Looking for the missing baryons in the local universe

Zappacosta Luca (INAF-OAR)

Fabrizio Nicastro (INAF-OAR), Roberto Maiolino (INAF-OAR)
The cosmic energy inventory

Convergence on the amount of high redshift baryons

- Cosmic Microwave Background (WMAP): 4.5% (e.g. Komatsu et al. 2011)
- Lyman $\alpha$ Forest: 4.4% (Tytler et al. 2004)
- Primordial Deuterium+Big Bang Nucleosynthesis: 4.4% (Kirkman et al. 2003)
The missing baryons problem

Local (z<1) baryon census

adapted from Fukugita & Peebles 2004

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameter</th>
<th>Known baryonic components</th>
<th>Undetected Baryons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1.</td>
<td>Dark energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2.</td>
<td>Dark matter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1.</td>
<td>Baryon rest mass:</td>
<td>Some form of undetected baryons</td>
<td>0.027</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Undetected clusters/groups of galaxies outskirts</td>
<td>~ 0.0054</td>
</tr>
<tr>
<td>3.2.</td>
<td>Local Lyman α absorber</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.3.</td>
<td>Intracluster plasma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.4.</td>
<td>Main-sequence stars: spheroids and bulges</td>
<td>0.0015 ± 0.0004</td>
<td></td>
</tr>
<tr>
<td>3.5.</td>
<td>Main-sequence stars: disks and irregulars</td>
<td>0.00055 ± 0.00014</td>
<td></td>
</tr>
<tr>
<td>3.6.</td>
<td>White dwarfs</td>
<td>0.00036 ± 0.00008</td>
<td></td>
</tr>
<tr>
<td>3.7.</td>
<td>Neutron stars</td>
<td>0.00005 ± 0.00002</td>
<td></td>
</tr>
<tr>
<td>3.8.</td>
<td>Black holes</td>
<td>0.00007 ± 0.00002</td>
<td></td>
</tr>
<tr>
<td>3.9.</td>
<td>Substellar objects</td>
<td>0.00014 ± 0.00007</td>
<td></td>
</tr>
<tr>
<td>3.10.</td>
<td>H I + He I</td>
<td>0.00062 ± 0.00010</td>
<td></td>
</tr>
<tr>
<td>3.11.</td>
<td>Molecular gas</td>
<td>0.00016 ± 0.00006</td>
<td></td>
</tr>
<tr>
<td>3.12.</td>
<td>Planets</td>
<td>10^{-6}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Condensed matter</td>
<td>10^{-5.6} ± 0.3</td>
<td></td>
</tr>
<tr>
<td>3.13.</td>
<td>Sequestered in massive black holes</td>
<td>10^{-5.4}(1 + \epsilon_n)</td>
<td></td>
</tr>
</tbody>
</table>
The missing baryons problem

Local (z<1) baryon census

50-60% of the baryons are missing from the local census

"Missing baryons" problem
Why do we care about the "missing baryons"

- a further confirmation of the current standard cosmological model at low redshift
- confirm the goodness of the high-redshift measurements and possibly fine tune them
- Understand
  - evolution of the baryons in the universe
  - processes of metal enrichment in the universe
  - interplay between the "missing baryons" and the visible baryons (i.e. galaxies)
The baryon history from simulations

From cosmological simulations

Cen & Ostriker 2006

Missing baryons
The Warm-Hot Intergalactic Medium (WHIM)

- Located in the filamentary large-scale structure of the local ($z<1$) universe
- Gas shock-heated during its infall in the large-scale structure gravitational potential
- Filaments size: $25-5 \times 3-5$ Mpc
- Warm-hot $T \rightarrow 10^5$-$10^7$ K
- Low density: $10-20\langle \rho_b \rangle$
- The bulk at overdensities $1-1000\langle \rho_b \rangle$

How to detect the WHIM

Mainly in the soft X-rays

- Soft X-ray imaging

- Far-UV/X-ray spectroscopy:
  - Line emission of the most abundant ions (oxygen: OVI, OVII, OVIII, Ne ions, C ions, ...)

