Analyzing the Milky Way's Hot Gas Halo with OVII and OVIII Emission Lines

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The CGM Ecosystem

- The circumgalactic medium (CGM) around Milky Way-sized galaxies includes...
  - Infalling / outflowing gas
  - Gas shock heated to $T_{\text{vir}}$ in quasi-static halo

- Properties tell us about galaxy formation / evolution

Nuza+ 14
The Milky Way's Ecosystem

- The Milky Way's X-ray halo gas has been observed in both emission and absorption.

<table>
<thead>
<tr>
<th>Emission Source</th>
<th>log(T)</th>
<th>$n$ (cm$^{-3}$)</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Halo</td>
<td>6.3</td>
<td>$10^{-5} - 10^{-3}$</td>
<td>$r_{\text{vir}} \sim 250$ kpc</td>
</tr>
<tr>
<td>Local Bubble (LB)</td>
<td>6.1</td>
<td>$10^{-3} - 10^{-2}$</td>
<td>100-300 pc</td>
</tr>
</tbody>
</table>

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Goals of This Work

• Improve constraints on the radial distribution of hot halo gas using X-ray emission lines
  • Do emission lines provide an improvement over absorption lines?

• Estimate the mass of the hot gas halo – is it a significant amount of baryons?
Diagnostics

- OVII - 0.56 keV – He-like triplet emission
- OVIII - 0.65 keV – H-like Lyα emission
- Large ion fractions at $\sim 10^6$ K
Sample

- Archival OVII and OVIII line intensities from Henley & Shelton 2012
  - Full Sample – 1868 pointings
  - Flux Filtered Sample – 1003 pointings

- Our additional screening removes pointings near the Galactic plane, Fermi bubbles, and bright X-ray sources
  - Our Sample – 649 pointings
Schematic

Halo Gas Temperature Fixed at $\log(T/K) = 6.3$

No observations within 10° of Galactic disk

Local Bubble Temperature Fixed at $\log(T/K) = 6.1$

649 pointings
Model

- Model has 2 components with 3 parameters
  - $\beta$ model at log(T/K) = 6.3 for halo emission

\[
n(r) = n_o \left[ 1 + \left( \frac{r}{r_c} \right)^2 \right]^{-\frac{3}{2}\beta} \approx \frac{n_o r_c^{3\beta}}{r^{3\beta}} \equiv \text{constant} \underbrace{\frac{r_{c}^{2}}{r^{3\beta}}}_{r_c << r}
\]

- Local Bubble at log(T/K) = 6.1
- Collisional ionization equilibrium

\[
l = \int n_e^2 \times \epsilon(T) \, dr
\]
## Results

<table>
<thead>
<tr>
<th>Lines Fitted</th>
<th>$n_0 r_c^{3\beta}$ (cm$^{-3}$ kpc$^{3\beta}$)</th>
<th>$\beta$</th>
<th>$n_{\text{local bubble}}$ (cm$^{-3}$)</th>
<th>$\chi^2_{\text{red}}$ (dof)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OVII</td>
<td>$0.89 \pm 0.06 \times 10^{-2}$</td>
<td>$0.43 \pm 0.01$</td>
<td>$3.86 \pm 0.26 \times 10^{-3}$</td>
<td>$4.69 \ (645)$</td>
</tr>
<tr>
<td>OVIII</td>
<td>$1.35 \pm 0.24 \times 10^{-2}$</td>
<td>$0.50 \pm 0.03$</td>
<td>No Contribution</td>
<td>$1.08 \ (644)$</td>
</tr>
</tbody>
</table>

$r_{\text{corr}} = 0.74$

Fitting OVIII Lines

Optically Thin Plasma
Mass Estimates

- Mass inferred from emission line results compared to absorption line results (Miller+ 13)

\[ M_{\text{absorption}} = 1.7^{+1.6}_{-1.1} \times 10^{10} M_\odot \]

\[ M_{\text{emission}} = 5.2^{+1.1}_{-1.0} \times 10^{10} M_\odot \]

Optically Thin

- Blue line: OVII Absorption Lines
- Red line: OVIII Emission Lines
Mass Estimates

- Mass inferred from emission line results compared to absorption line results (Miller+ 13)

\[
M_{\text{absorption}} = 1.7^{+1.6}_{-1.1} \times 10^{10} \, M_\odot
\]

\[
M_{\text{emission}} = 2.9^{+1.7}_{-1.2} \times 10^{10} \, M_\odot
\]
Milky Way Baryon Budget

- For a cosmological $f_{\text{bar}}$ of $0.171 \pm 0.006$ (WMAP)...
  - $M(\text{stars + cold gas + dust}) = 6-7 \times 10^{10} \, M_\odot$
  - $M_{\text{vir}} = 1-2 \times 10^{12} \, M_\odot$
  - $M_{\text{miss}} = 1-3 \times 10^{11} \, M_\odot$

- If the density profile extends to the virial radius...
  - $M_{\text{hot}} = 2-6 \times 10^{10} \, M_\odot$

- Halo gas contributes $\lesssim 20\%$ to the missing baryons

- Profile would need to extend to $2-3 \, r_{\text{vir}}$ to account for all of the Milky Way's missing baryons
Conclusions

- OVIII emission lines constrain the radial distribution of the Milky Way's hot gas halo significantly better than OVII absorption lines.

- Estimated hot gas mass is $2-6 \times 10^{10} \, M_\odot$
  - Significant, but not all of missing baryons.

- Future work will involve understanding optical depth effects in the plasma.