THE GALACTIC CORONA

In honor of

Jerry Ostriker

on his 80^{th} 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

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A THEORY OF THE INTERSTELLAR MEDIUM: THREE COMPONENTS REGULATED BY SUPERNOVA EXPLOSIONS IN AN INHOMOGENEOUS SUBSTRATE

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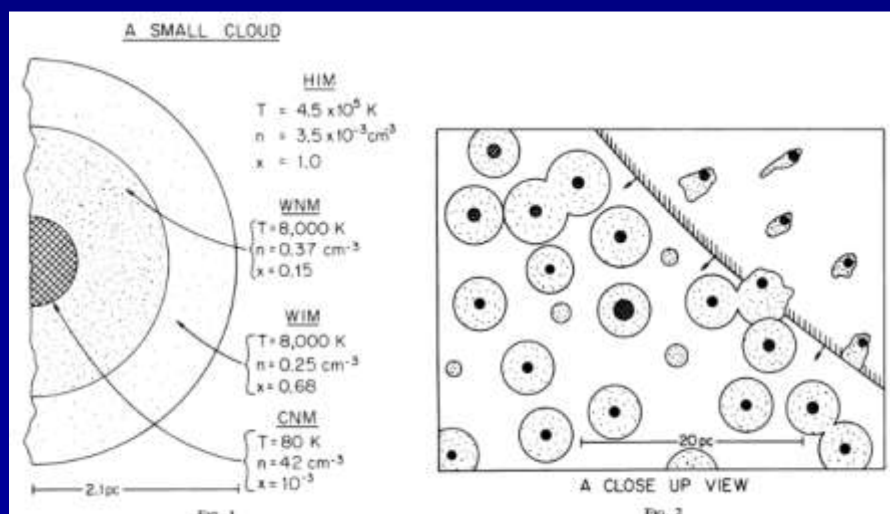

The problem of the missing baryons

WHERE ARE THE BARYONS?

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ABSTRACT

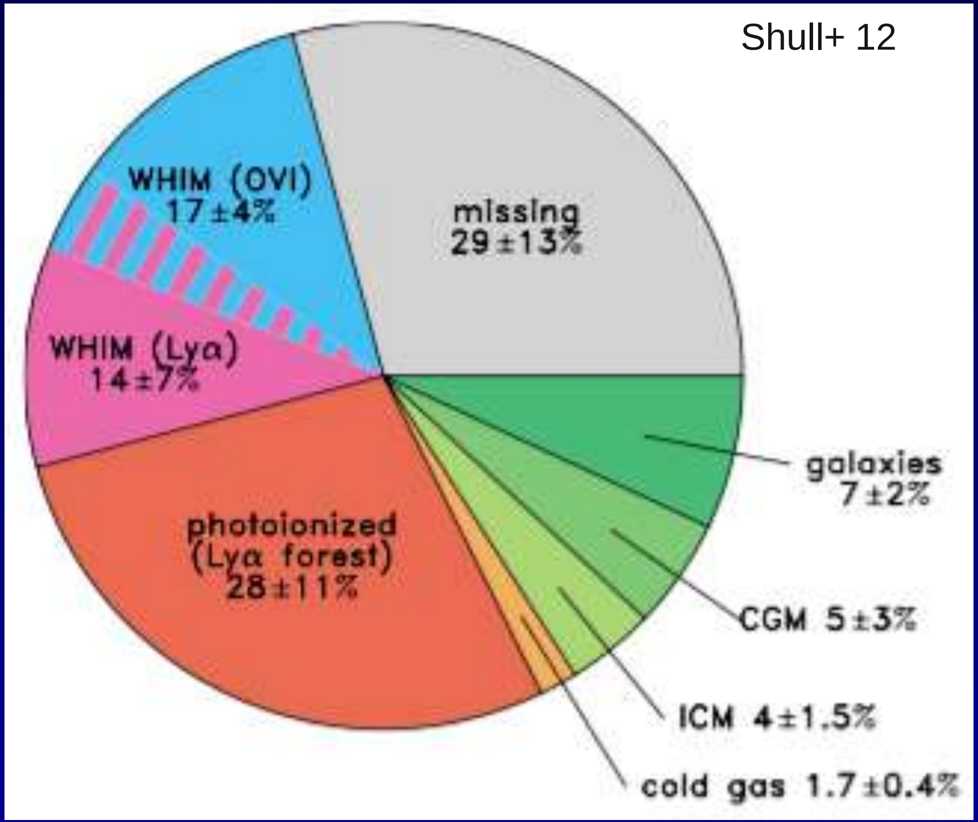
New high-resolution, large-scale cosmological hydrodynamic galaxy formation simulations of a standard cold dark matter model (with a cosmological constant) are utilized to predict the distribution of baryons at the present and at moderate redshift. It is found that the average temperature of baryons 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) Å lines, O VII 574 eV line], strong emission lines (e.g., O VIII 653 eV line), and low-redshift, broad, low column density Lyα 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 ~ ½ of the baryons are in the warm/hot IGM, heated primarily by structure formation

Missing baryons: the current situation

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 >~ 10^5 K) and the cool (T ~ 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)

