The CGM around Eris at z ~2-3: A Test for Stellar Feedback, Galactic Outflows and Cold Streams

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In collaboration with: Piero Madau, Javiera Guedes, Jason X. Prochaska, James Wadsley & Lucio Mayer

Shen et al. arXiv:1205.0270
The CGM-Galaxy Interactions
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- Galactic outflows

- 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 provide detailed map of the CGM metals (e.g., Steidel+2010) and H I (e.g., Rudie+2012) 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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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) and

2) “zoom-in” simulations (e.g., Fumagalli+ 2011; Faucher-Giguère & Kereš 2011; Kimm +2011; Stewart+2011; Goerdt+ 2012)
The Eris2 Simulation

- TreeSPH code Gasoline (Wadsley et al. 2004)

- SF: \( \frac{d\rho^*}{dt} = \varepsilon_{SF} \frac{\rho_{gas}}{t_{dyn}} \propto \rho_{gas}^{1.5} \) 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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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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High SF threshold, allow the inhomogeneous SF site to be resolved and localize feedback
Metal Cooling Under UV Radiation

- Metal cooling computed using CLOUDY (Ferland 1998)
- With UVB from Haardt & Madau (2001)
- Function of $\rho$, $T$, $Z$, $z$

\[ n_H = 0.01 \text{ cm}^{-3} \]

\[ \log(T) \text{ [K]} \]

Cooling Rate [erg/g/s]
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Effect of metal cooling: increase the total radiative cooling by > an order of magnitude

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Metal Cooling Under UV Radiation

Effect of UV:
Largely increase atomic cooling for $T < 10^4$ K
Decrease the cooling at $T > 10^4$ K (more significant for lower density gas)
Smagorinsky Model of Turbulent Diffusion

Wadsley+ (2008); Shen+ (2010)

• Most basic turbulent model: ($\kappa_{\text{Turb}}$ has units of velocity × 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
Eris2 and Its Metal-Enriched CGM at $z = 2.8$


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<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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<td>2.6 x 10$^{11}$</td>
<td>50</td>
<td>1.5 x 10$^{10}$</td>
<td>20</td>
<td>8.50</td>
<td>54%</td>
<td>~5 $R_{\text{vir}}$</td>
<td>0.7 $Z_{\odot}$</td>
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- 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 $R_{\text{vir}}$

600 x 600 x 600 kpc$^3$ 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 (Rubin + 2012; Kacprzak+2012)

- Average outflow velocity decrease at larger distances and join the inflow -- halo fountain (Oppenheimer+ 2010)
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inflow along filaments, lower Z or pristine
outflows: \( \perp \) to disk plane, higher Z
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Computing Fraction of Ions & Column Density Map

- 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 $M_{\text{sun/yr}}$.

- 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.
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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)} \sim 5 \times 10^7 M_{\odot} > 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_{\odot}/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~3-5 ×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 viral 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

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

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- Velocity range $\sim \pm 300$ km/s
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- 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

Friday, August 17, 2012
W₀-b Relation and Comparison with Observations

- Metal Line strength decline rapidly at 1-2 Rₗ₁
- Line strength decline less fast for C IV, OVI and H I
- Ly α: remains strong to >~ 5 Rₗ₁
- Broadly consistent with observations from Steidel+ (2010) and Rakic+ (2011)
- W₀ for metal ions: Higher than simulations without strong outflows (e.g., Fumagalli+ 2011; Goerdt + 2012)
- At small b, lines are mostly saturated -- W₀ determined by velocity

- 3 orthogonal projections, each has 500 x 500 evenly-spaced slightlines within b = 250 kpc region centered at the main host
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- Fumagalli+ (2011)
Covering Factor of H I and Metal Ions

- 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
HI 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_{vir}
  \(dM_{in, cold}/dt = 18 M_{sun}/yr\), comparable to the SFR; \(M_{in, hot}/dt \sim 5M_{sun}/yr\)

- 35% inflow gas from nearby dwarfs

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

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

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

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

• NOVI-b relation agreement with observations; but higher at b < 0.1 R_{vir}

• Typical NOVI >~ 10^{13-14} cm^{-2} up to 3 R_{vir}

• NOVI-b mostly determined by SFR?

• R_{vir} ~ 160 kpc for sub-L* galaxies (Prochaska+ 2011)
• R_{vir} ~ 200-300 kpc for L* galaxies (Tumlinson+2011)
The Evolution of the CGM (Down to z=2.8)
The Evolution of the CGM (Down to $z=2.8$)

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

- $z = 6.8$, $R_{\text{vir}} = 11$ kpc
- $z = 5.0$, $R_{\text{vir}} = 19$ kpc
- $z = 2.8$, $R_{\text{vir}} = 50$ kpc
The Effect of Gas Self-Shielding: $W_0$-b

- Transition from optically thin to thick: $n_H \sim 0.01 \text{ cm}^{-3}$ (e.g. Fumagalli +2011; Goerdt +2012)
- Increase $N_{\text{H I}}$, $N_{\text{Si II}}$, decrease $N_{\text{C IV}}, N_{\text{C II}}, N_{\text{Si IV}}$
- OVI is not affected by much
- Metal lines: change in $W_0$ is not significant since lines are saturated

Ly $\alpha$: The data points within 10 kpc increases significant, $W_0$ become much higher than observations
No turbulent mixing
1. Larger metal bubble (cf. Shen+ 2010);
2. “Clumpier” CGM due to higher $Z$ and metal cooling;
3. Inflowing dwarfs are enriched, but less for the material in between
No turbulent mixing 1. Larger metal bubble (cf. Shen+ 2010);
2. “Clumpier” CGM due to higher Z and metal cooling;
3. Inflowing dwarfs are enriched, but less for the material in between
The covering factor of metal ions at log N > 13 does not change significantly.

The covering factor of LLS H I, C II and Si II decreases because the CGM is clumpier.

CF for more diffuse H I and C IV increases because of more efficient wind.
• Covering factor of both H I and low ions decreases

• Inflowing gas with $N_{\text{HI}} > 10^{17.2} \text{ cm}^{-2}$ and $N_{\text{CII}} > 10^{13} \text{ cm}^{-2}$ decreases from 22% to 16% in $R_{\text{vir}}$ and from 10% to 5% in $2R_{\text{vir}}$
Effect of Metal Cooling on the CGM

Cooler phase of enriched CGM occurs in much colder gas.

SF occurs in much colder gas.
Distribution of Metals and Ions in ρ-T plane
Summary

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

- O VI absorbers have both collisional ionized and photoionized components, depending on distance. Large covering factor with typical N_{OVI} > 10^{14} cm^{-2}, consistent with the data from local starbursts (Tumlinson+2011, Prochaska+2011).

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

- W_0-b relation from Eris2 appears to be in reasonable 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_{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_{vir} are inflowing cold streams.

- The cold streams are enriched with CF of CII > 10^{13} about 22% within R_{vir} -- possible to detect inflows with metal line absorption.

- Metal mixing enhance the detection of cold flows using metals.

- Cooling due to metal lines are important for generating cooler phase of the CGM and possibly crucial for detection of the low ions.