The Circumgalactic Medium around Massive and Dwarf Galaxies in “Zoom-in” Simulations

Sijing Shen
UC Santa Cruz

Mind the Gap:
From Microphysics to Large Scale Structure in the Universe
July 12, 2013

In collaboration w/: Piero Madau, Javiera Guedes (ETH), Anthony Aguirre, Jason X. Prochaska, James Wadsley (McMaster) & Lucio Mayer (Zurich)
Why care about the CGM?

Rest-Frame B, U and NUV stellar composite of the Eris at $z = 3$, using SUNRISE (Jonsson 2006)
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Prochaska+ (2013)

Steidel+ 2010

Tumlinson + 2011
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Tripp+ (2011)

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Why care about the CGM?

Observers have a lot of data here:

Absorption line systems can tell us about:
1. Kinematics, temperature, ionization, metallicity
2. heating/cooling abilities of the halo
3. Morphology, clumping of the flows

--> Additional constraints on feedback mechanisms

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The “Eris2” Simulation

- TreeSPH code Gasoline (Wadsley+ 2004)
- Same initial condition, resolution, star formation, feedback recipe as “Eris” (Guedes+2011)
  - SF simple K-S relation: \(d\rho*/dt = \epsilon_{SF} \rho_{\text{gas}}/t_{\text{dyn}} \propto \rho_{\text{gas}}^{1.5}\) when gas has \(n_H > n_{\text{SF}}\)
- Blastwave feedback model for SN II (Stinson+ 2006): radiative cooling shut-off according to analytical solution from McKee & Ostriker (1977).
  \[
  t_{\text{max}} = 10^{6.85} \ E_{51}^{0.32} \ n_0^{0.34} \ P_{04}^{-0.7} \ \text{yr}
  \]
  \[
  R_E = 10^{1.74} \ E_{51}^{0.32} \ n_0^{-0.16} \ P_{04}^{-0.20} \ \text{pc}
  \]
- Non-equilibrium primordial cooling + equilibrium metal-line cooling from Cloudy (Ferland+ 1998), under uniform UVB (Haardt & Madau 2012)
- Smagorinsky turbulent diffusion model (Wadsley+ 2008; Shen+2010) to capture mixing of metal in turbulent outflows. Diffusion coefficient proportional to velocity shear (see James’ Talk)

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>(m_{\text{DM}}) (Ms)</th>
<th>(m_{\text{SPH}}) (Ms)</th>
<th>(\epsilon_G) (pc)</th>
<th>(n_{\text{SF}}) (cm(^{-3}))</th>
</tr>
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<tbody>
<tr>
<td>Eris2</td>
<td>(9.8 \times 10^4)</td>
<td>(2 \times 10^4)</td>
<td>120</td>
<td>20.0</td>
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Eris2’s properties at $z = 2-3$

- At $z=2-3$, 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)

Stellar mass consistent with the abundance matching results
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**Flat rotation curve: bulgeless at $z \sim 2-3$**

At $z = 0$, Eris small bulge and rotation curve that consistent with the observations (Guedes+2011). At $z \sim 3$, Eris2 has even shallower curve within 1kpc
Eris2 and Its Metal-Enriched CGM at $z = 2.8$

Shen et al. (2013)

$600 \times 600 \times 600$ kpc$^3$ projected map of gas metallicity. The disk is viewed nearly edge on.

- Max projected averaged velocity $\sim 300$ km/s (host)
- Metallicity is high along the minor axis but non-zero along the major axis (Rubin+ 2012; Kacprzak+2012)
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Max projected averaged velocity ~300 km/s (host)

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Calculating ion fractions:
- UVB + non-uniform stellar UV assuming constant SFR 20 Msun/yr
- Assuming escape fraction from the ISM is 3%

Shen et al. (2013)
CGM Metals Traced by Different Ions

- Low and high ions co-exist in the 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 3 $R_{\text{vir}}$, $M_\text{o(CGM)} \sim 5 \times 10^7 M_\text{sun} > M_\text{o(ISM)}$

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CGM Kinematics at $z = 2-3$

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<tr>
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- inflow: along the accretion plane
CGM Kinematics at $z = 2-3$

