THE GALACTIC CORONA

In honor of

Jerry Ostriker

on his 80th birthday

Chris McKee
Princeton  5/13/2017

with Yakov Faerman
Amiel Sternberg
A collaboration that began over 40 years ago and resulted in a lifelong friendship.
The problem of the missing baryons

WHERE ARE THE BARYONS?
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Received 1998 September 11; accepted 1998 October 29

ABSTRACT

New high-resolution, large-scale cosmological hydrodynamic galaxy formation simulations of a standard cold dark matter model (with a cosmological constant) are utilized to predict the distribution of baryons at the present and at moderate redshift. It is found that the average temperature of baryons is an increasing function of time, with most of the baryons at the present time having a temperature in the range of $10^5 - 10^7$ K. Thus not only is the universe dominated by dark matter, but more than one-half of the normal matter is yet to be detected. Detection of this warm/hot gas poses an observational challenge, which requires sensitive EUV and X-ray satellites. Signatures include a soft cosmic X-ray background, apparent warm components in hot clusters due to both intrinsic warm intracluster and intercluster gas projected onto clusters along the line of sight, absorption lines in X-ray and UV quasar spectra [e.g., O vi (1032, 1038) A lines, O vii 574 eV line], strong emission lines (e.g., O viii 653 eV line), and low-redshift, broad, low column density Ly$\alpha$ absorption lines. We estimate that approximately one-fourth of the extragalactic soft X-ray background (at 0.7 keV) arises from the warm/hot gas, half of it coming from $z < 0.65$, and three-quarters coming from $z < 1.00$, so the source regions should be identifiable on deep optical images.

Proposed that $\sim \frac{1}{2}$ of the baryons are in the warm/hot IGM, heated primarily by structure formation
Shull+ 12 estimate that 30% of the baryons in the universe have yet to be observed.

Intergalactic medium (59%) includes the warm-hot IGM ($T > \sim 10^5$ K) and the cool ($T \sim 10^4$ K) photoionized IGM.

Could some of the missing baryons be in the circumgalactic medium (CGM)?
Baryons in the Galaxy

Mass model of Galaxy (McMillan 2011)

\[ M_{\text{vir}} = (1.26 \pm 0.24) \times 10^{12} \, M_{\text{sun}} \]

\[ M_{\text{baryon, Gal}} = (6.4 \pm 0.6) \times 10^{10} \, M_{\text{sun}} \text{ in stars and ISM} \]

Expected baryon mass = 0.157 \( M_{\text{vir}} \) (Planck collaboration 2016)

\[ = (2.0 \pm 0.4) \times 10^{11} \, M_{\text{sun}} \]

Hence, circumgalactic medium (CGM) of Milky Way could contain

\[ (2 - 0.6) \times 10^{11} \, M_{\text{sun}} = 1.4 \times 10^{11} \, M_{\text{sun}} \sim 2.2 \times M_{\text{baryon, Gal}} \]

If Milky Way is typical, then CGMs of galaxies would contain 2.2 \( \times 7\% \sim 15\% \) of the baryons, not 5\% as estimated by Shull+

Or, the Milky Way could have expelled a significant mass outside the virial radius \( \sim 250 \text{ kpc} \)
A little history on the galactic corona:

Although its mass was small \((10^8 \, M_{\text{sun}})\)
The circumgalactic medium (CGM) of the Galaxy

Galactic corona:

Hot gas ($T > \sim 10^6$ K): OVII/OVIII emission/absorption

Warm gas ($10^5$ K $\sim< T \sim< 10^6$ K): OVI absorption

Cool CGM (not included in our model):

Photoionized gas at $T \sim 10^4$ K

Werk+ 14 give a lower limit $M_{\text{cool}} \sim M_{\text{baryon,Gal}}$, but this appears to be an overestimate.
Observational evidence for a Galactic corona: X-ray absorption and emission

OVII, OVIII absorption lines in AGN spectra

Galaxy, not Local Group (Fang+ 06)

\[ N(\text{OVII}) \sim 1-2 \times 10^{16} \text{ cm}^{-2} \] (Fang+ 15)

\[ N(\text{OVIII}) \sim 0.2-0.6 \times 10^{16} \text{ cm}^{-2} \] (Fang+ 15 & Gupta+ 12)

OVII, OVIII emission lines + continuum emission

Infer \( T \sim (1 - 3) \times 10^6 \text{ K} \)

However, this could include emission from old supernova remnants in the disk (Henley+ 10)
Observational evidence for a corona: OVI absorption lines

Line width > thermal width, suggesting turbulence

\( h = \text{impact parameter} \)

Virial radius \( R_{\text{vir}} \) is the expected radius of the accretion shock in the IGM around the Galaxy.

