Extreme Simulations of Starburst-Driven Galactic Winds

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Our theories of galaxy formation require galactic winds to:

• regulate star formation in galaxies,

• reproduce the stellar mass function,

• enrich the circumgalactic medium (CGM) and intergalactic medium (IGM) with metals,

• and more.

Davé et al. (2016)
Galactic Winds Are Multiphase

In nearby starbursts, outflows can be observed in spatially resolved X-ray emitting gas as well as cooler optical line emission.
Cool Gas Exists Around Galaxies

COS-Halos and other CGM surveys have found abundant neutral hydrogen in the halos of both star-forming and passive galaxies in the nearby universe.

Bordoloi et al. (2017)
Low-ionization, blue-shifted metal lines are frequently observed when looking “down the barrel” at star-forming galaxies, indicating cool, outflowing material.
... But Cool Gas Is Difficult To Accelerate.

$V_{\text{wind}}$  

--- 5 pc

0 kyr

AST 119 (Director’s Discretionary Time)

Schneider & Robertson (2017)
Can we build a coherent theory of outflows that explains the observations?

We want a physically-motivated model that:

• Reproduces the multiphase nature of outflows

• Explains the velocity structure of outflows

• Efficiently transports metals out of galaxies to enrich the CGM and beyond

• Ideally, can explain observations of the multiphase CGM
The Chevalier & Clegg Model

The Chevalier & Clegg outflow model assumes spherical symmetry and its solution is governed by three parameters:

\[ \dot{M} \quad \dot{E} \quad R \]

- \( \dot{M} \): mass injection rate
- \( \dot{E} \): energy injection rate
- \( R \): injection radius

The Chevalier & Clegg model neglects gravity, radiative cooling, and additional sources of momentum.

See also Bustard et al. (2016)
The Chevalier & Clegg Model
The Radiative Wind Model

\[ \dot{M}_{\text{wind}} = \beta \dot{M}_{\text{SFR}} \]

\[ \dot{E}_{\text{wind}} = 3 \times 10^{41} \text{ erg s}^{-1} \alpha \dot{M}_{\text{SFR}} \]

Mass-loading factor

Energy-loading factor
The Radiative Wind Model

Thompson et al. (2016)
Introducing the CGOLS project

- Via the INCITE program (AST 125), we have received ~100 million core-hours on Titan (over 2 years) to tackle the challenge of simulating galactic winds.

- We are running a series of high resolution simulations to develop a theory of winds in a systematic manner.

- We call this project **CGOLS** (Cholla Galactic OutfLow Simulations).

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Figure 4

M82, imaged by the Wisconsin Indiana Yale NOAO telescope in H$\alpha$ (magenta) and HST in BVI continuum colors (courtesy Smith, Gallagher & Westmoquette). Several of the largest scale filaments trace all the way back to super-star clusters embedded in the disk.
How does CGOLS compare?
CGOLS Year 1 Simulation Features

- Isothermal gas disk, $T = 10^4$ K in vertical hydrostatic and rotational equilibrium

- Static potential with a stellar disk + NFW dark matter halo, $M_{\text{stars}} = 10^{10} \, M_{\odot}$ and $M_{\text{DM}} = 5 \times 10^{10} \, M_{\odot}$

- All simulations run at 3 resolutions: 5pc, 10pc, and 20pc, in a 10 kpc x 10 kpc x 20 kpc box

- Starburst feedback is either “central” or “clustered”, with varied mass-loading, energy-loading, and SFR
CGOLS Year 1 Simulation Features

High mass-loading:
$\alpha = 0.9,$
$\beta = 0.6,$
SFR = 20 M$_\odot$/yr

Low mass-loading:
$\alpha = 1.0,$
$\beta = 0.3,$
SFR = 5 M$_\odot$/yr
Adiabatic
Adiabatic

Density

Velocity

Pressure

Temp
Radiative Cooling
Temperature Evolution in the Radiative Model

10 Myr
Early wind expansion

25 Myr
High mass-loading cooled wind state

50 Myr
Low mass-loading wind expansion

60 Myr
Late-time smooth flow

$\log_{10}(T) [K]$
Temperature Evolution in the Clustered Model

Early wind expansion
High mass-loading cooled wind state
Low mass-loading wind expansion
Late low mass-loading state
Radiative + Clustered FB: high state

- **Density**
  - 25 Myr
  - n [cm^{-3}]

- **Velocity**
  - V_r [km s^{-1}]

- **Pressure**
  - \log_{10}(P/k) [K cm^{-3}]

- **Temp**
  - \log_{10}(T) [K]
Radiative + Clustered FB: Low state

- **Density**: $n \text{ [cm}^{-3}\text{]}$ as a function of $r \text{ [kpc]}$.
- **Velocity**: $v_r \text{ [km s}^{-1}\text{]}$ as a function of $r \text{ [kpc]}$.
- **Pressure**: $\log_{10}(P/k) \text{ [K cm}^{-3}\text{]}$ as a function of $r \text{ [kpc]}$.
- **Temp**: $\log_{10}(T) \text{ [K]}$ as a function of $r \text{ [kpc]}$. 

The graphs show the evolution of density, velocity, pressure, and temperature with distance from the center of the system for a given time step (60 Myr). The plots include mean and median values for each parameter.
Comparison to X-ray Observations

Total luminosity sim: $1.4 \times 10^{40}$ erg s$^{-1}$
Total luminosity obs: $4.3 \times 10^{40}$ erg s$^{-1}$
How is the multiphase structure generated?
How is the multiphase structure generated?
And what is the effect of resolution?

\[ \Delta x = 20 \text{ pc} \]

\[ \Delta x = 5 \text{ pc} \]
Cosmological Simulations with Cholla

Villasenor, Schneider, and Robertson (in prep)