$M_{vir} = (1.26 \pm 0.24) \times 10^{12}\ M_{sun}$

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

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

$= (2.0 \pm 0.4) \times 10^{11}\ M_{sun}$

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

$(2 – 0.6) \times 10^{11}\ M_{sun} = 1.4 \times 10^{11}\ M_{sun} \sim 2.2 \times M_{baryon,Gal}$

If Milky Way is typical, then CGMs of galaxies would contain 2.2 x 7% ~ 15% of the baryons, not 5% as estimated by Shull+

Or, the Milky Way could have expelled a significant mass outside the virial radius ~ 250 kpc

A little history on the galactic corona:

ON A POSSIBLE INTERSTELLAR GALACTIC CORONA*

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Received March 24, 1956

ABSTRACT

The physical conditions in a possible interstellar galactic corona are analyzed Pressure equilibrium between such a rarefied, high-temperature gas and normal interstellar clouds would account for the existence of such clouds far from the galactic plane and would facilitate the equilibrium of spiral arms in the presence of strong magnetic fields. Observations of radio noise also suggest such a corona.

At a temperature of 10^6 degrees K, the electron density in the corona would be $5 \times 10^{-4}/cm^3$; the extension perpendicular to the galactic plane, 8000 pc; the total number of electrons in a column perpendicular to the galactic plane, about $2 \times 10^{19}/cm^2$; the total mass, about $10^8 M_\odot$. The mean free path would be 4 pc, but the radius of gyration even in a field of 10^{-16} gauss would be a small fraction of this. Such a corona is apparently not observable optically except by absorption measures shortward of 2000 A.

Radiative cooling at 10^6 degrees would dissipate the assumed thermal energy in about 10^9 years. Cooling by conduction can apparently be ignored, especially since a chaotic magnetic field of only 10^{-16} gauss will sharply reduce the thermal conductivity At 3×10^6 degrees, near the maximum value consistent with confinement by the Galaxy's gravitational field, radiative cooling is unimportant, and a corona at this temperature might be primeval. The energy source needed at the lower temperatures may be provided by material ejected at high speed from stars or possibly by compressional waves produced by the observed moving clouds Condensation of cool matter from the corona may perhaps account for the formation of new spiral arms as the old ones dissipate.

although its mass was small (10^8 M_{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 $M_{cool} \sim M_{baryon,Gal}$, but this appears to be an overestimate.

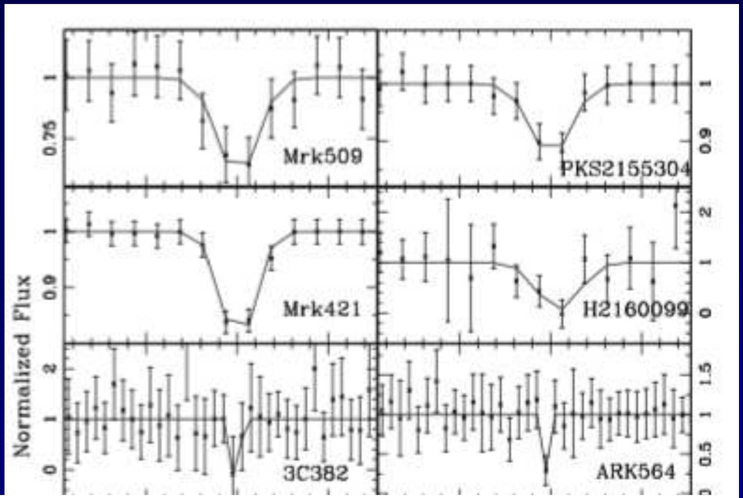
Observational evidence for a Galactic corona: X-ray absorption and emission

OVII, OVIII absorption lines in AGN spectra

Galaxy, not Local Group (Fang+ 06)

N(OVII) ~ 1-2 x 10^{16} cm^{-2} (Fang+ 15)

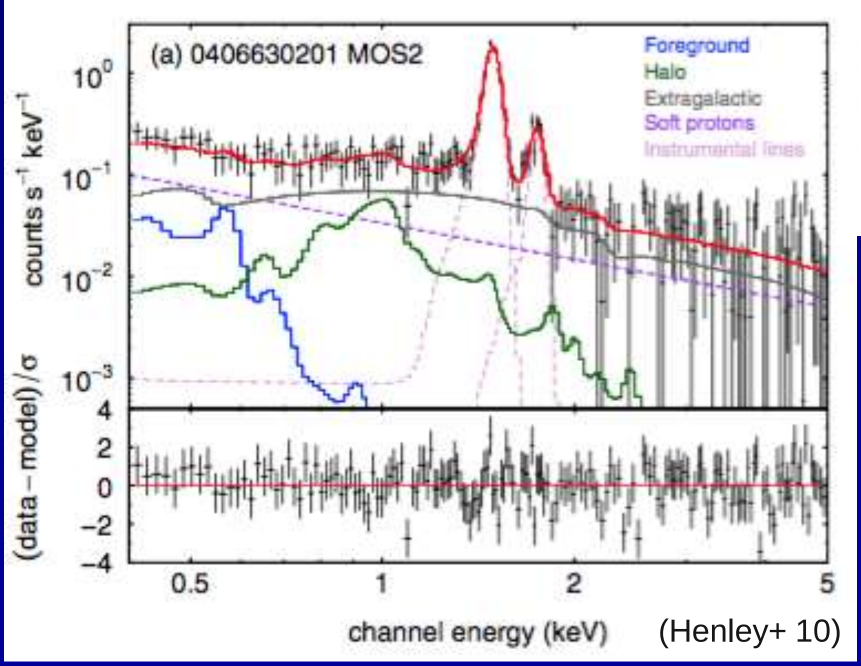
N(OVIII) ~ 0.2-0.6 x 10^{16} cm^{-2}
(Fang+ 15 & Gupta+ 12)



