Searching for emission from the warm-hot intergalactic medium

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• Current Universe is a consequence of
  • structure formation by gravity,
  • and chemical enrichment and feedback from smaller scale to larger scale.

• The warm-hot intergalactic medium (WHIM) is largest structures in the local Universe, tracing distribution of dark matter and imprinting enrichment history.
Warm-hot intergalactic medium

- Warm-hot intergalactic medium (WHIM):
  - $T=10^5-10^7$ K;
  - $n_H = 10^{-5}-10^{-3}$ cm$^{-3}$.

- Dominant baryon and metal reservoir at $z=0$.

- Chemical enrichment history is imprinted.
WHIM as a reservoir of baryons

Mass fraction

Metal mass fraction

Cen & Chisari 2010
“Cooler” WHIM has been detected

- ~20% of baryons are in the cooler (<10^6 K) WHIM.
- Though OVI and broad Lyα absorption lines in UV band.
- Remaining ~40% baryons is “hotter” (>10^6 K) WHIM.
  - Could be detected in X-rays.

Further Reading:
- OVI: Danforth & Shull 2005, 2008; Tripp et al. 2000, 2008; Thom & Chen 2008a,b
- BLAs: Richter et al. 2004, 2006; Lehner et al. 2007; Danforth, Stocke & Shull 2010
WHIM observed in X-rays so far (1)

- WHIM associated with Sculptor Wall
  - Buote+2009, Fang+2010
  - Redshifted OVII absorption line observed with 4σ significance.
  - Detected by both Chandra and XMM

![Graph and Diagram]

- Figure 3.

In Figure 3, we show the expanded range of the points in the upper panel. The blazar line of sight is indicated by the (red) dotted line in the wedge diagram. The range of the points in the upper panel define the range of declination of the galaxies displayed in the lower panel. The blazar line of sight is indicated by the (red) dotted line in the wedge diagram. The blazar line of sight is indicated by the (red) dotted line in the wedge diagram.
WHIM observed in X-rays so far (2)

- Similar strategy, but less significant reports for Virgo and Coma clusters
  - $2\sigma$ OVIII absorption for Virgo (Fujimoto, YT+ 2004)
  - $2.7\sigma$ NeIX absorption for Coma (YT+ 2007)
  - Possible excess emission lines. (redshift not constrained)
WHIM observed in X-rays so far (3)

- Bridge between A222 and A223 (Werner+ 2008)
- Explained by 0.9 keV gas with overdensity ($\rho/\langle\rho\rangle$) of $\sim$150.
And several “unconfirmed” detection reports...

- Kaastra+ 2003 (OVII/OVIII emission associated with clusters)
  - *Calibration and Galactic foreground problem.*
- Finoguenov+ 2003 (OVII/OVIII emission in Coma-11 field)
  - *Solar wind charge exchange (YT+ 2008).*
- Nicastro+ 2005 (OVII absorption in the line of sight of Mrk421)
  - *Not confirmed by XMM (Rasmussen + 2007, Kaastra+ 2007).*
Lessons learned from “unconfirmed” detection

- Significant detections are only those associated with densest parts in large scale structures.
  - Random search of absorption lines have not resulted in a significant detection.

- Understanding possible systematic uncertainties is essential.
  - Detector background and response.
  - Galactic foreground emission.
    - Spatial variation of OVII/OVIII emission (Yoshino+ 2009)
    - Variability due to solar-wind charge exchange emission (Fujimoto+ 2007)
Why do we search in emission?

- Emission may give us 3D distribution of the WHIM.
  - Absorption can only do pencil beam analysis.

- Interaction to dense nodes (clusters) may be studied.

- However, applicable for only dense region ($I \propto n_H^2$)
  - Absorption can probe less density region ($EW \propto n_H$)

Yoshikawa+ 2002

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Search for WHIM in emission

• Two approaches
  • CCD-based search using a current mission.
    • Search for *redshifted* OVII and OVIII lines to get “evidence” of WHIM.
  • *Suzaku* XIS used because it has low and stable detector background and line spread function at low energy is good.
  • Utilizing progress in understanding foreground emission.

