X-ray Detections of the Missing Baryons

The Warm-Hot Intergalactic Medium

Fabrizio Nicastro (CfA/INAF-OAR)

Collaborators: S. Mathur (OSU), R. Williams (OSU), M. Elvis (CfA), J. Drake (CfA), F. Fiore (INAF-OAR), Y. Krongold (IA-UNAM)
Outline

• *The Missing Baryons* problem

• The WHIM at Cosmological Distances

• First $\Omega_b^{WHIM}$, $dn/dz$ estimates

• The WHIM in our own Local Group

• Future Prospects: *Pharos*
Problem: **Missing Baryons**

Table 1  **Census of baryons in the high- and low-redshift Universe**

<table>
<thead>
<tr>
<th>Inferred from*</th>
<th>$\Omega_b$ (%) for $h_{70} = 1$</th>
<th>% of b</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBN + D/H</td>
<td>$(4.4 \pm 0.4)$</td>
<td></td>
</tr>
<tr>
<td>CMB anisotropy</td>
<td>$(4.6 \pm 0.2)$</td>
<td></td>
</tr>
<tr>
<td>Observed at $z &gt; 2$ in†</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lyman-α forest</td>
<td>$\geq 3.5$</td>
<td>&gt;76</td>
</tr>
<tr>
<td>Stars</td>
<td>$(0.26 \pm 0.08)$</td>
<td>5.7</td>
</tr>
<tr>
<td>H\textsc{i} + He\textsc{i} + H$_2$</td>
<td>$(0.080 \pm 0.016)$</td>
<td>1.7</td>
</tr>
<tr>
<td>X-ray gas in clusters</td>
<td>$(0.21 \pm 0.06)$</td>
<td>4.6</td>
</tr>
<tr>
<td>Lyman-α forest</td>
<td>$(1.34 \pm 0.23)$</td>
<td>29</td>
</tr>
<tr>
<td>Warm + warm–hot O\textsc{vi}</td>
<td>$(0.22 \pm 0.03)$</td>
<td>4.8</td>
</tr>
<tr>
<td>Total (at $z &lt; 2$)§</td>
<td>$(2.1 \pm 0.3)$</td>
<td>46</td>
</tr>
<tr>
<td>Missing baryons (at $z &lt; 2$)§</td>
<td>$(2.5 \pm 0.4)$</td>
<td>54</td>
</tr>
</tbody>
</table>
Solution: **WHIM**

(Cen & Ostriker, 2006)

Cool (Lyα) gas dominates volume at all $z$.

Warm-Hot gas dominates mass at low $z$.

(54 ± 9) % of Baryons are missing!
Why Should we Care?

(54 ± 9) % of Baryons are missing!

- Find the ‘Missing Baryons’ and verify theory
- Ecology of the Universe (Metal Pollution): $dZ/dz$
  - Absolute (needs UV) and Relative Metallicities.
  - Galaxy Superwinds (SN) vs AGN winds, jets
  - Nucleosynthesis
- Heating History of the Universe: $dT/dz$
- Cosmological parameters $> 10^3$ systems needed
  - LG-WHIM is a biased measure - Need $z>0$ WHIM absorbers to measure $\Omega_b$
- Local Group WHIM and Galaxy formation
The X-Ray Forest

Background X-ray Source

OVII Column Density Fluctuations of WHIM Filaments between z=0-1

OVII-Forest
WHIM Filaments are Faint

- **Size:** $\Delta R \sim 1 \text{ Mpc}$
- **Density:** $n_b \sim 10^{-6}-10^{-5} \text{ cm}^{-3}$
- **Temperature:** $T \sim 10^6 \text{ K} ; \xi_{\text{OVII}} \sim 1$
- **Metallicity:** $Z \sim 0.1 \, Z_\odot$

$$\Rightarrow \text{OVII-Forest Column Density:}$$
$$N_{\text{OVII}} \sim n_b \xi_{\text{OVII}} Z_0 \Delta R \sim 2.6 \times (10^{14}-10^{15}) \text{ cm}^{-2}$$

$$\Rightarrow \text{OVII-Forest EWs:}$$
$$W_{\text{OVII}} \approx 3 \times 10^{-18} (1+z)^2 N_{\text{OVII}} \approx 0.8 - 8 (1+z)^2 \, m\AA^0$$
WHIM Detectability

\[ W_{N\sigma}^{Thresh} = N_{\sigma} \frac{\Delta \lambda}{\sqrt{CPRE}} \]

\[ CPRE = f_{ph}^\lambda \Delta t \cdot A_{Eff} \Delta \lambda \]

Fluence \((\Gamma=2)\)

\[ f_{ph}^\lambda \Delta t = \frac{F(\lambda_1, \lambda_2)}{hc \ln(\lambda_2 / \lambda_1)} \]

\[
\left( N_{Thres}^{He-like} \right)_{Grat} \approx 6.4 \times 10^{15} \left( \frac{N_{\sigma}}{3} \right) \left( \frac{\lambda(A)}{25} \right)^2 \left( \frac{f_{ion}}{0.7} \right)^{-1} \sqrt{\frac{\Delta \lambda(mA)}{50}} \sqrt{\frac{10^{-6}}{F(erg \ cm^{-2})}} \sqrt{\frac{20}{A_{Eff}(cm^2)}}
\]

• Exceptionally high quality X-ray spectra of background AGN are needed.
Mkn 421 (z=0.03): WHIM and ISM

Local Group WHIM?