OVII, OVIII emission lines + continuum emission

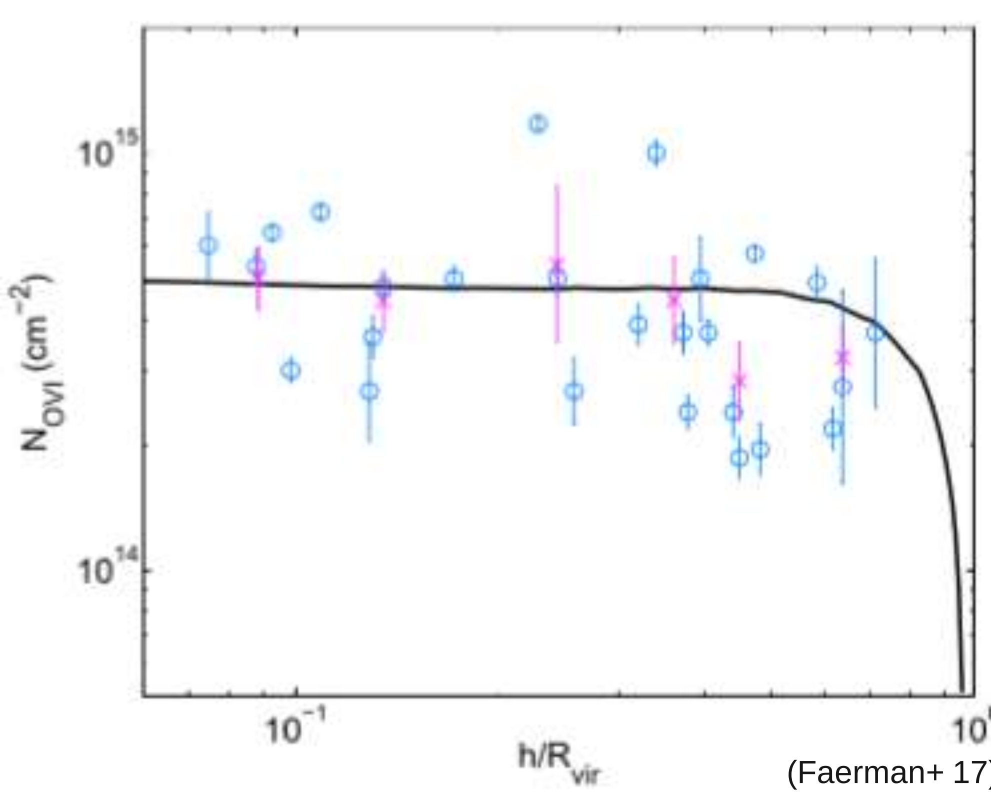
Infer T ~ (1 – 3) x 10^6 K

However, this could include emission from old supernova remnants in the disk



(Henley+ 10)

Observational evidence for a corona: OVI absorption lines



(Faerman+ 17)

