Cosmic rays in galaxy formation

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in collaboration with

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Virgo Consortium meeting, Durham, Jan 2020
Do cosmic rays matter in galaxy formation?
Puzzles in galaxy formation

- Dwarf galaxy
- Spiral galaxy
- Giant elliptical galaxy

\[
\frac{\log(\text{stellar mass})}{\log(\text{halo mass})}
\]

20% of baryons

Moster+ (2010)
Cosmic rays in galaxy formation

Puzzles in galaxy formation

- Dwarf galaxy
- Spiral galaxy
- Giant elliptical galaxy

\[
\frac{\text{stellar mass}}{\text{halo mass}} = \log(\text{stellar mass}) - \log(\text{halo mass})
\]

Approximately 20% of baryons

\text{stellar feedback}

Moster+ (2010)
Puzzles in galaxy formation

- **dwarf galaxy**
- **spiral galaxy**
- **giant elliptical galaxy**

- **log(stellar/halo mass)**
- **log(halo mass)**

- 20% of baryons
- Feedback by active galactic nuclei

Moster+ (2010)
How are galactic winds driven?

- thermal pressure provided by supernovae or AGNs?
- radiation pressure and photoionization by massive stars and QSOs?
- cosmic-ray pressure and Alfvén wave heating of CRs accelerated at supernova shocks?
Galactic cosmic ray spectrum

- spans more than 33 decades in flux and 12 decades in energy
- “knee” indicates characteristic maximum energy of galactic accelerators
- CRs beyond the “ankle” have extra-galactic origin

Cosmic Ray energy spectrum

89% protons
10% $^4$He (alphas)
1% mostly $\text{e}^-$ (betas)

1 m$^{-2}$ s$^{-1}$
1 m$^{-2}$ yr$^{-1}$
1 km$^{-2}$ yr$^{-1}$

data compiled by Swordy
Galactic cosmic ray spectrum

- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar
How are galactic winds driven?

- thermal pressure provided by supernovae or AGNs?
- radiation pressure and photoionization by massive stars and QSOs?
- cosmic-ray pressure and Alfvén wave heating of CRs accelerated at supernova shocks?

Observed energy equipartition between cosmic rays, thermal gas and magnetic fields not a coincidence
→ suggests self-regulated feedback loop with CR driven winds
Outline

1. Cosmic ray transport
   - Introduction
   - CR hydrodynamics
   - Observational tests

2. Cosmic ray feedback
   - Modeling physics
   - Galaxy simulations
   - Galaxy cluster physics
Cosmic ray transport: an extreme multi-scale problem

Milky Way-like galaxy:

\[ r_{\text{gal}} \sim 10^4 \text{ pc} \]

gyro-orbit of GeV cosmic ray:

\[ r_{\text{cr}} = \frac{p_\perp}{eB_{\mu G}} \sim 10^{-6} \text{ pc} \sim \frac{1}{4} \text{ AU} \]

⇒ need to develop a **fluid theory for a collisionless, non-Maxwellian component!**

Interactions of CRs and magnetic fields

Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency

CRs scatter on magnetic fields

→ isotropization of CR momenta

sketch: Jacob
Interactions of CRs and magnetic fields

**Gyro resonance:**
\[ \omega - k_{\parallel} v_{\parallel} = n\Omega \]

Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency

Sketch: Jacob
Interactions of CRs and magnetic fields

- **gyro resonance:** \[ \omega - k_\parallel v_\parallel = n\Omega \]
  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency

- CRs scatter on magnetic fields → isotropization of CR momenta
**CR streaming instability**: Kulsrud & Pearce 1969

- if $v_{cr} > v_a$, CR flux excites and amplifies an Alfvén wave field in resonance with the gyroradii of CRs.
- scattering off of this wave field limits the (GeV) CRs’ bulk speed $\sim v_a$.
- wave damping: transfer of CR energy and momentum to the thermal gas.
CR streaming and diffusion

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→ *CRs exert pressure on thermal gas via scattering on Alfvén waves*
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  - if $v_{cr} > v_a$, CR flux excites and amplifies an Alfvén wave field in resonance with the gyroradii of CRs
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$\rightarrow$ **CRs exert pressure on thermal gas via scattering on Alfvén waves**

**Weak wave damping:** strong coupling $\rightarrow$ CR stream with waves

**Strong wave damping:** less waves to scatter $\rightarrow$ CR diffusion prevails
Modes of CR propagation

$\nu_{adv} t$

Thomas, CP, Enßlin (2020)
Modes of CR propagation

- **Advection**
  - \( v_{\text{adv}}t \)

- **Diffusion**
  - \( \sqrt{2\kappa t} \)

Thomas, CP, Enßlin (2020)

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Cosmic rays in galaxy formation
Modes of CR propagation

- **Advection**: \( v_{\text{adv}} t \)
- **Diffusion**: \( \sqrt{2\kappa t} \)
- **Streaming**: \( v_\text{a} t \)

Thomas, CP, Enßlin (2020)
CR vs. radiation hydrodynamics

- capitalize on analogies of CR and radiation hydrodynamics (Jiang & Oh 2018)
- derive two-moment equations from CR Vlasov equation (Thomas & CP 2019)
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Lab-frame equ’s for CR energy and momentum density, $\varepsilon_{cr}$ and $f_{cr}/c^2$

$$\frac{\partial \varepsilon_{cr}}{\partial t} + \nabla \cdot f_{cr} = -w_{\pm} \cdot \frac{bb}{3\kappa_{\pm}} \cdot [f_{cr} - w_{\pm}(\varepsilon_{cr} + P_{cr})] - v \cdot g_{\text{Lorentz}} + S_{\varepsilon}$$

$$\frac{1}{c^2} \frac{\partial f_{cr}}{\partial t} + \nabla \cdot P_{cr} = -\frac{bb}{3\kappa_{\pm}} \cdot [f_{cr} - w_{\pm}(\varepsilon_{cr} + P_{cr})] - g_{\text{Lorentz}} + S_{f}$$

