Starburst winds, the CGM, and the origin of coronal-phase gas
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>
<thead>
<tr>
<th>logM$<em>*$/Log M$</em>\odot$</th>
<th>v$^b_c$/km s$^{-1}$</th>
<th>R$_{50}$/kpc</th>
<th>R$_{vir}$/kpc</th>
<th>$\rho$/kpc</th>
<th>f$_{burst}$/</th>
<th>t$_{burst}$/Myr</th>
<th>logsSFR/(Log yr$^{-1}$)</th>
<th>logSFR/(log M$_\odot$yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.34</td>
<td>129</td>
<td>3.2</td>
<td>184</td>
<td>179</td>
<td>0.17</td>
<td>280</td>
<td>-9.24</td>
<td>1.07</td>
</tr>
</tbody>
</table>
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 $\times 10^{13}$ and few $\times 10^{14}$ cm$^{-2}$ respectively
- Covering factor $\sim 50\%$ in outer CGM
Super-virial velocities

\[ v_{\text{cgm}} \sim 2v_{\text{vir}} \] (FWHM $\sim 425 \text{ km/s}$ 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 (create?) clouds and drive the outflow of metals
Can the wind fluid reach the outer CGM?

- Consider classic wind-blown bubble expanding into the CGM (Weaver + 1977)
- Volume-filling phase has a total mass $10^{10} M_\odot$ and $\rho \propto r^{-1}$ (cf. Miller & Bregman; Voit; Das)
- Adopt the mean starburst age of $\sim 300$ Myr
- Mean energy injection rate is $\sim 10^{43}$ erg/s
- Similarity solutions (cf. Dyson 1989)
- Energy-driven case:
  $$R_{\text{bubble}} \sim 195 \frac{dE}{dt} t_{300}^{3/4} M_{\text{hot},10}^{-1/4} \text{kpc}$$
- For momentum-driven case, get:
  $$R_{\text{bubble}} \sim 170 \frac{dp}{dt} t_{300}^{2/3} M_{\text{hot},10}^{-1/3} \text{kpc}$$
Summary #1

- 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
Bonus Coverage: Coronal Gas in the CGM

- Simple model of radiatively-cooling gas-flow (Heckman+02 and Bordoloi+17)
  \[ N_{\text{cool}} = n \, L_{\text{cool}} = n \, t_{\text{cool}} \, v_{\text{cool}} \]
- For radiatively cooling gas flow \( t_{\text{cool}} = 3kT/n\Lambda \), where \( \Lambda(T,Z) \) is the cooling function
- \( N_{\text{cool}} = (3kT/\Lambda) \, v_{\text{cool}} \) independent of density \( (n) \)
- For some specific ion \( X,i \): \( N_{X,i} = (3kT/\Lambda) \, v_{\text{cool}} \, (X/H) \, f_{X,i} \), where \( f_{X,i}(T) \) is the ionic fraction
- Since \( \Lambda \propto Z \) in coronal T-range, \( N_{X,i} \propto v_{\text{cool}} \, [T \, f_X(T)/\Lambda(T)] \), independent of \( n \) and \( Z \)
- Simple analytic arguments: \( \Delta v \sim v_{\text{cool}} \), where \( \Delta v \) is the LOS line-width
- Have shown this explicitly using radiative shock models
- “Natural” value for \( T \) is near the value where \( f_{X,i} \) peaks \( (T_{\text{peak}}) \)
- BOTTOM LINE: EXPECT RELATIONSHIP BETWEEN COLUMN DENSITY AND LINE WIDTH, WITH MODEST DEPENDENCE ON TEMPERATURE NEAR \( T_{\text{peak}} \)
Sanity-check using data on the Cygnus Loop and from numerical shock models
Results: model agrees with data for variety of systems and a range of high-ions
Inferred $T$ clusters around $T_{\text{peak}}$ for O VI
Model agrees with properties of O VI and Ne VIII when both are observed on the same LOS.
Consistent with CGM at $z \sim 0$ to 4

(Werk+16; Rudie+19)
Summary #2

- A simple model of a radiatively-cooling gas-flow can naturally account for the properties of coronal-phase gas in the CGM (and elsewhere).
- Successfully predicts the relationship between column density and line-width.
- Successfully predicts the different column densities and widths seen in N V, O VI, NeVIII, and O VII(?) lines.
- The model has only one free parameter, the column-density-weighted mean temperature for the observed ion, and this is highly constrained to be in the temperature range at which the ionic fraction is significant.
- Could apply to shocks, turbulent mixing layers, cooling winds, etc.
- Occam’s Razor.