The Gas–rich Halos of Massive ‘Red & Dead’ Galaxies

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Galaxies accrete gas from the intergalactic space, which fuels star formation.

Feedback and other processes in galaxies can drive winds, heat the gas, and regulate future accretion.

The CGM bears the imprint of this complex interaction.
Galaxy-gas coevolution: what’s the relationship between galaxy & halo gas?

An L* star-forming galaxy

M81 ($M_{\text{stellar}} = 5 \times 10^{10} \, M_\odot$)  

Tons of cool gas

Chynoweth+ (2008)

A massive elliptical galaxy

NGC 4555 ($M_{\text{stellar}} = 3 \times 10^{11} \, M_\odot$)  

Hot (not cool) gas?

Credit: NASA/CXC/SAO
Detecting diffuse gas beyond the local Universe with absorption spectroscopy

A suite of absorption lines imprinted on the background QSO spectrum by foreground gas

Observer

Background QSO at $z_{\text{qso}} > z_{\text{gal}}$

Foreground galaxy at $z_{\text{gal}}$

Projected distance $d$

Line-of-sight velocity relative to $z_{\text{gal}}$ (km/s)

Relative flux

Graph showing absorption lines in the spectrum with line-of-sight velocity relative to $z_{\text{gal}}$ and relative flux.
Correlation between CGM and galaxy properties at $z<1$

The incidence of chemically enriched cool ($T \sim 10^4 \text{K}$) gas in the CGM declines with increasing mass, but it is definitely non-zero in massive quiescent halos.

Cool CGM covering fraction in ellipticals: $>15\%$ on $\sim 100$ kpc scales.
Massive elliptical galaxies are surrounded by widespread, chemically enriched cool gas.

However, understanding the how’s & why’s (i.e. physics) requires empirical knowledge beyond just the incidence and extent of the gaseous halo.
How much cool gas is in the CGM of massive elliptical galaxies?
The COS–LRG survey: an HST/COS program characterizing the CGM of z~0.5 LRGs

Zahedy et al. 2019 (MNRAS, 484, 2257)

• Luminous Red Galaxies (LRGs) at z~0.5 are the distant counterparts of nearby ellipticals: high-mass galaxies with old stellar populations (>5 Gyr), and little star formation.

• **Goal:** Leverage Hubble’s UV sensitivity to constrain the bulk of the gas (hydrogen) in the CGM of LRGs

• **Mass-limited:** 16 SDSS LRGs with $M_{\text{star}} > 10^{11} \, M_\odot$, each found at $d < 160 \, \text{kpc}$ ($\sim 1/3 \, R_{200}$) from a background QSO.

• **Absorption-blind:** No prior knowledge of the presence/absence of absorption features
The COS–LRG survey: characterizing the CGM of massive ellipticals

High incidence of chemically enriched CGM: HI and ionic metals detected in $\approx 75\%$ of LRGs

Mass surface density profile of cool gas around massive quiescent galaxies

Zahedy et al. 2019a (MNRAS, 484, 2257)
The large reservoir of cool (~$10^4$ K) gas in massive quiescent halos

Cool gas mass (< 160 kpc) ≈ $2 \times 10^{10} M_\odot$

This is comparable to the cool CGM mass of L* star-forming galaxies!

see: Chen+ 2010; Prochaska+ 2011; Stocke+ 2013; Werk+ 2014; Stern+ 2016

Zahedy et al. 2019a (MNRAS, 484, 2257)
What physical processes shape the gaseous halo on both small (~kpc) and large (~100 kpc) scales?
Elevated gas-phase $[\text{Fe}/\alpha]$ at $d < \sim 30$ kpc in quiescent halos indicates significant chemical enrichment ($f_{\text{Ia}} \gtrsim 20\%$) from Type-Ia supernovae in the inner halo of elliptical galaxies.

Zahedy et al. (2016), MNRAS, 458, 2423
Zahedy et al. (2017), MNRAS, 466, 1071 + new data
Similar chemical signatures between cool & hot gas support the scenario that condensation from hot halo is an important mechanism of cool gas formation in massive ellipticals (at least in the ISM at $r < \sim 10$ kpc).

\[ z \sim 0.5 \text{ star-forming galaxies} \]

\[ z \sim 0.5 \text{ massive ellipticals} \]

\[ \text{mean observed log (Fe/Mg)} \]

\[ \text{projected distance } d \text{ (kpc)} \]

\[ \text{Solar Fe/Mg} \]

Chemical composition of the gaseous halo: a systematic study of $[\text{Fe}/\alpha]$
Multiphase ISM in a massive elliptical lens galaxy at z=0.4

Galaxy properties

- Massive (M_{star} \approx 10^{11} M_\odot)
- Elliptical (Sérsic index n \approx 4)
- Quiescent (SFR < 0.1 M_\odot yr^{-1})

Zahedy+ (2020a)
Multiphase ISM in a massive elliptical lens galaxy at z=0.4

Plenty of neutral gas
\[ N(\text{HI}) \approx 10^{20} \text{ cm}^{-2} \] (both A & B)

Some molecular gas present!
\[ f_{\text{H}_2} \sim 5\% \text{ (A); <0.1\% (B)} \]

Gas is highly enriched
\[ [\text{Fe/H}] \sim \text{solar}; [\text{Fe/\alpha}] > 0.1 \]

Lots of highly ionized gas!
\[ \log N(\text{OVI}) / \text{cm}^{-2} = 15.2 \]

Strong & broad OVI absorption indicates abundant transitional temperature (~10^5 K) gas:

• If radiatively cooling from a hot (~10^6 K) corona, the inferred accretion rate is 0.5-1.5 \( M_\odot \)/yr.

• The galaxy’s lack of star formation (<0.1 \( M_\odot \)/yr) suggests most of it is returned to the coronal phase, implying a heating rate of \( \sim 10^{48} \text{ erg/yr} \) within the galaxy.
Suppressed gas velocity dispersion in CGM of ellipticals

Observed velocity dispersion of cool CGM gas around sub-$L^*$ and $L^*$ galaxies is consistent with virial motion, but it is sub-virial ($\approx 0.6 \sigma_{\text{vir-1D}}$) for massive ellipticals with $M_{\text{star}} > 10^{11} M_{\odot}$

COS-LRG

$\sigma_v \approx 150 \text{ km/s}$

$\sim 400$ star-forming galaxies

Gas kinematics: LRGs vs lower-mass star-forming galaxies

$M_h \lesssim 10^{12} M_{\odot}$

$\sigma_v \sim 0.6 \sigma_{\text{vir}}$

$\sim 10^3$ LRGs

Huang et al. (2020)
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Summary

• Massive quiescent galaxies show a high incidence of cool gas on both small (~10 kpc, ISM) and large (~100 kpc, CGM) scales. A typical massive elliptical is surrounded by $\sim 10^{10} M_\odot$ of $\sim 10^4$ K gas, similar to star–forming galaxies.

• On ~10 kpc scale, the ISM has been significantly enriched by SNe Ia, pointing to SNe Ia as a potentially important maintenance/heating mechanism. In contrast, the outer CGM (~100 kpc scale) exhibits a more primitive chemical signature, consistent with gas originating from the intergalactic medium.

• While large reservoirs of cool gas exist on ~100 kpc scales around massive ellipticals, interactions with the hot halo likely prevent most cool clouds formed at large distances from successfully accreting into the galaxy.