Cosmic Rays in the Context of Multimessenger Astronomy

GeV Cosmic Ray Transport: Confronting Simulations with Observations

REFERENCES:  BUSTARD AND ZWEIBEL 2021
             BUSTARD & OH 2022, IN PREP
Background

• Two recent advances:

• **Multimessenger astronomy** helps us constrain cosmic ray propagation and cosmic ray sources

• **“Live” galaxy evolution simulations** with cosmic rays, spanning a range of galaxy types*


Cosmic rays help drive galactic winds, regulating star formation
Problem #1: Simulated dwarf galaxies have far too much $\gamma$-ray emission compared to Fermi-LAT data.
Cosmic Ray Propagation and Confinement

**Self-confinement** (E < 300 GeV)

- Cosmic rays scatter off waves driven by a resonant **streaming** instability
- Propagation is at \( v_A^{\text{ion}} = \frac{B}{\sqrt{4\pi \rho_{\text{ion}}}} \)
- Cosmic rays **do** transfer energy to the gas at a rate \( v_A^{\text{ion}} \cdot \nabla P_{CR} \)

**Extrinsic Turbulence** (E > 300 GeV)

- Cosmic rays scatter off waves in a turbulent cascade
- Propagation is diffusive along magnetic field lines
- Cosmic rays **don’t** transfer energy to gas

\[ F(x) = \sum_{n=0}^{\infty} a_n \sin(n \pi x) \]

Dogiel+ 2020
Cosmic Ray Hydrodynamics in the Multiphase ISM

MHD Simulations w/Athena++

- Single energy bin approximation for the CRs
- Evolve cosmic ray energy $E_{cr}$ and flux $F_{cr}$ using two-moment technique borrowed from radiative transfer (Jiang and Oh 2018)
- “Collisionless” energy loss at rate $v_{A}^{ion} \cdot \nabla P_{CR} +$ hadronic and Coulomb collisions

Case #1: Assume the gas is fully ionized. Streaming at $v_A = \frac{B}{\sqrt{4\pi \rho}}$, no diffusion

Case #2: Include ionization-dependent transport. Streaming at $v_A^{ion} = \frac{B}{\sqrt{4\pi \rho f_{ion}}}$, diffusion due to ion-neutral damping (see e.g. Skilling 1971, Everett and Zweibel 2011, Farber+ 2018)
Assuming Fully Ionized Gas

Ionization-Dependent Transport

$\frac{f_{\text{ion}}}{n_0} = 1.0$, $t = 40$ Myr

$\frac{f_{\text{ion}}}{n_0} = 10^{-4}$, $t = 40$ Myr

Bustard and Zweibel 2021
Case 1: Assuming fully ionized

Collisionless energy loss (streaming loss) is **distributed throughout the cloud**

Collisions are biased towards **cloud interfaces**

Case 2: Ionization-dependent

Collisionless energy transfer is **focused at cloud interfaces**

Collisions are biased towards **cloud interiors**

\[ \propto v_A \cdot \nabla P_{cr} \]

\[ \propto n E_{cr} \]
Total energy loss and $\gamma$-ray luminosity are largely **unchanged** when ionization-dependent transport is accounted for.

Possible solutions:
- Increased transport speeds in diffuse, ionized gas (*Chan+ 2019, Hopkins+ 2021*)
- A new damping mechanism?
- Improved statistics: more observed $\gamma$-ray luminosities for dwarf galaxies
- An entirely new paradigm for what scatters cosmic rays?

**Accumulated Cosmic Ray Energy Loss**

Within $h = 0.25$ kpc

**Calorimetric Limit**

**Initial Conditions**
- $L = 2$, $a = 1.5$
- $L = 2$, $a = 1.5$, $B = 1 \mu G$
- $L = 5$, $a = 1.5$
- $L = 5$, $a = 1.0$
- $L = 5$, $a = 0.5$

**Transport Model**
- $\beta_{\text{non}}^{\gamma} = 1.0$
- $\beta_{\text{non}}^{\gamma} = 1.0 + \kappa_B = 3 \times 10^{-7}$
- $\beta_{\text{non}}^{\gamma} = 1.0 + \kappa_B = 3 \times 10^{-8}$
- $\beta_{\text{non}}^{\gamma} = 10^{-4} + \kappa_B = 3 \times 10^{-7}$
Cosmic Rays in a Turbulent Medium

Turbulent Reacceleration (2nd order Fermi)

\[ \frac{\Delta E}{E} \sim \mathcal{O} \left( \frac{v^2}{c^2} \right) \]

= magnetic perturbations
  * Size \( \sim r_g \) (resonant scale)
  * Size \( \sim L_{outer} \) (non-resonant)

Bustard and Oh 2022, in prep
• Reacceleration is a favored explanation for radio haloes in merging galaxy clusters (Brunetti and Jones 2014)

• Reacceleration simultaneously explains the bump in B/C ratio at ~1 GeV while maintaining a single power-law diffusion coefficient (e.g. Heinbach and Simon 1995)

Problem #2:

• Propagation models fit to both $\gamma$-ray and synchrotron data disfavor reacceleration (Trotta+ 2011, Di Bernardo+ 2013, Orlando and Strong 2013, Gabici+ 2019)

• Too much power (possibly 50%) is in reaccelerated cosmic rays (Thornbury and Drury 2014, Drury and Strong 2017)

Heinbach and Simon 1995
Question: Is reacceleration efficient at GeV energies?

Resonant Reacceleration

\[ D_{xx}D_{pp} = p^2 V_A^2 \left( \frac{1 - \mu^2}{v_+ + v_-} \right) \left( \frac{(1 - \mu^2) v_+ v_-}{v_+ + v_-} \right) \quad \nu_- = 0 \]

Non-Resonant Reacceleration (Bustard and Oh 2022, in prep)

- Athena++ simulations of compressive, subsonic, isothermal turbulence
- With streaming energy loss included (relevant for E < 300 GeV), growth times are significantly longer in low-\(\beta\) environments like the ISM

CHAD BUSTARD, 01/18/2022
Conclusions

- Two examples of idealized, high-resolution, cosmic ray hydrodynamics simulations vs observations

- Propagation of self-confined (~ GeV) cosmic rays in the multiphase ISM (Bustard and Zweibel 2021)

  - Ionization-dependent transport doesn’t solve the overproduction of $\gamma$-rays in simulated dwarf galaxies

- Reacceleration of self-confined (~ GeV) cosmic rays in a turbulent ISM (Bustard and Oh 2022, in prep)

  - Streaming energy loss significantly reduces the efficiency of non-resonant reacceleration in ISM-like environments

  - Synchrotron observations and analytic estimates hint at this