The CGM around Massive Galaxies at $z=2-3$: A Test for Stellar Feedback, Galactic Outflows and Cold Streams

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The Baryon Cycle Conference, Irvine, CA June 14, 2012

In collaboration with: Piero Madau, Javiera Guedes, Anthony Aguirre, Jason X. Prochaska, James Wadsley & Lucio Mayer
The CGM-Galaxy Interactions: The Baryon Cycle
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Galactic outflows observed in local starburst with $v \sim$ hundreds km/s (e.g., Shapley+2003; Veilleux+2005; Weiner+2009)
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Far-UV spectra of angular pairs of galaxies/quasar-galaxies provides detailed map of the CGM metals (Steidel+2010) at higher $z$

Increasing amount of data about the CGM at low redshift (e.g., Prochaska & Hennawi 2009; Chen+2010; Crighton+2011; Prochaska+2011; Tumlinson+2012; Werk+2012)
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![Graph showing rest equivalent width $W_0$ vs. impact parameter $b$](image)

- Gas from IGM inflows into galactic halos

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Gas from IGM **inflows** into galactic halos

- At high $z$, “cold” accretion mode dominates (e.g., Kereš+ 2005, 2009; Dekel & Birnboim 2006; Ocvirk+2008)

- Prediction of cold stream detection
  1. statistical prescription using cosmological volumes (e.g., Dekel+2009; van de Voort+2012)
  2. zoom-in simulations that do not generate strong outflows (e.g., Fumagalli +2011; Faucher-Giguère & Kereš 2011; Kimm +2011; Stewart+2011)
The CGM-Galaxy Interactions

Our (not complete at all) wish list:
The CGM-Galaxy Interactions

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The Eris2 Simulation

- TreeSPH code Gasoline (Wadsley et al. 2004)
- SF: \( \frac{d\rho^*}{dt} = \varepsilon_{SF} \rho_{\text{gas}}/t_{\text{dyn}} \propto \rho_{\text{gas}}^{1.5} \) when gas has \( n_H > n_{SF} \)
- Blastwave feedback model for SN II (Stinson+ 2006): radiative cooling shut-off according to analytical solution from McKee & Ostriker (1977).
- Radiative cooling for H, He and metals were computed using Cloudy (Ferland+ 1998), assuming ionization equilibrium under uniform UVB (Haardt & Madau 2012)
- Turbulent diffusion model (Wadsley+ 2008; Shen+2010) to capture mixing of metals in turbulent outflows.
- Same initial set up as in Eris (Guedes+2011)

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<thead>
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<th>( m_{\text{DM}} ) (Ms)</th>
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<th>( \varepsilon_G ) (pc)</th>
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<tbody>
<tr>
<td>Eris2</td>
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Very high resolution - 4 M particles within \( R_{vir} \) at \( z = 2.8 \), to resolve the galaxy structure, the progenitor satellites and dwarfs.
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Very high resolution - 4 M particles within Rvir at \( z = 2.8 \), to resolve the galaxy structure, the progenitor satellites and dwarfs

High SF threshold, allow the inhomogeneous SF site to be resolved and localize feedback
Eris2 and Its Metal-Enriched CGM at z = 2.8

- At z=2.8, Eris2 has $M_{\text{vir}}$ and $M^*$ close to an LBG but lower than typical observed LBGs (e.g., Steidel+ 2010)

- More than half of metals locked in the warm-hot ($T > 10^5$) phase

- Cold, SF gas has $12+\log(O/H)=8.5$, within the $M^*-Z$ relationship (Erb +2006)

- The metal “bubble” extends up to 250 kpc, 5 Rvir

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<tr>
<th>$M_{\text{vir}} (M_{\odot})$</th>
<th>$R_{\text{vir}}$ (kpc)</th>
<th>$M^* (M_{\odot})$</th>
<th>SFR (M$_{\odot}$/yr)</th>
<th>$12+\log(O/H)$</th>
<th>$T&gt;10^5$ K (%)</th>
<th>$R_z$</th>
<th>$&lt;Z_g&gt;_{\text{vir}}$</th>
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<tr>
<td>$2.6 \times 10^{11}$</td>
<td>50</td>
<td>$1.5 \times 10^{10}$</td>
<td>20</td>
<td>8.50</td>
<td>54%</td>
<td>~5 Rvir</td>
<td>0.7 Z$_{\odot}$</td>
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600 x 600 x 600 kpc3 projected map of gas metallicity. The disk is viewed nearly edge on.
Kinematics of the Metal-Enriched CGM

