt{\frac{2k_bT}{m}} \]

\[ a = \frac{\Gamma_{ul}}{4\pi \Delta\nu_D}, \quad \Delta\nu_D = \nu_{lu} \frac{b}{c} \]

\[ x = \frac{\nu - \nu_{lu}}{\Delta\nu_D} \]

\[ \sigma_\nu = \left( \frac{\pi e^2}{m_e c} \right) \left[ \frac{1}{4\pi \epsilon_0} \right] f_{lu} \phi(a, \nu) \]

\[ \phi(a, \nu) \approx H(a, x) = \frac{a}{\pi} \int dy \frac{e^{-y^2}}{(x - y)^2 + a^2} \]
Gunn-Peterson effect

\[ \lambda_{lu} < \lambda < \lambda_{lu} \frac{a(t)}{a(t_0)} \]

\[ \tau_\nu = \int_{s_0}^{s} ds' n(s', t') \sigma_{\nu'} = \]

\[ = 1.2 \cdot 10^4 \frac{(1 + z)^3}{[\Omega_m (1 + z)^3 + \Omega_K (1 + z)^2 + \Omega_\nu]^{1/2}} \left( \frac{f_{lu} \lambda}{506.0 \text{Å}} \right) \left( \frac{\langle n \rangle}{\langle n_H \rangle} \right) \]

For an homogeneous medium
Discrete absorption features

\[ \tau_\nu = \sum_i \tau_\nu(i) \]

\[ \tau_\nu(i) = \int_{s_i-\Delta s/2}^{s_i+\Delta s/2} ds' n(s', t_i) \sigma_{\nu'} \quad \nu' = \nu \frac{a(t)}{a(t_i)} \]

\[ \tau_\nu = \pi^{1/2} \tau_0 \langle \phi(a, x) \rangle \]

\[ \tau_0 = \frac{\pi^{1/2} e^2}{m_e c} \left[ \frac{1}{4\pi \epsilon_0} \right] \frac{N}{b} \lambda_{lu} f_{lu} \quad \text{Optical depth line centre} \]

Espressing absorption features like discrete spatial structure is an approximation

IGM is an evolving spatial continuum
### Table I: Summary of absorption line system properties

<table>
<thead>
<tr>
<th>Absorber class</th>
<th>Line parameters</th>
<th>Physical characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N_{\text{HI}}$ (cm$^{-2}$)</td>
<td>$b^a$ (km s$^{-1}$)</td>
</tr>
<tr>
<td>Ly$\alpha$ forest</td>
<td>$\lesssim 10^{17}$</td>
<td>15–60</td>
</tr>
<tr>
<td>LLS</td>
<td>$10^{17} - 10^{19}$</td>
<td>~ 15</td>
</tr>
<tr>
<td>Super LLS</td>
<td>$10^{19} - 2 \times 10^{20}$</td>
<td>~ 15</td>
</tr>
<tr>
<td>DLA</td>
<td>$&gt; 2 \times 10^{20}$</td>
<td>~ 15</td>
</tr>
</tbody>
</table>

$^a$Approximate ranges. Not well determined for most Lyman Limit Systems and super Lyman Limit Systems.

$^b$Values not well constrained by direct observations.

$^c$Approximate metallicity range, expressed as a logarithmic fraction of solar: $[M/H] = \log_{10}(M/H) - \log_{10}(M/H)_{\odot}$. 

Meiksin, 2009
Ionization – Ultra Violet Background (UVB)

Steady state ionization equilibrium equations

\[ 1 - Y_{HI} = Y_{HI} I_{HI} \]
\[ Y_{HeII} = Y_{HeI} I_{HeI} \]
\[ 1 - Y_{HeI} - Y_{HeII} = Y_{HeII} I_{HeII} \]

where

\[ I_{HI} = \frac{\Gamma_{HI}}{n_e \alpha_{HI}(T)} \]

\[ \alpha_{HI} \quad \text{Recombination rate of hydrogen} \]

\[ \Gamma_{HI} = \int_{\nu_L}^{\infty} d\nu 4\pi \frac{J(\nu)}{h\nu} \sigma_{HI}(\nu) \]

Haardt et Madau, 1996
Equation of state for the IGM

The true equation of state of the gas is the ideal equation of state

The “equation of state” of the IGM is determined by equilibrium between:

- Photoheating of hydrogen and helium
- Cooling due to the adiabatic expansion of the Universe
- Recombination cooling

\[
\frac{dT}{dt} = -2HT + \frac{2T}{3(1 + \delta)} \frac{d\delta}{dt} - \frac{T}{\sum_i \tilde{X}_i} \frac{d}{dt} \sum_i \tilde{X}_i + \frac{2}{3k_B n_b} \frac{dQ}{dt}
\]