h = impact parameter

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

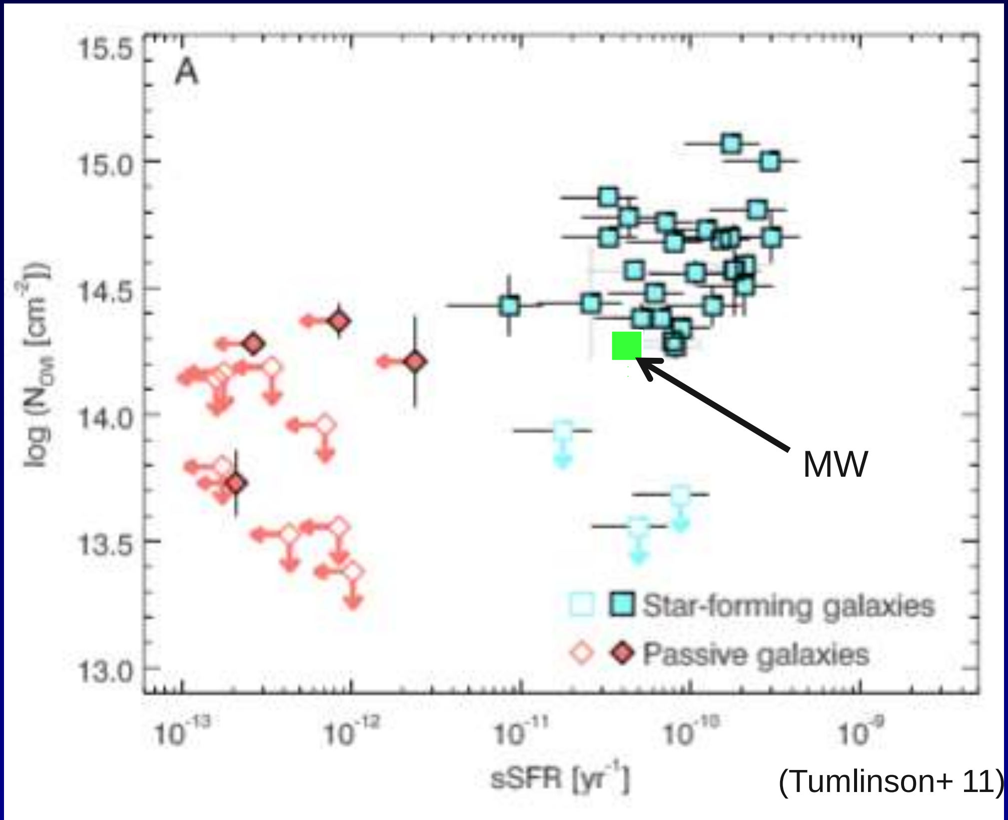
CGM expected to extend out to ~ R_{vir}

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

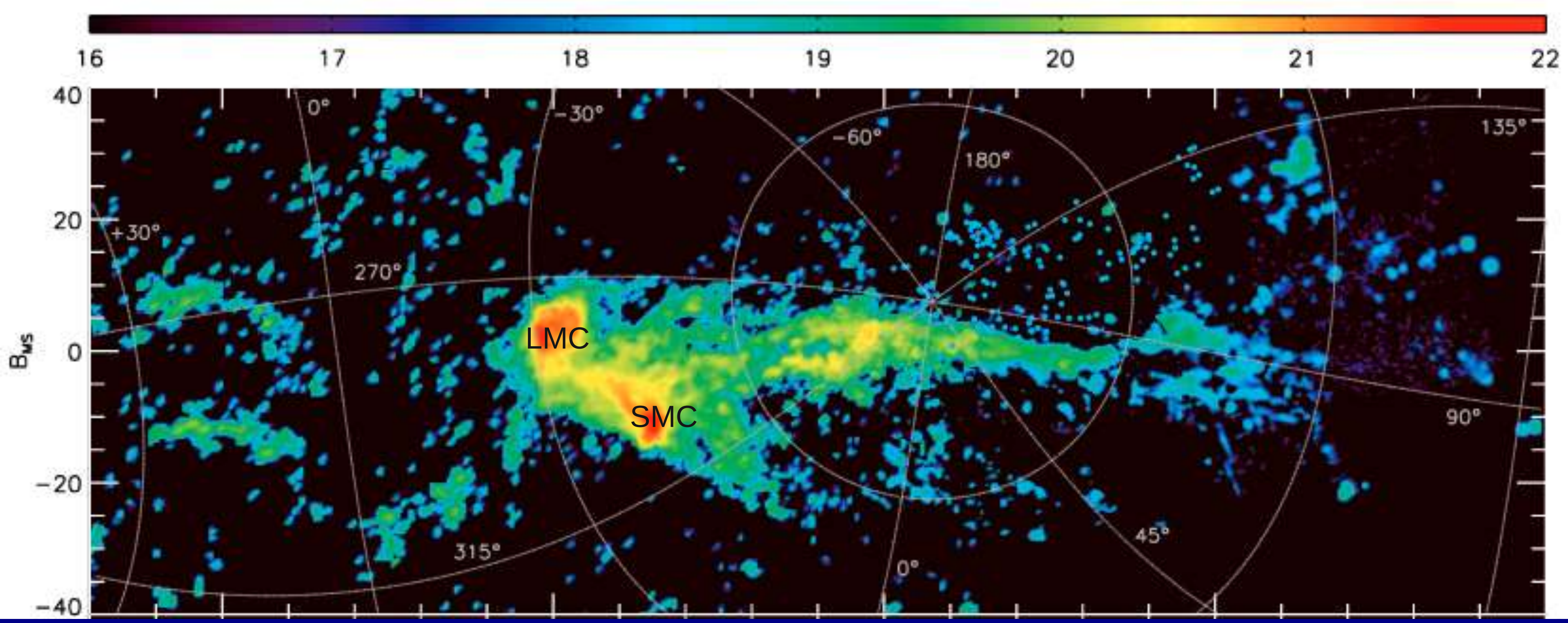


OVI absorption observed in most star-forming galaxies

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)

Observational evidence for corona: Ram pressure stripping



(Nidever+ 10)

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

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

Other data on CGM: Dispersion measure to LMC $= \int n_e dz < 23$ cm^{-3} 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)