• Proposing new mission with a microcalorimeter.
  • DIOS (Japan), XENIA (US, Europe, Japan)
  • Estimating detectability is important.
Search cluster vicinities with Suzaku

- Eight clusters and superclusters have been observed.
- Targets are selected based on the possible elongation in LOS and reported soft emission in literature.
- Additional observations to determine the foreground level are performed in most cases.

<table>
<thead>
<tr>
<th>Target</th>
<th>Redshift</th>
<th>Info</th>
<th>Observation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2218</td>
<td>0.18</td>
<td>Elongation in LOS is suggested</td>
<td>2005-10-27</td>
<td>YT+07</td>
</tr>
<tr>
<td>Coma-11</td>
<td>0.02</td>
<td>XMM detected OVII/OVIII liens</td>
<td>2007-06-21</td>
<td>YT+08</td>
</tr>
<tr>
<td>A399/401</td>
<td>0.07</td>
<td>Pair cluster</td>
<td>2006-08-22</td>
<td>Fujita+08</td>
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<tr>
<td>A2052</td>
<td>0.04</td>
<td>Soft excess reported with XMM</td>
<td>2005-08-20</td>
<td>Tamura+08</td>
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<tr>
<td>A1413</td>
<td>0.14</td>
<td>Suzaku observed to virial radius</td>
<td>2005-11-15</td>
<td>Hoshino+10</td>
</tr>
<tr>
<td>A2142</td>
<td>0.09</td>
<td>Big cluster under merger</td>
<td>2007-01-05</td>
<td>Akamatsu+ in prep.</td>
</tr>
<tr>
<td>Shapley</td>
<td>0.06</td>
<td>Soft excess reported with ROSAT</td>
<td>2008-07-10</td>
<td>Mitsuishi+ in prep.</td>
</tr>
<tr>
<td>Sculptor</td>
<td>0.11</td>
<td>Soft excess reported with ROSAT</td>
<td>2005-12-03</td>
<td>Sato+ submitted</td>
</tr>
</tbody>
</table>
Spectra obtained with **Suzaku**

- Spectra are consistent with a sum of background and foreground emission, and hot intracluster medium in some cases.

**Sculptor supercluster**

![Sculptor supercluster spectra](image)

**A2218 outskirts**

![A2218 outskirts spectra](image)
Summary of search with Suzaku

- No detection. Tight upper limits of OVII/OVIII surface brightness is obtained.

- Some upper limits are tighter than previously claimed “detections”.

- Discrepancy mainly due to incorrect foreground modeling.
Estimated upper limit of overdensity

\[ I \propto \int n_H n_e Z F(T) dL \]
\[ \propto n_H^2 Z L F(T) \]

- Surface brightness is proportional to density^2, abundance (Z), LOS path length (L) and emissivity (F(T)).
- Density is constrained with an assumption of Z, L and T.
- Suzaku upper limits correspond to δ~300 assuming Z = 0.1 Z_{solar} and L = 2 Mpc
  - Note: in A222-223 filament, δ=150.
Future missions optimized for WHIM study

- **ΔE**: 2 eV
- **Effective area**: ~100 cm²
- **N of pixels**: 12 x 12 pixels
- **FOV**: 0.7 deg x 0.7 deg
- **PSF**: 2 arcmin HPD

- **ΔE**: 2.5 eV (goal 1 eV)
- **Effective area**: ~1000 cm² (goal 1300)
- **N of pixels**: 2000 (goal 2176)
- **FOV**: 0.9 deg x 0.9 deg (goal 1 x 1)
- **PSF**: 4 arcmin HPD (goal 2.5)
Simulation for detectability with XENIA

- Studied mock spectra based on SPH simulation by Borgani+ 2004, based on GADGET-2 (Springel+ 2005)
- Spectrum is calculated assuming CIE.
- Metallicity is determined a posteriori, \( \min(0.3, 0.005(\rho/<\rho>) \) with scatter to reproduce Cen & Ostriker 1998).