Expansion of Universe  Change in number of species  Effect of surrounding radiation field

Hui et Gnedin, 1997
Equation of state for the IGM

\[ T = T_0 \Delta^{\gamma - 1} \]

\[ T_0 \approx 10^4 K \]

\[ \gamma \lesssim 1.62 \]

\[ \Delta = \frac{\rho}{\langle \rho \rangle} < 10 \]

Bolton et al, 2008
Hui et Gnedin, 1997
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• Physics of IGM

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• What are wavelets?

• How we applied wavelets

• Results

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• Future work
Thermal state of IGM

Lidz et al, 2010
Thermal state of IGM – Flux PDF

Viel et al, 2009

Bolton et al, 2008

Inverted equation of state

Furlanetto & Oh, 2008
Thermal state of IGM – Flux PDF

- $z = 2.976$
- $\gamma = 1.55$, $T_0 = 18200$
- regular
- dashed: 3 percent low continuum

- $z = 2.976$
- $\gamma = 0.71$, $T_0 = 17900$
- regular
- dashed: 3 percent low continuum
Thermal state of IGM – Wavelet filtering

McQuinn et al, 2009

Peeples et al, 2010
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Wavelets

\[ \psi_k(v) = A \exp\left(-i k v / 2\pi\right) \exp\left(-v^2 / 2s^2\right) \]

\[ s = \frac{2\pi}{k} \]

Theuns et Zaroubi (2002)
Zaldarriaga (2002)
Wavelets

\[ v \text{ (km/s)} \]
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Wavelet amplitude of a spectrum

\[ a(x) = \int dx' \psi(x - x') f(x') \]

\[ A_L(x') = \int_{-\infty}^{+\infty} dx' \Theta(|x - x'|, \frac{L}{2}) |a(x')|^2 \]
Wavelet and power spectra

\[ z=3, \ l_b = 50 \ \text{Mpc/h} \]

- \[ T_0 = 2.0 \times 10^4 \ \text{K}, \ \gamma=1.3 \]
- \[ T_0 = 1.0 \times 10^4 \ \text{K}, \ \gamma=1.6 \]

Lidz et al, 2010
Gas densities probed by wavelets

$0.9 < \Delta < 1.8$

for $z \sim 3$

Zaldarriaga et al, 2001
Linking theory with observations

**Observed spectra**
- 18 spectra from UVES of VLT (Kim et al, 2007)
  - Metal cleaned
  - Continuum fitted
  - Normalized
  - High S/ N ~ 50

**Hydrodynamical Numerical simulations**
- High resolution numerical simulations (gas + DM) – Gadget 3 (Springel, 2005)
  - 256-512^3 particles
  - 10Mpc boxsize
  - Uniform ultraviolet background (Haardt et Madau, 2001)

- Interpolation among cosmological and astrophysical parameters $T_0, \gamma, \tau_{\text{eff}}, H_0, \Omega_m, n_s, \sigma_8$

- Exploration of likelihood function by Multinest (Feroz et Hobson, 2008)
Observed & Simulated Spectra
Wavelet amplitude PDF

$z = 2.2$

$z = 2.5$

$z = 2.9$

$r = 70 \text{km/s}$
Interpolation scheme

Likelihood analysis

\[ \ln L(\theta) \propto (p(A, \theta) - \tilde{p}(A))^T \cdot C^{-1} \cdot (p(A, \theta) - \tilde{p}(A)) \]

\[ \theta = \{T_0, \gamma, \tau_{\text{eff}}, H_0, \Omega_m, n_s, \sigma_8\} \]

Continuous in \( \theta \)

interpolation scheme “taylor expansion” as in Viel et al, 2009

\[ p(A_i, \theta) = p(A_i, \theta^*) + f_{\theta_0}(\theta_0 - \theta_{0}^*) + \ldots + f_{\theta_n}(\theta_n - \theta_{n}^*) \]

Cubic spline interpolation
Interpolation scheme

\[ T_0 [10^3 K] = 22.2, \gamma = 1.0 \]

\( T_0 = 21037 \text{ K}, \gamma = 1.1 \)

\( z = 2.5 \)
Wavelets as a thermometer
Wavelets as a thermometer
Wavelets & cosmological parameters

Lower redshift  >  higher density fluctuations
Higher redshift  >  lower density fluctuations
Lidz et al, 2010
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- **Results**
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  - Future work
Constraints on IGM thermal state