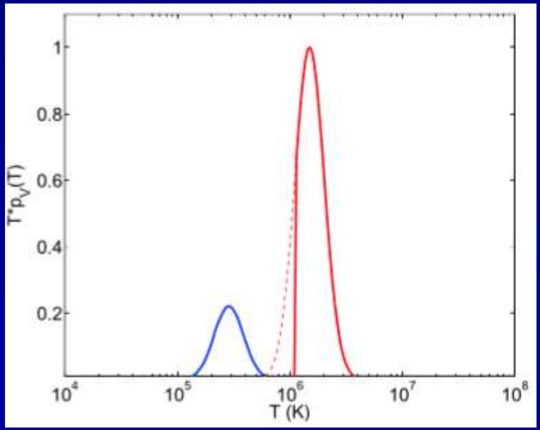
Gas is turbulent, with a log normal distribution of temperatures and densities such that the pressure is constant at each radius

Include turbulent, magnetic and cosmic ray pressure

Two models:

Isothermal: Two phases, hot (1.5×10^6 K => OVII, OVIII) + warm (3×10^5 K => OVI)

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



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

(Preliminary—in preparation)

Input parameters for modeling a galaxy of total mass 10^{12} M_{sun} and virial radius 250 kpc for isothermal (I) and adiabatic (A) models:

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

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

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

Metallicity: Z = 0.5 solar

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

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

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

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

Criterion for warm gas to form from hot gas: t_{cool} / t_{dyn} = 8 (I)

Results: Comparison with observation

Excellent agreement on absorption

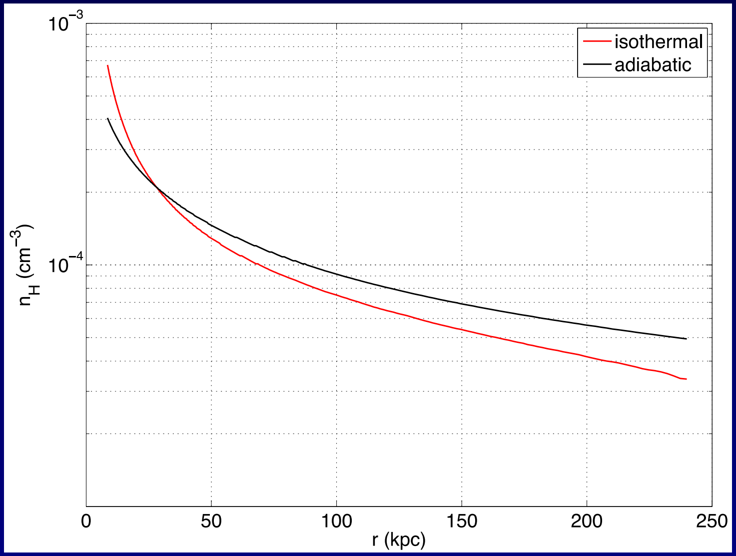
	Observations	Isothermal model	Adiabatic model
$N_{\rm OVII}$ (cm^{-2})	$1.4\ (1.0-2.0)\times 10^{16}$	1.6×10^{16}	1.3×10^{16}
$N_{\rm OVIII}$ (cm^{-2})	$0.36\ (0.22-0.57)\times 10^{16}$	3.8×10^{15}	3.0×10^{15}
OVII/OVIII ratio	4.0 (2.8 – 5.6)	4.5	4.7
DM (LMC) (cm^{-3} pc)	$\lesssim 23$	17.4	14.1
$S_{0.4-2.0}$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

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

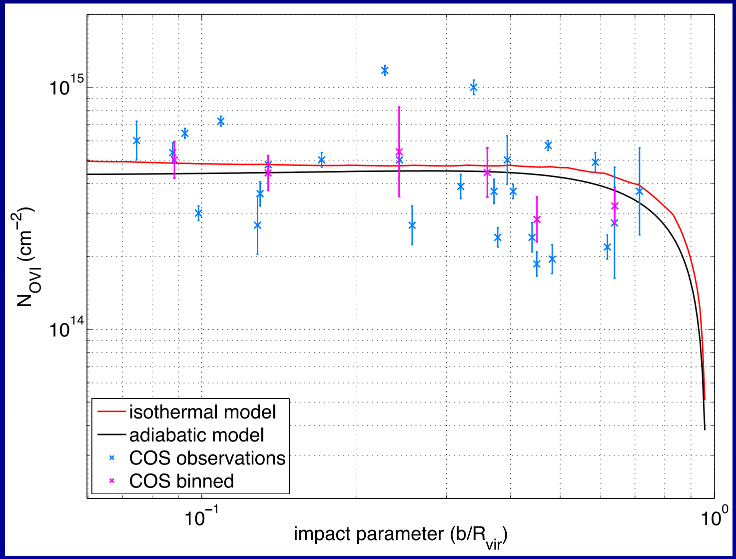
(Note: 19 A line is a combination of OVII and OVIII at low resolution of observations. OVIII/OVII depends sensitively on T and OVIII > 50% in our models)

Results: Comparison with observation

Density ≈ 10^{-4} 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

$M_{corona} = 1.2 \times 10^{11} M_{sun}$ (I & A)

