IXO Gratings and the Missing Baryons

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Outline

- The Missing Baryons problem and N-body solution: the Warm-Hot Intergalactic Medium
- How to detect it: the WHIM observables
- Dispersive vs Non-Dispersive Spectroscopy
- The Best WHIM sample for IXO/COS
Where are the Baryons?

- Warm-Hot gas dominates Mass at low $z$
- $T<10^9K$ (Warm)
- $T=10^9-10^8K$ (WHIM)
- $T>10^8K$ (Hot)
- Galaxies (Cold)

**Graph:**
- CMB Anisotropy
- BBN + D/H Ratio
- Total $z < 2$ Baryons
- $z < 2$ Lyα Forest
- OVI+BLAs
- Stars + Cold ISM
- X-ray ICM

**Legend:**
- WHIM (No GSW)

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IXO (Munich): Fabrizio Nicastro
Abundant Ions in the WHIM

Hybrid Ionization WHIM (delta=50)

Warm Phase: Needs Moderate S/N FUV

WHIM Phase: Needs Deep and very high S/N FUV & X-ray
Not “just” Baryon Census

According to SCM: (54 ± 9)% of Baryons are missing!

• Find the ‘Missing Baryons’ to test SCM

• Ecology of the Universe (Metal Pollution, Metal Transport): dZ/dz
  – Absolute (needs UV) and Relative Metallicities.
  – Galaxy Superwinds (SN) vs AGN winds, jets
  – Nucleosynthesis

• Heating History of the Universe (test LSS shocks and structure formation): dT/dz
Mass and Metal Content of the WHIM

\[
\Omega_b = \frac{1}{r_c} \frac{m_{m_p} \frac{\sum N_i}{N_H}}{d_{Tot}}
\]

\[
N_{H} = N_{ion} \cdot A_{element}^{-1} \cdot X_{ion}^{-1}
\]
**Eff. Area: Grating vs Calorimeter @ 0.5 keV**

\[ EW(CAL)^{5s}_{\text{Thresh}} \cdot \frac{5(125 mA)}{(S/N)_{RE}} = EW(GRAT)^{5s}_{\text{Thresh}} \cdot \frac{5(10 mA)}{(S/N)_{RE}} \]

- To detect at 5\(\sigma\) OVII with EW(OVII)=2 mA
  - \((S/N)_{RE(CAL)} \geq 31\) -> Factor of 1.2 in S/N
  - \((S/N)_{RE(GRAT)} \geq 25\) -> Factor of \(~1.4\) in \(A_{\text{Eff}}\) needed vs Factor of \(~10\) actual

Compensated by Factor >~ 10 in R
Typical OVII EW: $W_{OVII} \sim 0.8-8 \,(1+z) \text{ mA (X-Rays)}$

Detection Efficiency:

$$\eta = \frac{R}{(l/\text{EW})}$$

$\eta$ (OVII) = $R_{Grat} / 22/(0.0008-0.008) > (0.1-1)$

$\eta$ (OVII) = $R_{cal} / 22/(0.0008-0.008) \sim (0.01-0.1)$

Cf with:

$\eta$ (OVII; Chandra, XMM) \sim (0.01-0.1)

$\eta$ (OVI; FUSE, HST) \sim (1-10)

$\eta$ (HI; FUSE, HST) \sim (0.1-1)$
Moreover...

Disp. vs Non-Disp.

Intrinsic Gain

Gratings

\[
\left( N_{Thres}^{He-like} \right)_{Grat} = 4 \times 10^{14} \cdot \frac{N_s}{3} \cdot \frac{l}{25} \cdot f_{ion} \cdot \sqrt{\frac{Dl}{10} \cdot \frac{10^{-6}}{F(\text{erg cm}^{-2})} \cdot \frac{1000}{A_{Eff}(\text{cm}^2)} \cdot (1+z)^{-1}}
\]

Calorimeters

\[
\left( N_{Thres}^{He-like} \right)_{Cal} = 5 \times 10^{14} \cdot \frac{N_s}{3} \cdot \frac{l}{25} \cdot f_{ion} \cdot \sqrt{\frac{DE(eV)}{2.5} \cdot \frac{10^{-6}}{F(\text{erg cm}^{-2})} \cdot \frac{10000}{A_{Eff}(\text{cm}^2)}}
\]

e.g. Gratings detect 3x fainter CV at z=0.3
Finally... Kinematics and Multiphase Systems: WHIM lines are narrow!

- \( V_{th}(O,T=10^6 \text{ K}) \sim 33 \text{ km s}^{-1} \)
  
  \( \xrightarrow{\text{FWHM(OVII)}} 6 \text{ mA @ 0.5 keV} \)

Cf w FWHM(Grat) = 10 mA
FWHM(Cal) = 125 mA @ 0.5 keV

+ WHIM is multiphase with typical 10-100 km s\(^{-1}\) separation (e.g. Danforth&Shull+08)

\( \Omega_b \) measurements need secure identification of BLAs with Metal Lines.
What Can we Detect with IXO

> 3-10 Systems down to $N_{\text{OVII}} = 4 \times 10^{14} \text{ cm}^{-2}$ at $z > 0.3$

$\text{EW}_{\text{OVII}} = 1 \text{ mA} \iff N_{\text{OVII}} = 4 \times 10^{14} \text{ cm}^{-2}$
Optimal WHIM Sample for IXO

- $F(0.1-2.4\ \text{keV}) > 0.2\ \text{mCrab}$
- $Z > 0.3$
- $N_H(Gal) < 3 \times 10^{20}\ \text{cm}^{-2}$
- Mostly BL-LAC

Gives 69 AGNs

~ 3-10 Metal Systems per line of sight in 200-300 ks with IXO Gratings

200-700 OVII WHIM systems in 0.7 yrs

... BUT... Needs HI to derive Metal Content & Mass
X-Ray-FUV Bright WHIM targets

- BRASS vs VERON (+ from BRASS vs SDSS + BRASS vs 6DF)
  (+Sedentary BLLac Survey)
- Result vs Galex, HST, FUSE

69 AGNs
31 FUV Bright

\[ \nu f(\nu) \text{ (erg s}^{-1} \text{ cm}^{-2}) \]

\[ F(0.1-2.4) \text{ (mCrab)} \]

z > 0.3
0.25 < z < 0.3
GTO z > 0.3
IXO Grating Spectra of WHIM

300 ks, 0.2 mCrab

300 ks, 2 mCrab

Random Line of Sight from latest Cen&Ostriker+06 Simulations
Conclusions

• Dispersive Spectroscopy is crucial for WHIM studies:

• WHIM studies must exploit the strong synergy between FUV and X-Ray spectroscopy: FUV vital to measure HI column and metallicity, X-Ray needed to obtain ionization correction

• IXO gratings will allow the detections of 3-10 WHIM metal systems per line of sight between z=0-0.3, down to $N_{OVII} > 4 \times 10^{14}$ cm$^{-2}$

• < 300 ksec per line of sight are needed against the 69 brightest AGNs at z>0.3, with F>0.2 mCrab.

• IXO will detect 200-700 systems in only 0.7 yrs !!! (cf with 0-3 systems in 10 yrs Chandra/XMM), so allowing for:
  – Measure of $\Omega_b$ to better than 1%
  – Metallicity history of the Universe
  – Heating history (shocks, structure formation)
  – Cosmological parameters (2-point corr. Analysis)