The Impact of Starbursts on the CGM:
The COS-Burst Program
Talk Outline

• Motivation
• CGM properties in normal low-z star-forming galaxies
• Galactic winds
• Observations of the CGM around low-z starbursts
• Interpretation
• Summary
Motivation

• The CGM is the path through which (re)accretion of gas onto galaxies occurs
• Fuels future star-formation
• Energy/momentum released by massive stars will affect the CGM and possibly limit/reduce the accretion
• Potential feedback loop
• A key part of the galactic ecosystem
The Warm CGM in typical low-z galaxies

- Characteristic size of CGM in Lyα \( \sim \) virial radius
- Metals more concentrated \((\sim 0.5 R_{\text{vir}})\)
- Borthakur et al. 2016 (B16) – COS-GASS plus COS-Halos
Kinematics – Warm CGM Clouds are Bound

- Bordoloi – in prep
Warm CGM Structure and Star-Formation

B16: Lyα absorbers have a more uniform radial distribution in the blue galaxies. A “patchy” distribution in the CGM of red galaxies (smaller covering factor)
The warm gas in the CGM is metal-enriched (~10% to 100% solar) and mostly ionized.

The metal mass of this gas is similar to that of the stellar disk.

This material is in the form of cloud/sheets/filaments.

Werk et al. 2014
The hot ($\sim T_{\text{vir}}$) volume-filling phase

- Spectra of O VII through MW CGM (Fang et al.)
- Mass $\sim M_* \sim M_{\text{warm}}$ (Miller & Bregman)
Hot Starburst-Driven Winds

- For every solar mass of stars formed get $\sim 1.6 \times 10^{49}$ ergs of KE delivered by supernovae and stellar winds.
- Thermalize stellar ejecta and produce hot gas with $T \sim 10^8 (\alpha/\beta)$ K.
- Here $\alpha$ is thermalization efficiency and $\beta$ is the “poisoning factor” ($\beta = 1$ for pure stellar ejecta). The “mass-loading factor” $\sim \beta/3$.
- Adiabatic expansion leads to a wind with $v_{\text{term}} \sim 2800 (\alpha/\beta)^{1/2}$ km/s.
- KE flux = $7 \times 10^{41} \alpha$ SFR erg/s.
- Momentum flux of wind $\sim 10^{34} (\alpha \beta)^{1/2}$ SFR dynes.
- Metallicity = $1 + 5/\beta$ times solar.
• H- & He-like Fe lines at 6.9 & 6.7 keV: very hot gas ($T \sim 40$ million K) inside the starburst
• Best-fit values: $\alpha = 0.7 +/- 0.3$ and $\beta = 2 +/- 1$
• Implied $v_{\text{wind}} = 1700$ km/s
• Implied $Z_{\text{wind}} = 3.5 \times$ solar (Strickland & Heckman)
Wind Fluid Blows-Out Into the Halo

- Most of the halo volume is occupied by the very energetic and tenuous “WIND FLUID”
- Most of the emission and absorption comes from denser material interacting with the wind fluid ("clouds")
Not the wind
Effects of wind fluid probed on small (~10 kpc) scales

- Optical and soft X-ray emission from gas “targets” impacted by the wind
- “Down the barrel” absorption-lines from entrained material
What happens when a wind flows into the CGM?
Test using QSO sightlines through the CGM of starbursts using COS
COS-Burst: Heckman, Borthakur, Wild, Schiminovich, & Bordoloi 2017

Compare to control sample of normal star-forming galaxies matched in $M_*$ and impact parameter ($\rho$) observed with HST/COS
COS-Burst Sample

- Galaxies selected from SDSS legacy sample based on PCA approach
- 17 cases with suitable QSO
- Burst parameters derived from PCA vs. models plus Balmer emission-lines
- Median values given below
- Total supplied kinetic energy $\sim 10^{59}$ ergs

<table>
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<th>$\log M_\odot$</th>
<th>$v_c^b$</th>
<th>$R_{50}$</th>
<th>$R_{\text{vir}}$</th>
<th>$\rho$</th>
<th>$f_{\text{burst}}$</th>
<th>$t_{\text{burst}}$</th>
<th>$\log sSFR$</th>
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<td>(kpc)</td>
<td>(kpc)</td>
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<td>(Myr)</td>
<td>(Log yr$^{-1}$)</td>
<td>(log $M_\odot$yr$^{-1}$)</td>
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<td>1.07</td>
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Higher column densities of metals compared to the outer CGM of normal star-forming galaxies

- Note that Si III and C IV lines have $T \sim 1$, so that EQW traces column density
- Typical values are $\sim$ few x $10^{13}$ and few x $10^{14}$ cm$^{-2}$ respectively
- Covering factor $\sim$ 50% in outer CGM
Larger ratio of Si III/Ly$\alpha$ and C IV/Ly$\alpha$ EQWs

- C IV and Si III have $T \sim 1$ while Ly$\alpha$ has $T >> 1$
- Implication: higher gas column densities in CGM in COS-Burst sample enhances the ratio of EQW of optically-thin vs. saturated lines
Super-virial velocities

\[ v_{\text{cgm}} \sim 2 v_{\text{vir}} \] (FWHM $\sim$ 425 km/s in stacked spectrum)
Interpretation

- Starburst-driven wind-fluid drives an expanding bubble (shock) out into a pre-existing multiphase CGM (clouds and volume-filling hot phase)
- This can accelerate clouds and drive and outflow of metals
Can the wind fluid reach the outer CGM?

- Consider classic wind-blown bubble expanding into the CGM (Weaver et al. 1977)
- Volume-filling phase has a total mass $10^{10} \, M_\odot$ and $\rho \propto r^{-1}$ (cf. Miller & Bregman; Voit)
- Similarity solutions (cf. Dyson 1989)
- Energy-driven case:
  $$ R_{\text{bubble}} \sim 195 \frac{dE}{dt} 43^{1/4} M_{\text{hot,10}}^{-1/4} t_{300}^{3/4} \, \text{kpc} $$
- For momentum-driven case, get:
  $$ R_{\text{bubble}} \sim 170 \frac{dp}{dt} 34.7^{1/3} M_{\text{hot,10}}^{-1/3} t_{300}^{2/3} \, \text{kpc} $$
Wind fluid interaction with warm CGM

* For outer CGM cloud gas column densities ~ few \( \times 10^{18} \text{ cm}^{-2} \), the force due to wind ram pressure (out) exceeds the force due to gravity (in) by factor ~30.
* Predicted cloud terminal velocity ~400 km/s (~3 times \( v_{\text{vir}} \)).
* Consistent with observed Ly\( \alpha \) line width (if clouds can survive long enough).
* Could the enhanced metal content reflect the destruction of grains by wind-driven shocks (increasing the mass of gas-phase metals)?
* Does wind lead to cloud *creation* as uplifted adiabatically cooled CGM material becomes thermally unstable? Cf. Voit, Lehnert
A real wind-blown bubble: NGC 6888
Summary

- The CGM differs significantly in low-z galaxies that have recently undergone a starburst compared to normal star-forming galaxies:
  - Higher column densities of metal ions (C IV and Si III)
  - Higher velocity dispersions (velocities well in excess of $v_{\text{circ}}$)
- These properties reflect the interaction between a starburst-driven wind and a pre-existing CGM. This interaction extends to the virial radius
- Key new observational input to simulations of galactic winds
- Provides a new probe of the low-z CGM in typical galaxies
Coals to Newcastle