- **Inflow**
  - **H I**: inflow: well within the viral radius
  - **O VI**: inflow: along the accretion plane

- **Outflow**
  - **H I**:

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CGM Kinematics at z = 2-3

**Inflow**
- \( \text{HI} \)
  - Inflow: well within the viral radius
  - Majority of LLS (green) inflowing

**Outflow**
- \( \text{HI} \)

**Total**
- \( \text{HI} \)

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CGM Kinematics at $z = 2-3$

**Inflow**
- $\text{H I}$: inflow: well within the virial radius
- $\text{O VI}$: inflow: along the accretion plane

**Outflow**
- $\text{H I}$: outflow: increase $C_f$ for weaker ($\log N > 14.5$) absorbers

**Total**
- $\text{H I}$

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Coexistence of high and low ionization metals

- 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: $W_0 = c / v_0^2 \int [1 - e^{-\tau(\nu)}] d\nu$
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- Most, but not all, components exist in both high and low ions -- Multi-phase nature of absorbers
- Velocity range $\pm 300$ km/s
• 3 orthogonal projections, each has 500 x 500 evenly-spaced slightlines within b = 250 kpc region centered at the main host

- 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; Goerdt + 2012)
- At small b, lines are mostly saturated -- $W_0$ determined by velocity
$W_0$-b Relation and Comparison with Observations

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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).

$R_{\text{vir}} \sim 160$ kpc for sub-L$^*$ galaxies (Prochaska+ 2011).

$R_{\text{vir}} \sim 200-300$ kpc for L$^*$ galaxies (Tumlinson+2011).

OVI is sensitive to feedback mechanisms:

1. Kinetic feedback with decoupled winds (Oppenheimer & Davé 2008) -- most OVI are photoionized.

2. Thermal feedback (see also Stinson+12) result in mostly collisionally ionized OVI within 2 $R_{\text{vir}}$. 
Enrichment of Accretion Flows

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

- 35% inflow gas from nearby dwarfs

- Lyman-limit systems: 90% of LLS are inflowing gas, $v_{\text{in}} \approx 150 - 200$ 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 $2R_{\text{vir}}$

- Covering fraction of $N_{\text{CII}} > 10^{13}$ cm$^{-2}$ about 22% within $R_{\text{vir}}$, 10% within $2 \, R_{\text{vir}}$
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Simulation of Dwarf Galaxies

- Resolution: DM $1.6 \times 10^4 \, M_{\text{sun}}$; Gas $3300 \, M_{\text{sun}}$; Star $1000 \, M_{\text{sun}}$; force resolution $86 \, \text{pc}$
- “Field” dwarfs -- with nearest massive halo $> 3 \, \text{Mpc}$ away
Properties of the Most Massive Seven

- 4 luminous dwarfs, with $M^*$ from $9.6 \times 10^4 M_{\odot}$ to $1.1 \times 10^8 M_{\odot}$
- Bashful & Doc: $M^*/M_h$ on the Behroozi + 2012 curve
- Dopey & Grumpy: very small stellar fraction
- Grumpy: $M_{\text{HI}} \sim M^*$
- Dopey: $M_{\text{HI}} \sim 20 M^*$
• Bursty SFR & Low gas and Stellar Metallicity indicates effective winds

• Fraction of metals that is ejected out of the halo:
  Bashful: 90%
  Doc: 88.5%
  Dopey: 8.3%
  Grumpy: 54.1%

• Cumulative mass loading ($M_{\text{eject}}/M^*$) as function of redshift: generally > 10
• Mass loading similar to the dwarf satellites in Eris
Evolution of the CGM around Field Dwarf Galaxies

- Bashful has $R_{\text{vir}} = 85$ kpc;
- The extend of enriched region $R_z \geq 15 R_{\text{vir}}$

Box size: 3 comoving Mpc on a side
Centered at the most massive dwarf

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Column Density Map of Various Ions at $z = 0$

- High ionization metals extended further than low ions
- Low ions such as Mg II drop below $10^{13}$ rapidly as impact parameter increases, < 20 kpc or so
- Metals are highly ionized at larger distances
- The CGM is less "clumpy" as the one near massive galaxies