- Far-UV/X-ray absorption lines from intervening WHIM in the high-resolution spectrum of bright background sources (the X-ray forest; Hellsten et al. 1998)
Conventional terminology

From wavelength to energy
- \( E \text{ (keV)} \cdot \lambda \text{ (Å)} \approx 12.4 \)
  - Soft X-rays: 0.5-2 keV
  - Hard X-rays: 2-10 keV

Temperature from Kelvin to keV
- \( T(K) \approx 1.1 \cdot 10^7 T(\text{KeV}) \)
  - cold/warm: \( 10^4 \text{ K} \) (high-z Intergalactic Medium)
  - hot: \( 10^{7-8} \text{K} \) (intracluster medium, \(~1-10 \text{ keV}\))
  - warm-hot: \( 10^{5-7} \text{K} \) (WHIM, Local Hot Bubble, Galaxy halo)
X-ray satellites
Detecting WHIM in emission

Emission studies can probe the hotter \((T > 10^6 \text{ K})\) and denser \((>100\langle \rho_b \rangle)\) WHIM phase

Problems to deal with:

- Low surface brightness regions emitting in the soft X-ray energies \((< 1 \text{ keV})\)
- X-ray absorption by Galactic ISM (need low \(N_H\) regions)
- Lots of Galactic foregrounds and extragalactic backgrounds
- Large field of view needed (e.g. 3Mpc @ \(z=0.1 \rightarrow 27\) arcmin)
WHIM and galaxies in filaments

The dark matter large-scale structure gather galaxies and gas

Gas and galaxies traces each others in filaments

Viel et al. 2005
First results in emission

- ROSAT (0.5-2 keV)
- Correlated with clusters and galaxy distribution

Problems

- Pollution by intracluster medium outskirts
- no clear redshifts from galaxies
WHIM in the Warwick field

Zappacosta et al. 2002

Low $N_H$ field ($\leq 10^{20}$ cm$^{-2}$)

- Warwick et al. 1998 → ROSAT detection of diffuse filamentary emission

Re-analysis of one of the ROSAT fields

Aims:
- Correlate diffuse emission with galaxy overdensity
- Redshift of the correlated structures
- Measure flux and spectral shape
Diffuse emission in the soft X-rays

- 20ks ROSAT field (1/4 keV band) after point source removal
- Extended structures detected
- Structures in common → 5σ significant
Galaxy/X-ray distribution

Galaxy distribution (colors)
- optical observations obtained at Isaac Newton Telescope (Canary Islands)
  - central region of PSPC field of view
  - 5 photometric bands → photo-z

Correlation X-ray/galaxies
- Main structure in X-ray and projected galaxy distribution is coincident!
Photometric redshifts:
- galaxy overdensity significant at 6σ in the range $0.3 < z_{\text{phot}} < 0.6$.

A later spectroscopic survey (161 obj)
- $z_{\text{spec}} = 0.40$ (~20 obj)
  (Mannucci, Bonnoli, Zappacosta et al. 2007)

- **spectrum consistent with WHIM:**
  - $T \sim 3 \cdot 10^6$ K (assumed $Z = 0.05 - 0.3Z_{\odot}$)
  - Flux in agreement with simulations

Filament size: 6 Mpc
- 10 spectroscopically confirmed neighbour clusters/groups at $z \approx 0.395$
WHIM signature in the Sculptor Scl

Sculptor Supercluster ($z=0.1$), $N_H \sim 1.5 \times 10^{20}$ cm$^{-2}$

Zappacosta et al. 2005

Deepest fields $\geq 20$ks exposure
WHIM in the Sculptor Scl: color-color

“Pure” WHIM

Contaminants
WHIM in the Sculptor Scl: correlation

AGNs

WHIM at $z \sim 0.1$
WHIM in the Sculptor Scl: correlation

Correlation (>3σ significant) between galaxy distribution and regions of X-ray emission which corresponds to plasma with $T \leq 5-6 \times 10^6$ K

Evidence for warm-hot gas permeating the supercluster
Absorption spectroscopy
the X-ray Forest

- The **brightest AGNs**
  \( \geq 10^{-10} \text{ erg/s/cm}^2 \)
- Very long exposures
  \( \gg 100 \text{ ks} \)
- Low density filaments
  \( \rightarrow \) weak lines

High S/N spectrum

Distance from observer

Flux

Wavelength
X-ray Forest: no definitive WHIM detections from bright AGNs

**Mkn 421 case**
- Among the most luminous and intensely studied blazars
- X-ray high resolution spectroscopy absorption studies with Chandra and XMM with high quality grating data

**Pro WHIM**
- Nicastro et al. 2005
- Williams et al. 2006
- Chandra detection
- XMM non detection (consistent with Chandra)

**Against WHIM**
- Kaastra et al. 2006
- Rasmussen et al. 2007
- Non detection with Chandra
- Non detection with XMM

Disagreement between groups and satellites
Mkn 421 spectrum

Nicastro et al. 2005

Chandra data
- **blazar in outburst** $\sim 10^{-9}$ erg/s/cm$^2$ (0.5-2 keV)

Three absorption systems
- Local absorber
  - $(z=0; \text{ Nicastro et al. 2002})$,
  - (based on several lines detected)
- $z=0.011$ absorber
  - (based on 3 lines detected)
  - Significance: 3.5-5.8$\sigma$
- $Z=0.027$ absorber
  - (based on 6 lines detected)
  - Significance: 4.8-8.9$\sigma$
Why no detection from the bright AGNs

Different authors and different satellites have given controversial results so far.