<z>=0.011 WHIM

<z>=0.027 WHIM


Bernard's Cosmic Stories (F. Nicastro, Valencia, Spain)
1ES 1028+511 (z=0.361)

140 ks Chandra-LETG: F=3.3x10^{-6} erg s^{-1}

OVII Kα (z=0.330) ?
EW = 32±13
N_{OVII} = (6.3±2.6) \times 10^{15} \text{ cm}^{-2}

N_{CV}(z1,z2,z3) = (2.8,3.0,3.4) \times 10^{15} \text{ cm}^{-2}
Number Density and Cosmological Mass Density of WHIM

\[ \Omega_b(N_{\text{OVII}} > 7 \times 10^{14}) = \left( \frac{1}{P_c} \right) \left( \frac{\mu m_p \sum N_{i}^j}{d_{\text{Mkn421}} + d_{\text{1ES028+511}}^\text{equiv} \times 10^{15}} \right) = 2.4^{+1.9}_{-1.1} \times 10^{-1} [O/H]_{-1} \%
\]

Consistent with \( \Omega^{\text{missing}} = 2.5 \pm 0.4 \)

\(~\text{Ms Chandra Obs of 1ES 1028+511~}~

(Nicastro et al., 2005, Nature, 433, 495; Nicastro et al., 2006, in prep.)

Short-term Prospects

\(+40 \%\)

\(-30 \%\)
The $z=0$ Absorber

Hot Galactic Corona or

Local Group WHIM?

Or Both?
INTERGALACTIC MATTER AND THE GALAXY

F. D. Kahn* and L. Woltjer†
Princeton University Observatory and the Institute for Advanced Study, Princeton, New Jersey
Received May 18, 1959

ABSTRACT

It is shown that the Local Group of galaxies can be dynamically stable only if it contains an appreciable amount of intergalactic matter. A detailed discussion shows that this matter consists mainly of ionized hydrogen and that stars can contribute only a small fraction to its total mass. The most likely values for the intergalactic temperature and density are found to be $5 \times 10^4$ degrees and $1 \times 10^{-4}$ proton/cm$^3$, respectively. It is thought that this gas confines the halo. The distortion of the disk of the Galaxy, revealed by 21-cm observations, is analyzed. This effect cannot be regarded as a relic from a primeval distortion, which occurred at the time of formation of the Galaxy; a more promising explanation for it can be given in terms of the flow pattern of the intergalactic gas past the Galaxy and of the resulting pressure distribution on the halo.
The WHIM Filament in the Local Supercluster Environment

0.5-2 keV Brightness in ph/s/cm²/sr

OVI column density in cm⁻²

OVII column density in cm⁻²

OVIII column density in cm⁻²

(Kravtsov, Klypin & Hoffman, 2002)
Z=0 OVI-OVII Absorption

\[ N_{\text{OVII}} \sim \text{few} \times 10^{15} \text{ cm}^{-2} \]

LMC-X3
(Wang et al., 2005)

NGC 3783

PKS 2155-304

Mkn 421

HV-OVI: 90% l.o.s.

Velocity Segregation of HV-OVI

(HV-OVI
Strong Segregation in the LSR)

(Nicastro et al., 2003, Nature, 421, 719)
Mkn 421: 13 z=0 lines + FUSE

Doppler Parameter

OVII Gas ≠ LV-OVI Gas

Consistent with dispersion velocity in the LG

Low-Density Solution

The OVI Problem

LG vs Galactic Solution

If $OVI_{K\alpha}$ measures $N_{OVI}$: ➔ LG-WHIM:

$$M_b = (0.1 - 4.6) \times 10^{12} \, M_\odot f_{0.5}$$

[\text{[}M_{\text{LG\_bind}} = 3.5 \times 10^{12} \, M_\odot\text{]}]

If not: ➔ Gal. Corona or LG-WHIM

$$M_b = 2.5 \times 10^7 \, M_\odot$$
Summary

• WHIM at z>0:
  – 3 OVII + 3 CV detections so far (2 lines of sight)
  – First Estimates of $dN/dz$ and $\Omega_b$ consistent with predictions and with the total number of missing baryons (within large uncertainties due to the low statistics)

• z=0 Absorber:
  – Majority of HV-OVI at rest in the LGSR
  – OVII-OVIII and NeIX trace a low-density medium ➔ Local WHIM Filament?
Long-Term Prospects

• Long Term: mapping the WHIM up to z~1: needs high throughput and spectral resolution.