- 600 x 600 x 10 kpc slice, projected to x-y plane, disk nearly edge-on
- Max projected averaged velocity ~300 km/s (host)
- Metallicity is high along the minor axis but non-zero along the major axis (Kacprzak+2012)
- Average outflow velocity decrease at larger distances and join the inflow -- halo fountain (Oppenheimer+2010)
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Kinematics of the Metal-Enriched CGM

Inflow along filaments, lower Z or pristine
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Accreting dwarfs
CGM Metals Traced by Different Ions

- Multi-phase CGM: low and high ions co-exist in same absorbers
- Covering factors of low ions (C II, Si II) decrease more rapidly than high ions
- O VI has large covering factor up to 4 R_{vir}, M_{o}(CGM) ~5 \times 10^7 M_{sun} > M_{o}(ISM)

HI: $10^{14}-10^{21}$ cm$^{-2}$
Metals: $10^{11}-10^{16}$ cm$^{-2}$

Calculating ion fractions:
- UVB + non-uniform stellar UV assuming constant SFR 20 M\text{sun}/yr
- Photo-heating of local UV not included
- Assuming optically thin
High ions: Collisional Ionization or Photoionization?

- **O VI**: mostly collisional ionized within 2 Rvir, but photo-ionized at larger distance.

**Cooler** ($T \sim 3-5 \times 10^4 K$), clumpier, photoionized OVI

**Hotter** ($T > 10^5 K$), more diffuse, collisionally ionized OVI

**Si IV and C IV**: Mostly photo-ionized

- **O VI**: mostly collisional ionized within 2 Rvir, but photo-ionized at larger distance.
Coexistence of inflow and outflow in the CGM:

- H I: cold inflow perpetrates virial radius with \(2R_{\text{vir}}\), 90% system with \(N_{\text{HI}}>10^{17.2}\, \text{cm}^3\) (LLS) is inflowing.
- Outflow gas increases the H I covering factor at large \(b\).
- Low ions (C II or Si II) similar to H I

- O VI: by mass 68% outflow, 32% inflow
- C IV & Si IV: inflow and outflow contribute similarly

<table>
<thead>
<tr>
<th></th>
<th>H I</th>
<th>Si II</th>
<th>C II</th>
<th>Si IV</th>
<th>C IV</th>
<th>O VI</th>
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<td>Inflow mass (%)</td>
<td>77%</td>
<td>66%</td>
<td>66%</td>
<td>50%</td>
<td>44%</td>
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Synthetic Absorption Spectra

- Optical depth $\tau(\nu) = \sum_j (m_j Z_j / m) W_{2D}(r_{jl}, h_j) \sigma_j(\nu)$; $\sigma_j(\nu)$ - cross section (Voigt function), $W_{2D}(r_{jl}, h_j)$ - 2D SPH kernel

- Rest frame equivalent width: $W_0 = c/\nu_0^2 \int [1 - e^{-\tau(\nu)}] d\nu$
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• Most, but not all, components exist in both high and low ions -- Multi-phase nature of absorbers
• Velocity range $\sim \pm 300$ km/s
• Metal enriched infalling gas:
  • $R_{\text{vir}} < r < 2R_{\text{vir}}$
  • $\delta \sim 100$
  • $Z > 0.03 Z_{\odot}$
• Enriched gas around nearby dwarf galaxy
W₀-b Relation and Comparison with Observations

- Metal Line strength decline rapidly at 1-2 \( R_{\text{vir}} \)
- Line strength decline less fast for C IV, OVI and H I
- Ly \( \alpha \): remains strong to \( >\sim 5 \ R_{\text{vir}} \)
- Broadly consistent with observations from Steidel+ (2010) and Rakic+ (2011)
- \( W_0 \) for metal ions: Higher than simulations without strong outflows (e.g., Fumagalli+ 2011)
- At small \( b \), lines are mostly saturated -- \( W_0 \) determined by velocity

- 3 orthogonal projections, each has 500 x 500 evenly-spaced slightlines within \( b = 250 \ \text{kpc} \) region centered at the main host
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• W_0 for metal ions: Higher than simulations without strong outflows (e.g., Fumagalli+ 2011)

