The Role of Cosmic Rays in Isolated Disk Galaxies

Iryna Butsky
Blue Waters Graduate Fellow
University of Washington Astronomy Department
PI: Tom Quinn

BLUE WATERS
SUSTAINED PETASCALE COMPUTING
Outline

- Why it Matters (Background)
- Methods & Key Challenges
- Why Blue Waters?
- Preliminary Results
- Broader Impact
Cosmic Rays

- Charged particles (p+, e-, etc.)
Cosmic Rays

- Charged particles (p+)

Gaisser 2006
Cosmic Rays

- Charged particles (p+)
- Move at relativistic speeds
Cosmic Rays

- Charged particles (p+)
- Move at relativistic speeds
- Accelerated in shocks: supernovae, active galactic nuclei (AGN), quasars, gamma-ray bursts
Propagation of Cosmic Rays

- Mean free path for CR collisions $\sim 10 \text{ n Mpc}$ ($10^{-4} < n < 10^2 \text{ cm}^{-3}$)
- Escape time of CRs from galaxy $\sim 3 \times 10^7 \text{ years}$
- Must be some scattering mechanism present
Propagation of Cosmic Rays

Magnetic field

ion

globular clusters

disc \( h = 300 \text{ pc} \)

gas/CR halo

Sun

8 kpc
Galactic Magnetic Fields

Butsky et al. 2017
CR Driven Dynamo

- **dynamo** converts kinetic energy into magnetic energy
- CRs create magnetic instabilities which grow the magnetic field and drive galactic winds

![Diagram](image.png)
CIRCUMGALACTIC MEDIUM (CGM)

Intergalactic medium (diffuse gas between galaxies)

Circumgalactic medium (diffuse gas near galaxy)

CGM contains:

- majority of baryons
- majority of metals
- reservoir of cool gas necessary for star formation in disk

Peeples 2015
CIRCUMGALACTIC MEDIUM (CGM)

- Intergalactic medium (diffuse gas between galaxies)
- Circumgalactic medium (diffuse gas near galaxy)

Cosmic Rays:
- drive mass-loaded outflows
- provide non-thermal pressure support
- alter structure of CGM

Peeples 2015
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ENZO Basics

- Adaptive mesh grid code
- Simulate a fluid moving through cells
- Time evolution of conserved quantities governed by Euler’s equations
Euler’s Equations

1. \[ \frac{dU}{dt} + \nabla \cdot F = S \]
   - change over time
   - flux through cell
   - source term

2. Numerically approximate solution using a Riemann solver
   - density
   - velocity
   - B field
   - total energy
   - CR energy
Adding CRs to the Equation

\[
U = \begin{pmatrix}
  \rho \\
  \rho v \\
  B \\
  \epsilon 
\end{pmatrix}
\quad \text{density, velocity, B field, total energy}
\]

\[
F = \begin{pmatrix}
  \rho v \\
  \rho vv^T + P1 - BB^T \\
  Bv^T - vB^T \\
  (\epsilon + P)v - B(v \cdot B)
\end{pmatrix}
\]

\[
S = \begin{pmatrix}
  0 \\
  0 \\
  0 \\
  0 
\end{pmatrix}
\]

\[
\frac{dU}{dt} + \nabla \cdot F = S
\]
Adding CRs to the Equation

\[ U = \begin{pmatrix} \rho \\ \rho v \\ B \\ \epsilon \\ \epsilon_{cr} \end{pmatrix} \quad \text{density, velocity, B field, total energy, CR energy} \]

\[ F = \begin{pmatrix} \rho v \\ \rho vv^T + P1 - BB^T \\ Bv^T - vB^T \\ (\epsilon + P)v - B(v \cdot B) - \kappa_\epsilon b(b \cdot \nabla \epsilon_{cr}) \\ \epsilon_{cr}(v + v_{st}) - \kappa_\epsilon b(b \cdot \nabla \epsilon_{cr}) \end{pmatrix} \]

\[ S = \begin{pmatrix} 0 \\ 0 \\ 0 \\ -P_{cr} \nabla \cdot (v + v_{st}) \end{pmatrix} \]

\[ \frac{dU}{dt} + \nabla \cdot F = S \]
CR Diffusion

Initial CR overdensity

Isotropic diffusion
\[ \nabla \cdot \kappa_\epsilon \nabla^2 \epsilon_{CR} \]

Anisotropic diffusion
\[ \nabla \cdot [\kappa_\epsilon \mathbf{b} (\mathbf{b} \cdot \nabla \epsilon_{CR})] \]
Key Challenge: Time Stepping with CRs

- **Diffusion:** \( t_D = \frac{\Delta x^2}{\kappa_{cr}} \)

- **Courant:** \( t_c = \frac{\Delta x}{c_f} \)
  \( \quad c_f \propto \sqrt{\frac{\gamma_{cr} P_{cr}}{\rho}} \)
Key Challenge: Pick Two

- "Short" Computational Time
- Cosmic Rays
- Magnetic Fields
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Why Blue Waters?

- Huge variation in simulation scale
- Each cell follows complex interaction rules
- Efficient parallelization
- Sufficient data storage
- Awesome support team!
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Preliminary Results: A (Short) Tale of Two Galaxies

- **Initial Conditions:**
  - AGORA isolated disk
  - Background magnetic field of $10^{-16}$ Gauss
  - 1 galaxy with uniform CR energy density of 10-3 erg/g
  - 1 galaxy with no CR physics
  - ~2000 core-hours to evolve 800 Myr
Circumgalactic Medium

$t = 3$ Myr

- Metals\(^*\) are produced by stars in disk
- Metallicity of halo traces galactic outflows

\(^*\) metal = heavier than H or He
Circumgalactic Medium

No CRs

$t = 800$ Myr
Circumgalactic Medium

No CRs

Includes CRs

$t = 800$ Myr
Hubble Space Telescope
Cosmic Origins Spectrograph
Circumgalactic Medium

Future Work:

- Evolve galaxies longer
- Dynamically important CRs
- Different mass galaxies
- Different diffusion coefficients / feedback
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Broader Impact

- ENZO is a community-developed, publicly available code (enzo-project.org)

- Rich, multi-physics hydrodynamic astrophysical simulations

- Cosmic ray physics will be available for:
  - all HD and MHD solvers
  - all scales
Summary

- Understanding the structure of the CGM and the physical processes that govern its evolution is important for understanding galaxy evolution.
- Cosmic rays drive large outflows and provide non-thermal pressure support which alter the structure and composition of the CGM.
- Need magnetic fields and anisotropic diffusion to properly model CR behavior.
- CR physics in ENZO compatible with MHD solvers.
- Future work will use Blue Waters to run isolated galaxies with varying masses, feedback prescriptions, and CR diffusion coefficients.
- We can compare our results to observations made with the HST COS-Halos instrument using synthetic spectra generated with Trident.
Questions?