FUV and X-ray Absorption
in the
Warm-Hot Intergalactic Medium

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The IGM and the Ly α forest

![Graph showing absorption lines in the intergalactic medium](image)
The missing baryon problem

The *baryon matter density* $\Omega_b^{(\text{Ly } \alpha)}$ can be obtained from Ly $\alpha$ absorber statistics:

$$\Omega^{(\text{Ly } \alpha)} = \frac{\mu_H m_H H_0}{\rho_c c} \int N_{HI} \frac{n_H}{n_{HI}} f(N_{HI}) dN_{HI}$$

From Ly $\alpha$ forest observations follows that:

$$\frac{\Omega_b^{(\text{Ly } \alpha)}}{\Omega_b^{(\text{total})}} = 0.95 \text{ at } z=3$$

$$\frac{\Omega_b^{(\text{Ly } \alpha)}}{\Omega_b^{(\text{total})}} = 0.30 \text{ at } z=0$$
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Where have all the baryons gone at $z=0$ ??
Distribution of the baryonic matter in the Universe

(Davé et al. 2001)
FUV and X-ray Absorption in the Warm-Hot Intergalactic Medium

Introduction

Distribution of the baryonic matter in the Universe

- **Diffuse ionized intergalactic gas (Lya forest)**
- **Warm-hot intergalactic gas (WHIM)**
- **Stars and gas in galaxies**

Figure 1: High resolution (Hβ) width at half maximum (WHIM) of Ly α line (11) spectrum of the 3C 295-620 (z = 1.0), taken with the Keck High Resolution Spectrograph (HRS). The red line is the Lya forest, the blue line is the WHIM. Data from Davé et al. (2001).

(Davé et al. 2001)

Detailed image with comments.

highly ionized, $T = 10^5 - 10^7$ K
The Warm-Hot Intergalactic Medium (WHIM)

\[ T = 10^5 - 10^7 \text{ K} \]

\[ kT = \frac{8\pi}{9} \mu_p G \rho R_V^2 \]
Collisional ionization equilibrium and high ions

(from Sutherland & Dopita 1993)
Collisional ionization equilibrium and high ions

<table>
<thead>
<tr>
<th>Ion</th>
<th>[X/H]$^a$</th>
<th>Ionisation potential [eV]</th>
<th>Absorption lines [Å]</th>
<th>Band</th>
<th>CIE temperature$^b$ range [$10^5$ K]</th>
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<tbody>
<tr>
<td>O vi</td>
<td>−3.34</td>
<td>138</td>
<td>1031.926</td>
<td>FUV</td>
<td>0.2–0.5</td>
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<td>1037.617</td>
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<td>739</td>
<td>21.602</td>
<td>X-ray</td>
<td>0.3–3.0</td>
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<td>O viii</td>
<td>−3.34</td>
<td>871</td>
<td>18.969</td>
<td>X-ray</td>
<td>1.0–10.0</td>
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<tr>
<td>Ne viii</td>
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<td>770.409</td>
<td>EUV</td>
<td>0.5–1.3</td>
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<td>780.324</td>
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<td>Ne ix</td>
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<td>1196</td>
<td>13.447</td>
<td>X-ray</td>
<td>0.6–6.3</td>
</tr>
</tbody>
</table>

(Richter et al. 2008)
The WHIM and intervening OVI systems

More than 50 of such intervening OVI systems have been detected at \( z = 0 \sim 0.5 \) (Savage et al. 1998; Tripp & Savage 2000; Oegerle et al. 2000; Richter et al. 2004; Sembach et al. 2004; Danforth & Shull 2005, 2008; Tripp et al. 2007; Richter et al. 2008).
Intervening OVI absorbers

(Tripp et al. 2007)
Intervening OVI absorbers

\[ \Omega_b(\text{O VI}) = \frac{\mu_H m_H H_0}{\rho_c c} \sum \frac{N_i(\text{O VI})}{f_i \Delta X_i (O/H)_i} \sim 0.002 h_{70}^{-1} \]