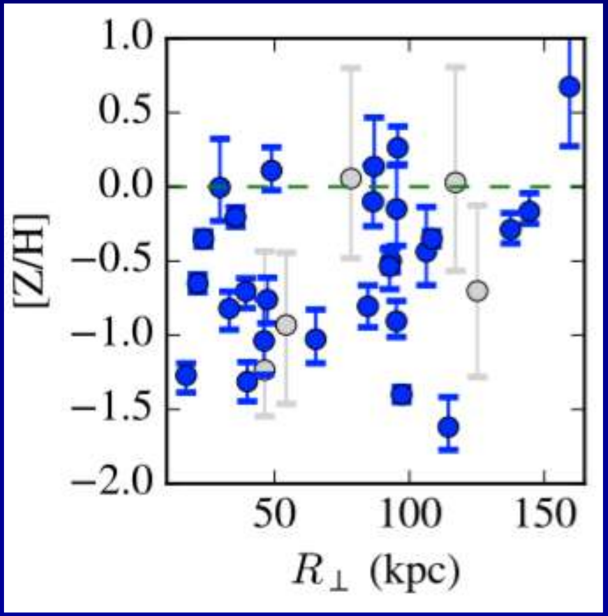
Expected coronal mass for $10^{12} M_{sun}$ halo:

Baryon mass $1.6 \times 10^{11} M_{sun}$ – Galaxy mass $0.6 \times 10^{11} M_{sun} = 10^{11} M_{sun}$

=> 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 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):

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

$= 7 \times 10^8\ M_{sun}$

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

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

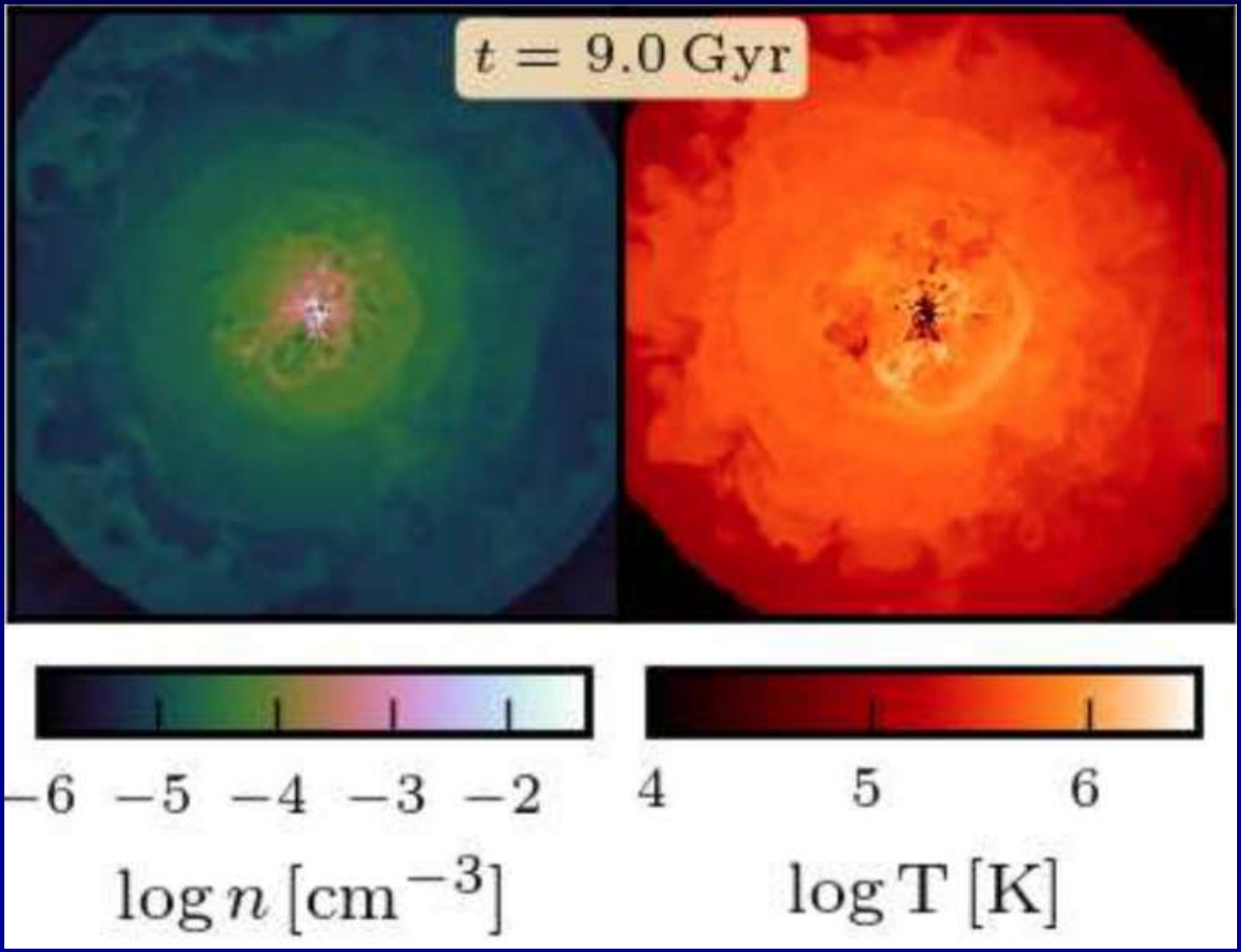
=> $M(O)_{produced} = 6 \times 10^8\ M_{sun}$

Peeples+ 14 estimate a higher yield => $1.6 \times 10^9\ M_{sun}$ 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)