- \( \Omega_\Lambda = 0.7 \)
- \( \Omega_b = 0.04 \)
- \( h = 0.7 \)
- \( \sigma_8 = 0.8 \)
- Box size = 192h\(^{-1}\) Mpc
- particles = 480\(^3\) + 480\(^3\)
- Gravitational softning: \( \epsilon = 7.5h^{-1}\) Mpc at z=0.
- SF: included as sub-resolution multiphase mode (Springel & Hernquist 2003)
- FB from SNe: weak galactic outflows
- Radiative cooling assumes zero metallicity
Detecting emission lines from mock spectra

- Created mock spectra for 0<z<0.5 gas, for each 2.6’x2.6’ angular size.
- Detection is based on pixel-by-pixel (2.6’x2.6’) spectrum
- XENIA goal: $\Delta E = 1$ eV, $t_{\text{exp}} = 1$Ms gives 0.07 ph s$^{-1}$ cm$^{-2}$ sr$^{-1}$ as the 5σ detection limit.

$\sigma_{\text{line}} = \frac{f_{\text{line}}}{\sqrt{[f_{\text{line}} + (f_{\text{CXB}} + f_{\text{FG}})\Delta E]}} \sqrt{\Delta \Omega t_{\text{exp}} A_{\text{eff}}}$,
Detectability with XENIA

- Expected detection is $dN/dz > 1$ for both OVII and OVIII lines for a single sight line.

- With 1 deg $\times$ 1 deg FOV, $dz = 0.5$, and 2.6$'$x2.6$'$ angular element size, More than 600 OVII/OVIII pairs are expected to be detected with one 1 Ms observation.
Identified gas in \( \rho-T \) plane

All gas > \( 10^5 \) K, averaged in 2.6’ x 2.6’x 3 Mpc
Identified gas in $\rho$-$T$ plane

Detected with 1Ms exposure
Mass fraction probed with emission

- Most of $\delta>100$ and half of $\delta>30$ region can be probed with 1 Ms exposure of XENIA.

- With 100 ks, only $\delta>100$-300 can be probed.
Expected 3D map at $z=0.22$

Gas density

OVII/OVIII emission line

5.5 deg = 48 Mpc/$h$

54 Mpc/$h$ ($\Delta z = 0.02$)
Expected 3D map at z=0.1

Gas density

OVII/OVIII emission line

5.5 deg = 23 Mpc/h

58 Mpc/h (Δz = 0.02)
Prospects with other missions

• Suzaku
  • Sensitivity reaches to $\delta \sim 300$. Possibly we will get evidence of redshifted O lines for a few cluster outskirts

• DIOS
  • Similar energy resolution, but x10 smaller effective area as XENIA.
  • Expected to provide similar 3D maps as XENIA. However, only denser nodes can be probed.

• Astro-H (2014)
  • First microcalorimeter in orbit. But small effective area (100 cm$^2$) and small FOV (2.9’x2.9’) limits the study at cluster outskirts/groups.

• IXO
  • Quite larger effective area (x10), but small FOV (x1/1000). Good to probe smaller scale blobs, but not suitable for mapping. For absorption study, IXO will provide a significant progress.
XENIA as a probe of chemical evolution

- Current Universe reflects
- not only structure formation by gravity,
- but also chemical enrichment and feedback from smaller scale to larger scale.

- The warm-hot intergalactic medium (WHIM) forms largest structures in the local Universe, tracing distribution of dark matter.
XENIA as a probe of chemical evolution

Evolution of the Universe

Past

Stars

Galaxies

Clusters

Small scale

GRBs

SNRs

Starburst galaxies/AGNs

Feedback & Enrichment

Clusters

Large scale

WHIM

Present

Structure formation

XENIA

First metal creation at z>5

Metal creation/injection by super novae

Absorption in GRB host galaxies

Cluster temperature/mass study to virial radius

Cluster abundance to virial radius

Missing baryons at low redshift
Summary

- WHIM study using emission still remains to be done.
  - No significant detection yet.
  - Will be a new probe for cosmic chemical evolution.
- XENIA will certainly make a remarkable progress.
  - ~600 O\text{VII}/O\text{VIII} pairs in a 1 Ms exposure.
  - Half of mass of $\delta$~30 detected.
  - 3D maps.
- CCD-based analysis (Suzaku) is quite tough, but maybe detect a few redshifted O lines associated with the large scale structure.
Energy budget on a dish

Baryons (pepper and sauce)

Dark energy (beef)

Dark matter (potato)