The Warm-hot Gaseous Halo of the Milky Way

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With
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In the low-redshift Universe, baryons are missing on all scales.
Where are the Galactic missing baryons?

Local WHIM filament
scale length $> 1$ Mpc

Local Group Medium
scale length of $\sim 1$ Mpc

Circum-Galactic Medium: extending up to the virial radius ($\sim 250$ kpc)

$10^5$ K $< T < 10^7$ K
Simulations of the CGM

Stinson et al. 2011
Diffuse Warm-hot CGM

Low Feedback

High Feedback

$L = 0.79 \, L^*$

$L = 0.84 \, L^*$
$z = 0$ X-ray Absorption

In several high S/N Chandra and XMM spectra

- **OVII absorption** (@21.60 Å)
- **Sometimes OVIII** (@18.96 Å)
  and/or **Ne IX** (@13.44 Å)

Mathur et al. 2003
Z=0 X-ray absorption
PKS 2155-304
Nicastro et al. 2002
\( z = 0 \) X-ray Absorption

- In several high S/N Chandra spectra:
  - Mkn 421 (Williams et al. 2005)
  - Mkn 279 (Williams et al. 2006)
  - PKS 2155-304 (Nicastro et al. 2002)
  - 3C 273 (Fang et al. 2003)
  - Other sightlines with lower significance (McKernan et al. 2004)
- Always OVII, sometimes other species
- Chandra-LETG resolution 700 km/s, so all lines are unresolved
Origin

• Hot Galactic Halo/Corona…
  – From galaxy formation / feedback processes
  – Some OVII seen within 50 kpc (Wang et al. 2005)

• … or Local Warm-Hot IGM?
  – Predicted by simulations (Kravtsov et al. 2002)
  – Upper limit on OVII emission implies very low density (Rasmussen et al. 2003)
Our Chandra Survey of OVII and OVIII

- Chandra sight lines
- Previous OVII detection
Our Chandra Survey of OVII and OVIII

- 29 sight lines with good S/N near OVII $z=0$ region
- OVII detection in 21 sight lines
- OVIII detection in 8 sight lines
OVII EW Distribution

- OVII detection
- OVII upper limit
OVII and OVIII $z=0$ Absorption

- $\log T = 6.1-6.4 \, K$
Column Density Measurement

- Optically thin line
  \[ N(\text{ion}) = 1.3 \times 10^{20} \left( \frac{\text{EW}}{f\lambda^2} \right) \text{ cm}^{-2} \]
- For OVII
  \[ \frac{\text{EW}(K\beta)}{\text{EW}(K\alpha)} = 0.156 \]

| Target   | \text{EW} (OVII \text{K}\alpha) (m\text{\AA}) | \text{EW} (OVII K\beta) (m\text{\AA}) | \text{EW} (OVIII \text{K}\alpha) (m\text{\AA}) | \text{OVII} \left( \frac{\text{EW}(K\beta)}{\text{EW}(K\alpha)} \right) | \text{b} (\text{km/s}) | \text{log(NO VII)} (\text{cm}^{-2}) |
|----------|---------------------------------------------|------------------------------------|---------------------------------------------|------------------------------------------------|-------------------|---------------------------------|
| Mrk290   | 18.9 ± 4.5                                  | 5.1 ± 3.7                          | 8.4 ± 2.9                                   | 0.27 ± 0.21                                        | > 55              | 16.14 ± 0.32*                   |
| PKS2155-304 | 11.6 ± 1.6                                  | 4.2 ± 1.3                          | 6.7 ± 1.4                                   | 0.36 ± 0.12                                        | 35 – 94           | 16.09 ± 0.19                   |
| Mrk421   | 9.4 ± 1.1                                   | 4.6 ± 0.7                          | 1.8 ± 0.9                                   | 0.49 ± 0.09                                        | 24 – 55           | 16.22 ± 0.23                   |
| Mrk509   | 23.9 ± 5.0                                  | 11.7 ± 4.1                         | 10.3 ± 4.3                                  | 0.49 ± 0.20                                        | 70 – 200          | 16.7 ± 0.27                    |
| 3C382    | 17.3 ± 5.0                                  | 7.8 ± 3.0                          | 6.8 ± 3.8                                   | 0.45 ± 0.22                                        | > 40              | 16.50 ± 0.49*                  |
| Arp564   | 12.0 ± 1.9                                  | < 3.8                              | 9.5 ± 4.1                                   | ...                                                | > 20              | 15.82 ± 0.20*                  |
| NGC3783  | 14.4 ± 2.5                                  | 5.6 ± 1.6                          | 4.5 ± 2.9                                   | 0.39 ± 0.13                                        | 50 – 130          | 16.30 ± 0.25                   |
| H2106-099| 48.3 ± 18.0                                 | < 34.2                             | 28.8 ± 13.8                                 | ...                                                | > 70              | 16.23 ± 0.16*                  |