• At small b, lines are mostly saturated -- W_0 determined by velocity
• O VI has covering factor \( (f_c) \) of unity in 2 \( R_{\text{vir}} \). C IV also have large \( f_c \)

• C II, Si II, Si IV: smaller \( f_c \), decline fast when \( b > R_{\text{vir}} \)

In reasonable agreement with Rudie+ (2012) for H I, but in the low side

H I covering factor: slightly higher, but comparable to simulations without strong outflows (e.g. Fumagalli+2011, Faucher-Giguère & Kereš 2011)
Detecting the Cold Streams: H I and Low Ions

- Cold (T < $10^5$ K) inflow rates at $R_{\text{vir}}$
  $\frac{dM_{\text{in}, \text{cold}}}{dt} = 18 \, M_{\odot}/yr$, comparable to the SFR; $\frac{dM_{\text{in}, \text{hot}}}{dt} \sim 5M_{\odot}/yr$

- 35% inflow gas from nearby dwarfs

- Within 2 $R_{\text{vir}}$: 90% of LLS are inflowing gas, $v_{\text{in}} \leq 150$ - 200 km/s
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- 35% inflow gas from nearby dwarfs

- Within 2 R_{vir}: 90% of LLS are inflowing gas, \( v_{in} \approx 150 - 200 \text{ km/s} \)

- Cold inflows are enriched: \( Z_{LLS} > 0.03 Z_{\odot} \) for \( r < R_{vir} \), and \( Z_{LLS} > 0.01 Z_{\odot} \) within 2R_{vir}

- Still lower than outflow metallicities \( Z_{out} = 0.1 - 0.5 Z_{\odot} \)
The $N_{\text{OVI}}$-b Relation in Eris2: Comparison with Low z Starburst Galaxies

- At $z = 2.8$, Eris2 has $sSFR \sim 10^{-9}$ yr$^{-1}$, close to the local star burst galaxies in Tumlinson + (2011) and Prochaska+ (2011).

- $N_{\text{OVI}}$-b relation in good agreement with observations typical $N_{\text{OVI}} > \sim 10^{13-14}$ cm$^{-2}$ up to 100 - 150 kpc.

- $N_{\text{OVI}}$-b mostly determined by SFR?
The Evolution of the CGM (Down to $z=2.8$)
The Evolution of the CGM (Down to z=2.8)

- From $z = 7$-8 to $z \sim 3$, the metal "bubble" grows with increasing $R_{\text{vir}}$
- $z \sim 3$ to $z = 0$?

$z = 5.0, R_{\text{vir}} = 19$ kpc
$z = 2.8, R_{\text{vir}} = 50$ kpc

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- $z \sim 3$ to $z = 0$?
Summary

- A comparison of the CGM properties between Eris2, a high resolution zoom-in simulation, and observations;

- Inflows and outflows coexist, about 1/3 of gas (by mass) within $R_{\text{vir}}$ is outflowing, consistent with findings from cosmological simulations (van de Voort +2012);

- Low ions ($\text{Si II}$ & $\text{C II}$): photoionized, $\delta > 100$, extends to $2R_{\text{vir}}$, but covering factor drops fast at $b > R_{\text{vir}}$

- High ions, in particular $\text{O VI}$, has both collisional ionized and photoionized components, depending on distance. *Large covering* factor with typical $N_{\text{OVI}} > 10^{14}$ cm$^{-2}$, consistent with the data from local starbursts (Tumlinson+2011, Prochaska+2012).

- Synthetic spectra shows inflows and outflows are multi-phase, although not all the $\text{O VI}$ systems has corresponding low ion counterpart.

- $W_0$-$b$ relation from Eris2 appears to be in good agreement of observations of Steidel + (2010). Feedback & outflows are important, however inflowing material contributes significantly to the absorption line strength.

- The covering factor of LLS system is about 27% within $R_{\text{vir}}$, in good agreement with Rudie+ (2012), it is slightly higher than, but consistent with simulations with no strong outflows (Fumagalli+ 2011; Faucher-Giguère & Kereš 2011); 90% of LLS within $2R_{\text{vir}}$ are inflowing cold streams.