CGM expected to extend out to \( \sim R_{\text{vir}} \)

Observations of absorption in galaxies near quasar lines of sight (blue)

(Tumlinson+ 11, Werk+ 13)

Binned data (magenta) and theoretical curve (Faerman+ 17)

Line width > thermal width, suggesting turbulence
Observational evidence for corona: OVI absorption lines

OVI absorption observed in most star-forming galaxies

Milky Way OVI consistent with COS-Halos data (e.g., Zheng+ 15)

Lack of OVI in passive galaxies could be due larger black holes in their nuclei (Reines & Volonteri 15), which could have ejected the CGM (Mathews & Prochaska 17)
Other data on CGM: Dispersion measure to LMC = \(< 23 \text{ cm}^{-3} \text{ pc}\)

Gas stripped from Local Group dwarfs: \(n > 2.5 \times 10^{-5}\) (Blitz & Robishaw 00)

Gas stripped from the Magellanic Clouds \(\Rightarrow\) density at 50-70 kpc from Galaxy \(\sim 10^{-4} \text{ cm}^{-3}\) (Moore & Davis 94, Hammer+ 15)

Other data on CGM: Dispersion measure to LMC \(= \int n_e dz < 23 \text{ cm}^{-3} \text{ pc}\)
Phenomenological model for coronae of L* galaxies
(Faerman, Sternberg & McKee 17, in prep)

Assumptions:

Gas in hydrostatic equilibrium in spherical gravitational potential due to $M(r)$ associated with stellar disk + NFW halo (Klypin+ 02)

Gas is turbulent, with a log normal distribution of temperatures and densities such that the pressure is constant at each radius

Include turbulent, magnetic and cosmic ray pressure

Two models:

Isothermal: Two phases, hot ($1.5 \times 10^6$ K $\Rightarrow$ OVII, OVIII) + warm ($3 \times 10^5$ K $\Rightarrow$ OVI)

Warm gas formed from hot gas with $t_{\text{cool}} < 8 t_{\text{dyn}}$

Adiabatic: Thermal gas ($\gamma = 5/3$) and non-thermal (B, CR $\Rightarrow \gamma = 4/3$)

(Preliminary—in preparation)
Input parameters for modeling a galaxy of total mass $10^{12} \, M_{\odot}$ and virial radius 250 kpc for isothermal (I) and adiabatic (A) models:

Temperature.  I: Median hot = $1.5 \times 10^6$ K, warm = $3 \times 10^5$ K

\[ A: T(R_{\text{vir}}) = 7 \times 10^5 \text{ K} \]

Dispersion in log normal temperature distributions: 0.3 (I), 0.5 (A)

Metallicity: $Z = 0.5$ solar

Thermal pressure at solar radius: $P_{\text{th}} = 2200 \, \text{K cm}^{-3}$ (I), $2700 \, \text{K cm}^{-3}$ (A)

Less than local observed value: $P_{\text{th}} = 3800 \, \text{K cm}^{-3}$ (Jenkins & Tripp 11)

$P_{\text{total}} / P_{\text{th}} = \text{const} = 2.1$ (I), $= 1.7$ at $R_{\text{vir}}$ (A)

Turbulent velocity dispersion 60 km s$^{-1}$ (I)

Criterion for warm gas to form from hot gas: $t_{\text{cool}} / t_{\text{dyn}} = 8$ (I)
Results: Comparison with observation