(Tripp et al. 2007)
OVI absorbers in galaxy halos

(Richter et al. 2004; Stocke et al. 2006; Wakker et al. 2008; Savage et al. 2010)
COS observations of intervening OVI

(Savage et al. 2010)
Intervening NeVIII absorbers

HE 0226-4110

z=0.207

(FUSE + HST/STIS)

(Savage et al. 2005; Richter et al. 2004)
**Intervening X-ray absorbors**

![Graphs showing X-ray absorption features](image)

(Williams et al. 2005)
Only a few intervening high-ion X-ray absorber candidates have been found so far; not all of them represent convincing detections (Fang et al. 2002, 2005; Nicastro et al. 2005a, 2005b; 2008; Williams et al. 2005).
Simulations of intervening high-ion absorbers

(Tepper-García et al. 2010; Schaye et al. 2010)
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Simulations of intervening high-ion absorbers

(Tepper-García et al. 2010)
Simulations of intervening high-ion absorbers

OVI and other high ions trace metal-enriched hot gas around galaxies, but **NOT** the bulk of the baryons!
Broad Lyman $\alpha$ Absorbers (BLAs)

$log N(\text{HI})=13.0$ ; Lyman Alpha Absorption

$b=20 \text{ km/s}; \log T=4.4; \log N(\text{HII})=16.4$ (CIE)

\[
b_{th} = \sqrt{\frac{2kT}{m}} \approx 0.13 \sqrt{\frac{T}{A}} \text{ km s}^{-1}
\]

\[
\log f_{H \text{ I, coll}} \approx 13.9 - 5.4 \log T + 0.33 (\log T)^2
\]

(Richter et al. 2008)
Broad Lyman $\alpha$ Absorbers (BLAs)

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- $b=40 \text{ km/s}; \log T=5.0; \log N(HII)=17.8$ (CIE)

(Richter et al. 2008)
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- \( b=80 \ \text{km/s}; \log T=5.9; \log N(HII)=19.5 \) (CIE)

(Richter et al. 2008)
Broad Lyman $\alpha$ Absorbers (BLAs)

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- $b=80 \; \mathrm{km/s}$; $\log \; T=5.9$; $\log N(HII)=19.5$ (CIE)
- $b=150 \; \mathrm{km/s}$; $\log \; T=6.1$; $\log N(HII)=19.8$ (CIE)

(Richter et al. 2008)
Broad Lyman $\alpha$ Absorbers (BLAs)

log $N$(HI)=13.0 ; Lyman Alpha Absorption

$b=150\,\text{km/s}; \log \, T=6.1; \log \, N$(HII)=19.8 (CIE)

(Richter et al. 2008)
Observations of BLAs

PG 1116-215 (HST/STIS)

(Sembach et al. 2004)
Baryon density in BLAs

Baryon density estimate (no metallicity bias!):

\[
\Omega_b(\text{BL}) = \frac{\mu m_{\text{H}}H_0}{\rho_c c \Delta X} \sum_i f_{\text{H},i} N(\text{H I})_i \sim 0.004 \, h_{70}^{-1}
\]

(Richter et al. 2006a; Lehner et al. 2007; Danforth et al. 2010)
Simulations of BLAs

(Richter et al. 2006b)
Conclusions

- The WHIM may contain up to 40 percent of the baryons at low redshift

- Space-based observations in the UV and in the X-ray band show a population of intervening OVI, OVII, OVIII and NeVIII absorbers, indicating the presence of hot gas in the IGM

- Recent simulations indicate that high-ion absorbers trace metal-enriched circumgalactic gas, but NOT the bulk of the baryons ("intergalactic fountain")

- The search for Broad Lyman $\alpha$ Absorbers (BLAs) possibly represent the best method to find the "missing baryons" at low redshift