• Tens to hundreds systems would enable:
  – $\Omega_b$ and $dN/dz$ to better than few/tens %
  – WHIM density in galaxy voids vs galaxy overdensities
  – Multi-phase studies

• Hundreds to Thousands of Systems would enable:
  – $\Omega_b$ and $dN/dz$ to better than few tenth of %
  – Cosmological Parameters
  – Dark-Matter Maps
  – Metallicity History: $dZ/dz$ (Ecology of the Universe) (needs UV)
  – IGM/galaxy/AGN Feedback
  – Heating History of the Universe ($dT/dz$)
distant beacons as cosmological probes

A GRB MIDEX mission concept

\[ R > 3000 \text{ @ } 0.5 \text{ keV} \quad (R_{\text{LETG}}=400) \]
\[ A_{\text{eff}} > 600 \text{ @ } 0.5 \text{ keV} \quad (A_{\text{LETG}}=20 \text{ cm}^2) \]

1 arcmin ASM localization

Slew in 30-60 s

"Pharos" of Alexandria, one of the Seven Wonders of the ancient world, was the tallest building on Earth (120m). Its mysterious mirror, whose reflection could be seen more than 55 km off-shore fascinated scientists for centuries.

Fabrizio Nicastro & Martin Elvis

On behalf of the Pharos Team (CfA, MIT, GSFC, MSFC, OAR-INAF, IASF-INAF)
Studies with quiescent targets

PKS 2155-304 (z=0.116) 
~ 200 CPREs 
Fang et al., 2002

H 1821+643 (z=0.297) 
500 ks ACIS-LETG 
~ 50 CPREs 
Mathur et al., 2003

• 6 QSOs with MEG: No abs. down to $N_{\text{OVI}} > 10^{16} \text{ cm}^{-2} \Rightarrow Z_{\odot} < 0.3 Z_{\odot}$ (Fang et al., 2005)
Extraordinary Claims Require Extraordinary Evidence

(Sagan, Carl, 1979, "Broca's Brain", p.73)]

The O vii X-ray forest toward Markarian 421: Consistency between XMM-Newton and Chandra
J.S. Kennea, N. Werner and J.W.A. den Herder
SRON Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands
P.B.S. Peebles
Columbia Astrophysics Laboratory, Department of Astronomy, Columbia University, 550 West 129th Street, New York, NY 10027, USA
J. de Plaa¹
SRON Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands
A.P. Hamann⁴
Kavli Institute for Particle Astrophysics and Cosmology, and Department of Physics, Stanford University, CA 94305, USA
and
C.P. de Vries
SRON Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands

ABSTRACT

the sky. Therefore, the highly ionised component of the WHIM still remains to be discovered.

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On the Putative Detection of z > 0 X-ray Absorption Features in the Spectrum of Mrk 421
Andrew P. Hamann¹, Steven M. Kahn¹,²
Stanford Linear Accelerator Center, Menlo Park, CA 94325
aram@slac.stanford.edu
Frisa Pedraz³
Columbia Astrophysics Laboratory, New York, NY 10027
Jan Wilken den Herder, Jelle Kaastra and Cor de Vries
SRON, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands

Neither has been refereed
One has been rejected before referee
But...both are on astro-ph!
The Power of (Manipulated?) Images

BUT:

\[ \text{EW}^{\text{RGS}}(\text{OVII}) = 13.6 \pm 1.1 \text{ (R06)} \]

\[ \text{EW}^{\text{RGS}}(\text{OVII}) = 14.8 \pm 0.7 \text{ (K06)} \]

\[ \text{EW}^{\text{LETG}}(\text{OVII}) = 9.4 \pm 1.1 \text{ (W06)} \]

\[ \implies \text{Re-normalized Model?} \]

(continuum clearly underestimated)
Reassuring Numbers...

1.5 sigma for 1 interesting parameter

Our Measurements in the LETG:

\[
\begin{align*}
\lambda &= 21.85 \pm 0.02 \text{ } \text{ } A N_i = (1.0 \pm 0.3) \times 10^{15} \text{ cm}^{-2} \\
\lambda &= 22.20 \pm 0.02 \text{ } \text{ } A N_i = (0.7 \pm 0.3) \times 10^{15} \text{ cm}^{-2}
\end{align*}
\]

⇒ Consistent within \( 1\sigma \)
Real Sensitivity...

In the RGS: 26188 Cts per 50 mA @ 21.6 A (R06)

In the LETG: 5300 Cts per 50 mA @ 21.6 A (N06)

\[ \text{FACTOR of } \sim 5 \]

\( N_i(\text{RGS}) > 10^{15}\ \text{cm}^{-2}\ (21-22.5\ \text{A})\text{ at }1.5\sigma\ (R06) \)

\( N_i(\text{LETG}) > 4.5 \times 10^{14}\ \text{cm}^{-2}\ (21-22.5\ \text{A})\text{ at } >1.5\sigma\ (N06, K06) \)

\[ \text{FACTOR of } \sim 2 \]

Factoring the Difference in \( A_{\text{eff}} \) (~2 where both RGS are present)

The LETG is \( \sim 5 \) x sensitive than the RGS (to Ion Column Density Detection)

(Williams et al., 2006)