Details of the data analysis and statistical assessment are crucial for weak lines detection.
Strategies for WHIM detection

- Blind searches
- Very bright AGNs
- Very long exposures
- Low density filaments → weak lines

Distance from observer

Wavelength

High S/N spectrum

Flux
Strategies for WHIM detection

- Targeted searches
- Moderately bright AGNs behind superstructures
- Lower exposure times
- Larger gas densities
- A priori redshift knowledge
- Higher metallicities → stronger lines

During outbursts
Better S/N spectrum

Higher S/N spectrum

Flux

Wavelength
Targeted searches: clusters

XMM first attempts

- **Fujimoto et al 2004** (54ks)
  - Virgo cluster outskirts
  - modest QSO \(< 10^{12} \text{ erg/s/cm}^2, 0.5-2 \text{ keV}\)
  - Marginal detection of OVIII at 96.4\% level

- **Takei et al 2007** (~260ks)
  - Coma cluster outskirts
  - modest QSO \((1-2 \times 10^{12} \text{ erg/s/cm}^2, 0.3-2 \text{ keV})\)
  - NeIX (2.3\%)\), OVIII (1.9\%)\) → 3\% combined
WHIM in filaments: our strategy

Since 2005

Proposing ToO observations of blazars during their outburst state located behind local known large-scale unvirialized filamentary structures traced by the galaxy distribution to obtain a firm detection of the WHIM.

(approved in Chandra Cycle 7/8/9, XMM-AO6, PI: Zappacosta)
The Sculptor Wall

- Blazar H2356-309 (z=0.165)
- Sculptor Wall z=0.03 (@blazar location)

Observation triggered in 2007 with both XMM and Chandra during two different short outbursts

- Source flux $1.2-1.5 \times 10^{-11}$ erg/s/cm$^2$ (0.5-2 keV) (~quiescent state)

Nonetheless...
OVII WHIM evidence

From both XMM and Chandra

- Evidence of local and intervening OVII in **both** Chandra and XMM spectra
- The intervening OVII line is consistent with the redshift of the Sculptor Wall 
  
  \((z=0.028-0.032)\)
- Joint OVII significance 3\(\sigma\)
- \(N_{\text{OVII}}(z=0.03) > 1.0 \times 10^{16} \text{ cm}^{-2}\)

---

Buote, Zappacosta et al. 2009
OVII absorption confirmation

- Further analysis with further 500ks Chandra grating observation
- OVII line at $z=0.0306\pm0.0007$ confirmed at $4\sigma$
  (joint analysis Chandra+XMM)
- $\log N_{OVII} = 16.84^{+1.30}_{-0.92}$ cm$^{-2}$

**WHIM in the Sculptor Wall**

Alternative explanation:
- Absorption from the halo(s) of nearby galaxies in the filament

*Fang et al. 2010*
H2356-309 a line of sight rich in superstructures
Chandra analysis of two other structures

New analysis method

- **WHIM spectral model** (Krongold et al. 2003, Nicastro et al. 2009)
  - > 3000 electronic transitions (elements < Ni)
  - Collisionally ionized plasma
  - Photoionized gas

→ determination of temperature and column density
Pisces-Cetus supercluster

Hint of two intergalactic phases
- $z \approx 0.062$ (same as PCS)

Zappacosta et al. (2010)
Farther Sculptor Wall
Serendipitous CV absorber

- $3.9\sigma$ significant
- $z=0.1117 \pm 0.0003$
- Small filament
- No galaxy around within 2.2 Mpc

Zappacosta et al. in prep.
Conclusions

- WHIM is difficult to detect.... but we are slowly gathering more and more evidences!

- WHIM in filamentary structures can be detected especially in dense supercluster environments with data and satellites already available
  - Soft X-ray diffuse emission (Warwick field, Sculptor Scl)
  - X-ray absorption in background AGN spectra (Sculptor region)

- Galaxy distribution provides a valid tracer for the WHIM distribution in superclusters