*TI analysis Most of OVII K\alpha are saturated
$\log(N_{\text{OVII}})$ and $b$ contour
• $\log N_{\text{OVII}} = 16.19 \pm 0.08 \text{ cm}^{-2}$

2-3 times higher than previous estimates

• Column density $N_H = \mu n_e L$
Galactic Halo Emission Measure

Henley et al. (2010) and Yoshino et al. (2009)

• Galactic Halo temperature is fairly constant
  \[ T = (1.8 - 2.4) \times 10^6 \text{ K} \]

• Halo emission measure varies by an order of magnitude
  \[ \text{EM} = (0.0005 - 0.005) \text{ cm}^{-6} \text{ pc} \]

\[ \text{EM} = 0.003 \left( \frac{Z}{Z_\odot} \right) \text{ cm}^{-6} \text{ pc} \]
Combining Absorption and Emission Measurement

\[ n_e = (2.0 \pm 0.6) \times 10^{-4}(0.5/f_{\text{OVII}})^{-1} \text{ cm}^{-3} \]

\[ R = (71.8 \pm 30.2) \left(8.51 \times 10^{-4}/(A_O/A_H)\right)(0.5/f_{\text{OVII}})^2(Z_{\Theta}/Z) \text{ kpc} \]

\[ L > 41.6 \text{ kpc} \]

\[ n_e < 2.6 \times 10^{-4} \text{ cm}^{-3} \]
Mass Probed by OVII and OVIII X-ray Absorbing/Emitting Gas Phase

\[ M_{\text{total}} > 1.7 \times 10^9 \left( \frac{f_c}{0.72} \right) \left( 8.51 \times 10^{-4} / (A_O/A_H) \right)^3 \left( 0.5/f_{\text{OVII}} \right)^5 \left( \frac{Z_\odot}{Z} \right)^3 M_\odot \]

For \( Z = 0.3Z_\odot \)

\[ L > 138 \text{ kpc} \]

\[ M_{\text{total}} > 6.1 \times 10^{10} M_\odot \]

Gupta, Mathur + 2012, 2014
Fang, Bullock +2012
This is a robust result!

• Is the z=0 absorption mostly from the Galactic disk? **No.**

• What about the uniform density profile? **No problem: gives a lower limit on mass.**

• Are the emission and absorption at different temperatures? **No.**
..... no anticorrelation between EW and sin(b)
Future directions

• Probing the anisotropy: emission and absorption along the same sightline.
  -- New Suzaku observations
  -- New XMM-Newton Observations.

• Different density and temperature profiles: e.g. Maller-Bullock profile in NFW halo.

• Probing the multi-phase medium: other ions dominant at different temperatures.
Conclusion

• X-rays provides evidence for hot (T>10^6 K) gas in and around the Milky Way.

• X-ray OVII and O VIII absorption lines at z=0 probe the hot gas extending over a large region around the Milky Way, with a radius of over 100 kpc.

• The mass content of this phase is over 10^{10} M_Ω.

• A large fraction of Galactic missing baryons are in this hot phase.

• Appears to be a robust result supported by theoretical models.