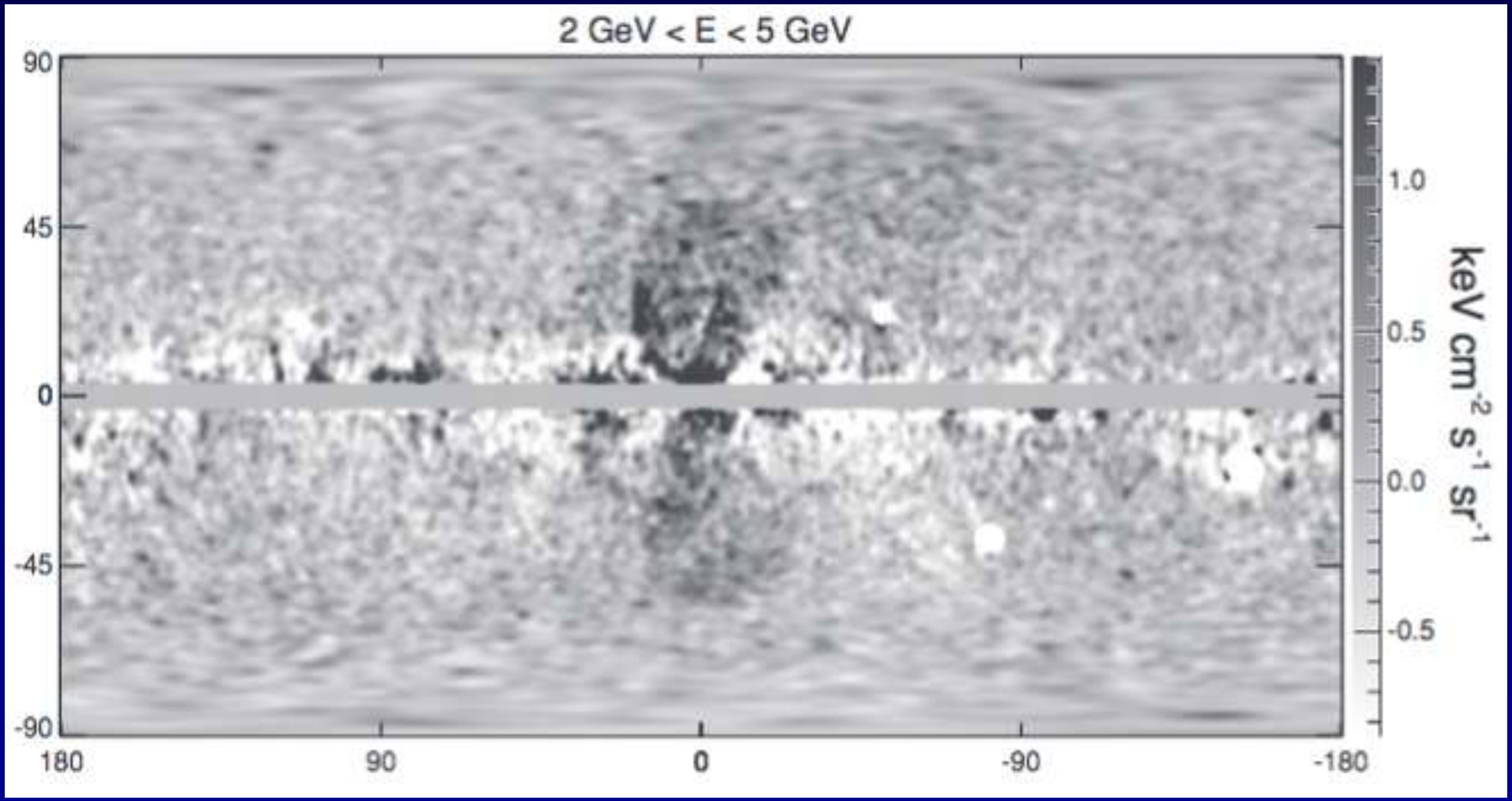


Fielding, Quataert, McCourt, Thompson (2016)

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

AGN heating not included

Can the corona be heated by AGN activity at the Galactic Center?



(Su et al 2010)