- The cold streams (within $2R_{\text{vir}}$) are enriched to $Z > 0.01$ $Z_{\text{sun}}$, with typical value around 0.03 $Z_{\text{sun}}$, making the presence of cold stream detectable with metal absorption lines.
Backup Slides
**Contribution of Host, Satellites Progenitors and Nearby Dwarf Galaxies**

- Nearby dwarfs: satellite has not accreted yet at $z = 3$
- Progenitors: satellite has accreted by $z = 3$

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<th>$r \leq 2R_{\text{vir}}$</th>
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<th>$r &gt; 3R_{\text{vir}}$</th>
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<tr>
<td>Host</td>
<td>61%</td>
<td>58%</td>
<td>58%</td>
<td>0</td>
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<tr>
<td>Sat. Progenitors</td>
<td>39%</td>
<td>38%</td>
<td>37%</td>
<td>3%</td>
</tr>
<tr>
<td>Nearby dwarfs</td>
<td>0</td>
<td>4%</td>
<td>5%</td>
<td>97%</td>
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Computing Fraction of Ions

- Post-processing using photo-ionization code Cloudy (Ferland+ 1998)

- Incident radiation includes the extragalactic UV background (Haardt & Madau 2012) and stellar UV

- Stellar UV radiation: using Starburst99 (Leitherer+ 1999), assuming a constant SFR of 20 \( M_{\odot}/yr \).

- Escape fraction \( f_{\text{esc}} = 3\% \), \( J_d = J_0 / (4\pi d^2) \)

- Assuming gas is optically thin: not valid for column \( N_{\text{HI}} \) above LLS.

Photo-ionization heating due to local UV radiation is not taken into account.
The Effect of Gas Self-Shielding: Column density

- Self-shielding approximation: for $n_H > 0.01 \, \text{cm}^{-3}$, the UV radiation rapidly decrease to zero, and ionization fraction recalculated in Cloudy. Except for the center region (< 10 kpc), the columns of metals are *not* significantly affected.
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- Self-shielding approximation: for $n_H > 0.01 \text{ cm}^{-3}$, the UV radiation rapidly decrease to zero, and ionization fraction recalculated in Cloudy. Except for the center region ($< 10 \text{ kpc}$), the columns of metals are not significantly affected.
The Effect of Gas Self-Shielding: $W_0$-b

- Lyα: The data points within 5 kpc increases significant, $W_0$ become much higher than observations
- Metal lines: change is not significant since lines are saturated
Outflow gas mostly has $v \lesssim 400$ km/s, but can be up to $\sim 700$-800 km/s.

Highest velocity gas is not reflected in the synthetic spectra because the column is very low.
Eris vs. Eris2 at high Redshift: The Rotation Curve

\[ V_{\text{circ}} \text{ [km/s]} \]

\[ r \text{ [kpc]} \]

\[ z = 2.8 \]
Nature of the Clumps & Possible Numerical Effects
Smagorinsky Model of Turbulent Diffusion

• Most basic turbulent model: ($\kappa_{\text{Turb}}$ has units of velocity $\times$ length)

\[
\frac{\partial \bar{u}}{\partial t} + \bar{v} \cdot \nabla \bar{u} = -(\gamma - 1)\bar{u}(\nabla \cdot \bar{v}) + \nabla \kappa_{\text{Turb}} \nabla \bar{u}
\]

• Smagorinsky model (Mon. Weather Review 1963) -- Diffusion Coefficient determined by velocity Shear

\[
\kappa_{\text{Turb}} = l_s^2 S, \quad S = \sqrt{S_{ij} S_{ij}}
\]

• $S_{ij}$ = trace-free strain rate of resolved flow; $l_s$ = Smagorinsky length. For incompressible grid models $l_s^2 \sim 0.02 \Delta x^2$

• For SPH we use $\kappa_{\text{Turb}} = C |S_{ij}| h^2$ with $C \sim 0.05$ (Wadsley, Veeravalli & Couchman 2008; See also Scannapieco & Brüggen 2008, Grief et al 2009)

• After implementation of turbulent diffusion, SPH is able to produce the entropy profile similar to grid codes
Effect of Turbulent Metal Mixing

- SPH does not mix scalar quantities, metallicity ‘locked’ in gas particles
- ErisMD: same parameters as Eris but with a turbulent diffusion model (Shen et al. 2010). Simulation finish at $z \sim 2.5$.
- Smagorinsky model (Smagorinsky 1963): mixing proportional to velocity shear
Outflow Properties: Wind Speed

- Outflow radial velocity \( \sim 100-400 \) km/s, with maximum up to > 800 km/s;
- \( v_{\text{eject}} \) has no obvious relation with \( z \) (or \( M_{\text{halo}} \)).