Box Size 500 kpc on a side

N HI: $10^{14}$ to $10^{20}$ cm$^{-2}$
Metals: $10^{10}$ to $10^{14}$ cm$^{-2}$
Yellow color = $10^{13}$ cm$^{-2}$
Comparison With COS-Dwarfs Data
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Only galaxies $< 10^{8.5}$ M$_\odot$
Comparison With COS-Dwarfs Data

- COS-Dwarf Survey data from (Werk et al. in prep);
- The most massive dwarf (Bashful) has $M^* = 1.5 \times 10^8 \text{ M}_\odot$, 10% of the median $M^*$ in COS-Dwarf Sample
- Needs simulations with different mass halos

![Graphs showing comparison with COS-Dwarfs data](image)
ErisMC: weaker feedback
No thermal or metal diffusion

ErisMC

Eris2
A Test For Feedback

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The Effect of Metal and Thermal Diffusion - I

No turbulent mixing
1. Larger metal bubble (also seen in cosmological volume simulations, Shen+ 2010)
2. “Clumpier” CGM, because metals are locked in SPH particles;
3. Inflowing dwarfs are enriched, but less for the material in between
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The Effect of Metal and Thermal Diffusion II

With Metal Diffusion

No Metal Diffusion

- Covering factor of both HI and low ions decreases

- Inflowing gas with $N_{\text{HI}} > 10^{17.2}$ cm$^{-2}$ and $N_{\text{CII}} > 10^{13}$ cm$^{-2}$ decreases from 22% to 16% in $R_{\text{vir}}$ and from 10% to 5% in $2R_{\text{vir}}$
Summary

- Take-home point: Galaxies and the CGM are fundamentally related. Together they provide great labs for testing gas accretion, cooling, feedback mechanisms. Lot of observational data are waiting to be explained.

- Zoom-in simulations provide rich information on the distribution, kinematics and evolution of the CGM. Using ‘Eris2’ and ‘Seven Dwarfs’, the CGM of two very different mass systems are studied.

- CGM around Eris2: coexistence of high and low ions for most absorbers, although not all the OVI systems has corresponding low ion counterpart.

- W0-b relation of 5 ions appears to be simultaneously in reasonable agreement of observations of Steidel +(2010). Feedback & outflows are crucial to reproduce the W0-b relation for metals.

- The cold streams are enriched with Cf of C II > 10^{13} cm^{-2} about 22% within Rvir. Metal mixing increases the covering fraction.

- Galactic winds are more efficient in field dwarf galaxies, which leads to bursty SF and mass loading factor about few tens. ~90% of metals ejected into the IGM.

- Dwarfs have very extended enriched region (>15 Rvir at z = 0), much larger than disk galaxies. Probably the main polluters of the IGMs.
Future

- Do we really understand the halo gas?
- Not there yet -- turbulence, conduction, cosmic rays, magnetic fields (to name a few) all change gas morphology, temperature, cooling etc...
- Need to calibrate various feedback models with smaller scale experiment -- closing the gap from the bottom.

Starburst outflows (Cooper, Bicknell & Sutherland; from Veilleux 2005)

Super bubble (Keller & Wadsley, in prep)
Comparing with other implementation and codes

Welcome to Project AGORA: Assembling Galaxies Of Resolved Anatomy! We investigate galaxy formation with high-resolution numerical simulations and compare the results.

Project Announcements & News

Announcing 2nd AGORA Workshop (Aug. 16-19, 2013) We are pleased to announce that the 2nd Workshop of the AGORA Project will be held 16-19 August 2013 at the University of California, Santa Cruz. This workshop is ...

Posted May 21, 2013, 9:16 PM by Ji-hoon Kim
The “Clumps”

- Origin: 1. ISM entrainment; 2. thermal instability of wind fluid (Binney+2009); 3. Non-linear perturbation in the fluid; 4. Numerical

- Standard SPH does not destroy clumps easily

- Runs with new SPH ongoing...

Maybe clumps are there in nature?

- Galactic winds & CGM are often multi-phase: kinematically correlated high and low ionization absorbers

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