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

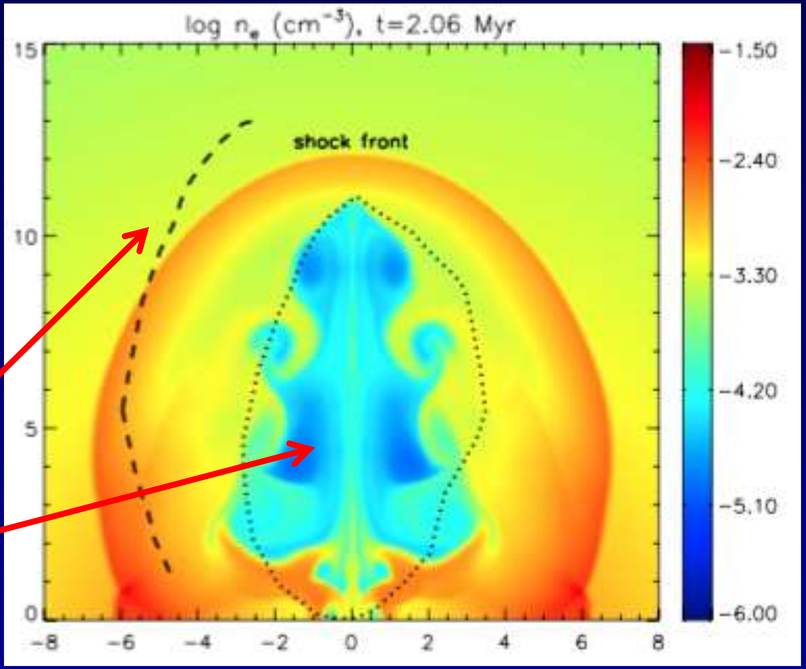
Bubble height ~ 10 kpc, width ~ 6 kpc

Wide range of models for Fermi Bubbles:

Shock velocity ~ R/2t ~ (5000 / t_6) km s^{-1} for R varying as t^{η}, with η ~ 1/2

1. Strong explosion (E=1.6 x 10^{57} erg) driven by jets from Sgr A^{*}.
Age ~ 2 Myr, v_s ~ 2000 km s^{-1}
(Guo & Mathews 12)

Consistent with flash photoionization of Magellanic Stream (Bland-Hawthorn+ 13)



Edge of Rosat X-ray feature

Cosmic ray bubble

2. Wind-driven bubbles: ages ~ 4 – 20 Myr , E~ 6 x 10^{55} – 3 x 10^{56} erg
v_s ~ 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 ~ 0.03 $\Delta m\, c^2$

Sadowski & Gaspari (2017)

Energy released in building Sgr A*: 0.03 Mc^2 = 2 x 10^{59} erg

>~100 Fermi Bubbles

Large compared to thermal energy in corona, 4 x 10^{58} $M_{11} T_6$ erg

Comparable to total core-collapse SN energy over the life of the Galaxy, ~ 5 x 10^{59} erg

Dynamics and cooling of Fermi Bubbles

$E = \sigma M v_s^2$

For $\rho \sim r^{-k}$,

$\sigma = (3-k)(5-k) / 2(10-3k)$

For gas in hydrostatic equilibrium, $k \sim 1 – 1.5$
$\Rightarrow \sigma \sim 0.5$

Cooling time $t_c \sim T_s^{3/2}/n$

$\sim (E / M)^{3/2}/n$

Approximately valid for non-spherical bubbles

Astrophysical blastwaves

Reviews of Modern Physics 60, 1 (1988)

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The authors present a general discussion of spherical, nonrelativistic blastwaves in an astrophysical context. A variety of effects has been included: expansion of the ambient medium, gravitation, and an embedded fluid of clouds capable of exchanging mass, energy, or momentum with the medium. The authors also consider cases of energy injection due either to a central source or to detonations. Cosmological solutions are extensively treated. Most attention is devoted to problems in which it is permissible to assume self-similarity, as in the prototype Sedov-Taylor blastwave. A general virial theorem for blastwaves is derived. For self-similar blastwaves, the radius varies as a power of the time, $R_s \propto t^{\eta}$. The integral properties of the solution are completely specified by two dimensionless numbers measuring the relative importance of thermal and kinetic energy. The authors find certain exact kinematical relations and a variety of analytic approximations to determine these numbers with varying degrees of accuracy. The approximations may be based on assumptions about the internal density distributions (e.g., shell-like), pressure distribution, or velocity distribution. In many cases exact conditions from, for example, boundary conditions or other constraints may be used to determine unspecified parameters. One new set of exact integral constraints has been derived. The various approximation schemes are tested with known solutions. The authors find that for blastwaves in which the flow extends to the origin, the assumption that the internal velocity is linear with radius is reasonably accurate. For blastwaves in which an interior vacuum develops, the equally simple approximation of constant interior velocity is accurate. These lowest-order approximations are shown to give numerical coefficients in the relation $R = \text{const} \times t^{\eta}$ which are accurate to about 1–2%. The higher-order approximations show an accuracy that in some cases equals that obtained, to date, by direct numerical integration. In addition to the new methods presented, the authors have obtained new results for evaporative blastwaves, impeded blastwaves, blastwaves with cloud crushing, bubbles, cosmological blastwaves (self-similar and non-self-similar, radiative and nonradiative), blastwaves in a wind, and detonations. Some of the new results found are exact. Included are the radiative, cosmological self-similar solution, appropriate to the universe ($z > 10$) when inverse Compton cooling is efficient [$\ln R = \text{const} + (\ln t)(15+\sqrt{17})/24$], and certain properties of the solutions mentioned above. In a series of appendixes several related issues are treated: energy conservation for multicomponent fluid in an expanding universe; central and edge derivatives of physical quantities in self-similar adiabatic blastwaves; shock jump conditions including energy input (detonations), and a variety of other matters.

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 ~ 200 km s^{-1}

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

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

Low density of corona + high energy of Fermi Bubbles

=> significant mass in corona heated with cooling time ~ 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 ~ 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 Msun yr^{-1}) for > 50 Gyr

HAPPY BIRTHDAY, JERRY!