Excellent agreement on absorption

<table>
<thead>
<tr>
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<th>Observations</th>
<th>Isothermal model</th>
<th>Adiabatic model</th>
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<tbody>
<tr>
<td>$N_{\text{OVII}}$ (cm$^{-2}$)</td>
<td>1.4 (1.0 – 2.0) $\times 10^{16}$</td>
<td>1.6 $\times 10^{16}$</td>
<td>1.3 $\times 10^{16}$</td>
</tr>
<tr>
<td>$N_{\text{OVIII}}$ (cm$^{-2}$)</td>
<td>0.36 (0.22 – 0.57) $\times 10^{16}$</td>
<td>3.8 $\times 10^{15}$</td>
<td>3.0 $\times 10^{15}$</td>
</tr>
<tr>
<td>OVII/OVIII ratio</td>
<td>4.0 (2.8 – 5.6)</td>
<td>4.5</td>
<td>4.7</td>
</tr>
<tr>
<td>$DM$ (LMC) (cm$^{-3}$ pc)</td>
<td>$\lesssim 23$</td>
<td>17.4</td>
<td>14.1</td>
</tr>
<tr>
<td>$S_{0.4-2.0}$ (erg s$^{-1}$ cm$^{-2}$ deg$^{-2}$)</td>
<td>2.1 (1.9 – 2.4) $\times 10^{-12}$</td>
<td>0.82 $\times 10^{-12}$</td>
<td>0.98 $\times 10^{-12}$</td>
</tr>
<tr>
<td>22 Å (photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$)</td>
<td>2.8 (2.3 – 3.4)</td>
<td>1.2</td>
<td>0.87</td>
</tr>
<tr>
<td>19 Å (photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$)</td>
<td>0.69 (0.58 – 0.83)</td>
<td>0.33</td>
<td>0.50</td>
</tr>
<tr>
<td>22 Å/19 Å ratio</td>
<td>4.3 (3.4 – 5.5)</td>
<td>3.6</td>
<td>1.7</td>
</tr>
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</table>

Emission $\sim 0.4$ times observed and 22/19 low in adiabatic model; possible contamination by old supernova remnants in Galactic disk (Slavin+ 00)

(Note: 19 Å line is a combination of OVII and OVIII at low resolution of observations. OVIII/OVII depends sensitively on T and OVIII $> 50\%$ in our models)
Results: Comparison with observation

Density \(\approx 10^{-4} \text{ cm}^{-3}\) at 50-100 kpc, consistent with models for Magellanic Stream (Hammer+ 15)

Spatial distribution of OVI consistent with observation (Data from Tumlinson+11, Werk+ 13)
Results: Mass and metallicity of corona

\[ M_{\text{corona}} = 1.2 \times 10^{11} \, M_{\odot} \quad (I & A) \]

Expected coronal mass for \( 10^{12} \, M_{\odot} \) halo:

- Baryon mass \( 1.6 \times 10^{11} \, M_{\odot} \) – Galaxy mass \( 0.6 \times 10^{11} \, M_{\odot} = 10^{11} \, M_{\odot} \)

\[ \Rightarrow \text{no significant amount of missing baryons in the Galaxy} \]

Metallicity must be high (>~0.3): Lower metallicity requires more than the available number of baryons to explain X-ray absorption

Observations of quasar absorption lines in cool \( (10^4 \, \text{K}) \) gas show that metallicity can be high: Median is 0.3.

(Prochaska+ 17)
Where does the oxygen come from?

Mass of O observed based on Asplund 09 abundances ([O]=8.69):

\[
M(O) = 4 \times 10^8 M_{\text{sun}} \text{ (stars+gas, } Z=1) + 3 \times 10^8 M_{\text{sun}} \text{ (corona, } Z=1/2)
\]

\[= 7 \times 10^8 M_{\text{sun}}\]

Mass of O produced for \( M_* = 5.4 \times 10^{10} M_{\text{sun}} \) in Galactic stars:

Yield of 0.007 \( M_{\text{sun}} \) per \( M_{\text{sun}} \) formed and return fraction of 0.35 (Zahid+ 12)

\[\Rightarrow M(O)_{\text{produced}} = 6 \times 10^8 M_{\text{sun}}\]

Peeples+ 14 estimate a higher yield \( \Rightarrow 1.6 \times 10^9 M_{\text{sun}} \) produced

Conclude that SNe produce enough O to account for the inferred high metallicity in corona.
Galactic coronae form via cosmological gas accretion and galactic winds (e.g., Cen & Ostriker 06)

Cosmological gas accretion dominates for Milky Way halos ($M \sim 10^{12} M_{\text{sun}}$)

AGN heating not included
Can the corona be heated by AGN activity at the Galactic Center?

