The Hot Gaseous Halos of Spiral Galaxies

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Rich clusters have nearly all their baryons. Galaxies become increasingly baryon-poor. “Average” spiral (like M33) is missing 90% of baryons.
Baryons Aren’t Really Missing

• Matter must be conserved
• Baryons are just hard to see
• Where are they?
• Models: Hot dilute gas in galaxy halos and surrounding galaxies
• Why should we care?
• It’s all about galaxy formation and the formation of structure
  • Formation of structures from Dark Matter is (more or less) a solved problem
  • Baryons are different because of cooling and heating
  • Heating comes from accretion and feedback
• Gas should have $T \sim T_{\text{virial}} \Rightarrow X$-rays
• Prediction: lower mass galaxies don’t have a hot halo

Keres et al. 2008
The Milky Way

- The best data for study
- Hot Halo: mass, cooling rate, metallicity
- Rotation of the Hot Halo
- Interaction of the Fermi Bubbles with the Hot Halo

Model for the Milky Way
Nuza et al. 2014
Observations Samples

- Archival XMM data projects have produced all-sky samples of line strengths
  - Absorption lines: 26 AGN, 3 X-ray binaries
  - Emission lines: 683 sight lines from Henley & Shelton 12
MW Halo Masses (With Optical Depth Correction)

\[ \beta \approx \frac{1}{2} \]
\[ n \propto r^{-3/2} \]

Gas detected to 50 kpc
Extrapolation beyond 50 kpc

This is not the missing baryons (1-3x10^{11} \, M_{\odot})

Need to extrapolate gas to 2-3R_{virial} to account for missing baryons.

\[
M_{\text{absorption}} = 1.7^{+1.6}_{-1.1} \times 10^{10} \, M_{\odot}
\]
\[
M_{\text{emission}} = 2.9^{+1.7}_{-1.2} \times 10^{10} \, M_{\odot}
\]

Miller & Bregman 2015
Cooling time of the hot halo:

“Cooling flow” within 40 kpc

Cooling rate is about 0.2 Msun/yr (Z = 0.3 Zsun) (if cooling flows occur)
Hot Gas Kinematic Models

- Modeling absorption line shapes for bulk velocity flows
  - \( v_\Phi(R) = \) flat rotation curve
  - \( v_{r/z}(r,z) = \) constant accretion or outflow

face-on view

edge-on views

Rotation constrained by objects at various Galactic longitudes (but not high b)

Inflow/outflow constrained by looking up/down (high/low Galactic latitude)
Line of Sight Velocity Effects

- Line shapes and centroids encode information on the velocity structure

$l, b = 90°, 0°$
- Red = stationary
- Blue = corotating

Broad line shapes similar to HI profiles for gas in the disk.

XMM RGS was not expected to have this precision but it does!

Centroid differences can be measured
Observed Line Centroids

- 37 OVII absorption line centroids from Hodges-Kluck+ 16
- Corotating model is a better fit to the data than a stationary profile
  - Best-fit model lags behind the disk with $v_\phi = 183 \pm 41$ km s$^{-1}$
The Interaction of the Fermi Bubbles with the Hot Halo

• Elevated OVIII/OVII ration near Fermi Bubbles → shocked gas

• Modeling the emission lines shows
  • thermal gas density to be $\approx 10^{-3} \text{ cm}^{-3}$ and $\log(T) = 6.6-6.7$
  • $v_{\text{exp}} = 490 \text{ km s}^{-1}$
  • $\dot{E} = 2.3 \times 10^{42} \text{ erg s}^{-1}$
  • $t = 4.3 \text{ Myr}$

• FB origin consistent with a Sgr A* accretion event
• Not consistent with star formation origin
Hot Gas Around Spiral Galaxies

The gas is oriented perpendicular to the disk, and is usually visible only when there is active star formation.

Dilute hot halo extends to the virial radius; accreted gas. Challenging to detect.

Spirals: most likely a SN-driven galactic fountain + hot mode accretion
Global Formation Mechanisms

• **Accretion Shock**
  - Gas shock-heats to $T_{\text{vir}}$ at $r_{\text{vir}}$ as it accretes onto the dark matter halo
  - Expect spherical power law structure at $\approx 2 \times 10^6$ K

• **Supernovae-driven ‘galactic fountain’**
  - Supernovae heat the ISM and break out of the disk
  - Expect an exponential disk structure confined within $|z| < 10$ kpc

[Diagram of accretion and galactic fountain]

Photo courtesy of NASA/IPAC Extragalactic Database (NED)
Halos Around Two Massive Galaxies
NGC 1961 and UGC 12591

UGC 12591: Early-type spiral (left)   NGC 1961: Later-type spiral (right)

Stellar Mass is 6-8x the Milky Way
Summary from Anderson et al. (2015); also NGC 720 (Humphreys), NGC 266 (Bogdan); UGC 12591 (Dai et al. 2015) Metallicity of 0.1 – 0.5 Solar
Entropy increase with radius
Density and Mass Summary

• General results
  • $\beta = \frac{1}{2}; n \sim r^{-3/2}$
  • 20-30% of missing baryons within $R_{\text{virial}}$
  • Gas mass comparable to stellar mass
  • Still missing half of the baryons (or more)

• Could density law be flatter (Kauffmann et al. 2008, Feldmann et al. 2012)?
  • No (inconsistent with observed $S_x, T_x$)
  • $T$ also gives $n \sim r^{-3/2}$
Summary and Conclusions
(in case you concentration is compromised after the dinner last night)

- Extended hot halos exist around spiral galaxies
  - To at least 50 kpc and probably to $R_{200}$
  - Comparable to (less than) stellar mass within $R_{200}$
  - Hot mode accretion of $0.1-0.3\, M_\odot/\text{yr}$ (less than star formation rate)
  - Does not account for missing baryons unless extended to 2-3$R_{200}$
  - Metallicity of $\sim 0.3$ Solar
  - Variation in properties unknown due to small samples

- Milky Way hot halo rotates
  - About $180\, \text{km}\, \text{s}^{-1}$ ($60\, \text{km/s}$ slower than the disk); could use more objects
  - Consistent with theory, but few predictions

- Fermi Bubbles shock hot halo ($v = 500\, \text{km/s}$); AGN origin