Wavelet filtering

Flux PDF (Viel et al, 2009)

Lidz et al, 2010
Results: wavelet filtering & joint analysis

Lidz et al, 2010

Wavelet filtering

Becker et al, 2011

\[ T_0 \left[ 10^3 \text{K} \right] \]

Redshift, z

Hell reionization \( z \approx 3 \)
(McQuinn et al 2009)
Results: wavelet filtering & joint analysis

- Ricotti et al, 2000
- Lidz et al, 2010
- McDonald et al, 2001
- Schaye et al, 2000

HeII reionization @ z=6

McQuinn et al, 2009 – L1

McQuinn et al, 2009 – L1b
Results: wavelet filtering & joint analysis

<table>
<thead>
<tr>
<th>$\langle z \rangle = 2.1$</th>
<th>$T_0$ [$10^3$ K]</th>
<th>Wavelet PDF</th>
<th>Flux PDF</th>
<th>Joint analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\gamma$</td>
<td>$16 \pm 5$</td>
<td>$15 \pm 3$</td>
<td>$17 \pm 2$</td>
</tr>
<tr>
<td></td>
<td>$\tau_{\text{eff}}$</td>
<td>$&gt; 0.86$</td>
<td>$0.99 \pm 0.14$</td>
<td>$1.11 \pm 0.11$</td>
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<tr>
<td></td>
<td></td>
<td>$(0.14 \pm 0.04)$</td>
<td>$0.133 \pm 0.004$</td>
<td>$0.130 \pm 0.004$</td>
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</table>

<table>
<thead>
<tr>
<th>$\langle z \rangle = 2.5$</th>
<th>$T_0$ [$10^3$ K]</th>
<th>Wavelet PDF</th>
<th>Flux PDF</th>
<th>Joint analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\gamma$</td>
<td>$16 \pm 4$</td>
<td>$14 \pm 9$</td>
<td>$13 \pm 4$</td>
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<tr>
<td></td>
<td>$\tau_{\text{eff}}$</td>
<td>$&gt; 0.92$</td>
<td>$&gt; 0.69$</td>
<td>$&gt; 0.95$</td>
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<tr>
<td></td>
<td></td>
<td>$(0.22 \pm 0.05)$</td>
<td>$0.212 \pm 0.011$</td>
<td>$0.200 \pm 0.009$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\langle z \rangle = 2.9$</th>
<th>$T_0$ [$10^3$ K]</th>
<th>Wavelet PDF</th>
<th>Flux PDF</th>
<th>Joint analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\gamma$</td>
<td>$20 \pm 5$</td>
<td>$21 \pm 7$</td>
<td>$19 \pm 4$</td>
</tr>
<tr>
<td></td>
<td>$\tau_{\text{eff}}$</td>
<td>$&gt; 0.80$</td>
<td>$&lt; 1.24$</td>
<td>$1.1 \pm 0.2$</td>
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<tr>
<td></td>
<td></td>
<td>$(0.36 \pm 0.09)$</td>
<td>$0.290 \pm 0.019$</td>
<td>$0.27 \pm 0.02$</td>
</tr>
</tbody>
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- TeV emission from Blazars
- Universe at high redshift opaque to TeV emission
- IGM as a calorimeter for Blazar emission
- Changed Temperature Density plane distribution

Puchwein et al, 2012
Blazar heating

Lidz et al, 2010

Our work

Strong blazar heating (Puchwein et al 2011)
Intermediate blazar heating
Weak blazar heating
No blazar heating

$T_0 [10^3 \text{K}]$

Redshift, $z$

△ Lidz et al, 2010
+
Our work
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\[ \frac{y''}{(1 + y'^2)^{3/2}} \]

Curvature

\[ T_0 [10^3 K] \]

Redshift, z

\[ \triangle \quad \text{Lidz et al, 2010} \]

\[ \oplus \quad \text{Our work} \]

\[ \square \quad \text{Becker et al, 2011} \]
\[ \gamma = 1.5 \]

\[ T_0 = 30000K \]

\[ T_0 = 5000K \]
Conclusions

- Wavelet filtering analysis of the thermal state of the IGM: agreement with results from Lidz et al, 2010

- Varied the relevant cosmological parameters, mild dependence from $\sigma_8$ in the lowest redshift bin

- Joint analysis with flux PDF

- Thermal history consistent with previous observations, compatible with additional source of heating at $z < 4$

- Result from joint analysis consistent with $\gamma \sim 1.1 - 1.3$ inverted temperature-density relation still possible ($\gamma < 1$)