Fermi Bubbles seen in gamma rays (Su+ 10), X-rays (e.g., Miller & Bregman 16), UV absorption lines (Bordolo+ 17), & microwaves (Finkbeiner 04)

Bubble height ~ 10 kpc, width ~ 6 kpc
Wide range of models for Fermi Bubbles:

Shock velocity \( \sim \frac{R}{2t} \sim \frac{5000}{t_6} \) km s\(^{-1}\) for \( R \) varying as \( t^n \), with \( n \sim 1/2 \)

1. Strong explosion (\( E=1.6 \times 10^{57} \) erg) driven by jets from Sgr A*.
   Age \( \sim 2 \) Myr, \( v_s \sim 2000 \) km s\(^{-1}\)
   (Guo & Mathews 12)
   Consistent with flash photoionization of Magellanic Stream (Bland-Hawthorn+ 13)

2. Wind-driven bubbles: ages \( \sim 4 - 20 \) Myr, \( E \sim 6 \times 10^{55} - 3 \times 10^{56} \) erg
   \( v_s \sim 300-500 \) km s\(^{-1}\). Consistent with observed X-ray line emission
   (e.g., Miller & Bregman 16, Sarkar+ 17)

3. Equilibrium bubbles: age \( > 10^8 \) yr. Consistent w. current SFR (Crocker+ 14)
Energetics of AGN-driven Fermi Bubbles

Mechanical energy released in black hole accretion $\sim 0.03 \Delta m c^2$
Sadowski & Gaspari (2017)

Energy released in building Sgr A*: $0.03 \, M c^2 = 2 \times 10^{59} \, \text{erg}$
$> \sim 100 \, \text{Fermi Bubbles}$

Large compared to thermal energy in corona, $4 \times 10^{58} \, M_{11} \, T_6^{6} \, \text{erg}$

Comparable to total core-collapse SN energy over the life of the Galaxy, $\sim 5 \times 10^{59} \, \text{erg}$
E = σMv_s^2

For ρ ~ r^{-k},

σ = (3-k)(5-k) / 2(10-3k)

For gas in hydrostatic equilibrium, k ~ 1 – 1.5

=> σ ~ 0.5

Cooling time t_c ~ T_s^{3/2}/n

~ (E / M)^{3/2}/n

Approximately valid for non-spherical bubbles
Dynamics and cooling of Fermi Bubbles--2

Bubbles become large: If $n = n_0 r^{-1}$, then $v$ varies as $1/r$ and bubbles expand to $r > 100$ kpc, where $v \sim 200$ km s$^{-1}$

Mass of shocked gas with cooling time $> t_c$ for $n = n_0 r^{-k}$:

$$M(> t_c) \text{ varies as } \left( \frac{E^{3/2}}{n_0^{5/2} t_c} \right)^{2(3-k)/(9-5k)}$$

Low density of corona + high energy of Fermi Bubbles

$=>$ significant mass in corona heated with cooling time $\sim 10^{10}$ yr

Numerical modeling needed to determine global effect on corona
CONCLUSIONS

X-ray and UV data => large, hot coronae around MW-type galaxies

Our model accounts for X-ray and OVI absorption data; underestimates X-ray emission, which could have contribution from old supernova remnants near the disk (Slavin+ 00).

Require high metallicity: $Z \sim 0.5$

Account for most, if not all, of the baryons associated with Galactic dark matter

Fermi Bubbles can provide significant heating to corona

The Galaxy will live on: Coronal gas can supply gas for star formation at the observed rate ($1-2 \text{ Msun yr}^{-1}$) for $> 50$ Gyr
HAPPY BIRTHDAY, JERRY!