Alfvén wave velocity in lab frame: $w_{\pm} = v \pm v_a$,
CR scattering frequency $\bar{\nu}_{\pm} = c^2/(3\kappa_{\pm})$
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Alfvén wave velocity in lab frame: $w_{\pm} = v \pm v_{a}$,
CR scattering frequency $\bar{\nu}_{\pm} = c^2/(3\kappa_{\pm})$

Lab-frame equ’s for radiation energy and momentum density, $\varepsilon$ and $f/c^2$

(Mihalas & Mihalas, 1984, Lowrie+ 1999):

\[
\frac{\partial \varepsilon}{\partial t} + \nabla \cdot f = -\sigma_s v \cdot [f - v \cdot (\varepsilon 1 + P)] + S_a
\]

\[
\frac{1}{c^2} \frac{\partial f}{\partial t} + \nabla \cdot P = -\sigma_s [f - v \cdot (\varepsilon 1 + P)] + S_a v
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Alfvén wave velocity in lab frame: $w_\pm = v_\pm v_a$,

CR scattering frequency $\bar{\nu}_\pm = c^2/(3\kappa_\pm)$

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$$\frac{1}{c^2} \frac{\partial f}{\partial t} + \nabla \cdot P = -\sigma_s \cdot [ f - v \cdot (\varepsilon 1 + P) ] + S_a v$$

Problem: CR lab-frame equation requires resolving rapid gyrokinetics!
CR vs. radiation hydrodynamics

- capitalize on analogies of CR and radiation hydrodynamics (Jiang & Oh 2018)
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**lab-frame equ’s for CR energy and momentum density, \( \varepsilon_{\text{cr}} \) and \( f_{\text{cr}}/c^2 \)**

\[
\frac{\partial \varepsilon_{\text{cr}}}{\partial t} + \nabla \cdot f_{\text{cr}} = - \bm{w}_\pm \cdot \frac{bb}{3\kappa_\pm} \cdot [f_{\text{cr}} - \bm{w}_\pm (\varepsilon_{\text{cr}} + P_{\text{cr}})] - \bm{v} \cdot \bm{g}_{\text{Lorentz}} + S_\varepsilon
\]

\[
\frac{1}{c^2} \frac{\partial f_{\text{cr}}}{\partial t} + \nabla \cdot P_{\text{cr}} = - \frac{bb}{3\kappa_\pm} \cdot [f_{\text{cr}} - \bm{w}_\pm (\varepsilon_{\text{cr}} + P_{\text{cr}})] - \bm{g}_{\text{Lorentz}} + S_f
\]

Alfvén wave velocity in lab frame: \( \bm{w}_\pm = \bm{v}_\pm + \bm{v}_a \),

CR scattering frequency \( \nu_\pm = c^2/(3\kappa_\pm) \)

**lab-frame equ’s for radiation energy and momentum density, \( \varepsilon \) and \( f/c^2 \)**

(Mihalas & Mihalas, 1984, Lowrie+ 1999):

\[
\frac{\partial \varepsilon}{\partial t} + \nabla \cdot f = -\sigma_s \bm{v} \cdot [f - \bm{v} \cdot (\varepsilon \mathbf{1} + P)] + S_a
\]

\[
\frac{1}{c^2} \frac{\partial f}{\partial t} + \nabla \cdot P = -\sigma_s \ [f - \bm{v} \cdot (\varepsilon \mathbf{1} + P)] + S_a \bm{v}
\]

**solution:** transform in comoving frame and project out gyrokinetics!
Non-equilibrium CR streaming and diffusion
Coupling the evolution of CR and Alfvén wave energy densities

Thomas & CP (2019)
Non-equilibrium CR streaming and diffusion
Varying damping rate of Alfvén waves modulates the diffusivity of solution

\[ \epsilon_{\text{cr}} \]

\[ \epsilon_{\text{a,+}} \]

\[ \epsilon_{\text{a,−}} \]

\[ x \]

\[ \alpha = 1 \times 10^{11} \]
\[ \alpha = 5 \times 10^{11} \]
\[ \alpha = 1 \times 10^{12} \]
CR streaming and diffusion along magnetic field lines in the self-confinement picture

- moment expansion similar to radiation hydrodynamics
- accounts for kinetic physics: non-linear Landau damping, gyro-resonant instability, . . .
- Galilean invariant and causal transport
- energy and momentum conserving

Thomas, Pakmor, CP (in prep.)
MeerKAT image of the Galactic Center

Haywood+ (Nature, 2019)
MeerKAT image of the Galactic Center

Haywood+ (Nature, 2019)
Radio synchrotron harps: the model

shock acceleration scenario

Thomas, CP, Enßlin (2020)
Cosmic ray transport
Cosmic ray feedback

Introduction
CR hydrodynamics
Observational tests

Radio synchrotron harps: the model

shock acceleration scenario

magnetic reconnection at pulsar wind

Thomas, CP, Enßlin (2020)
Radio synchrotron harps: the model

shock acceleration scenario

CR diffusion vs. streaming + diffusion

Thomas, CP, Enßlin (2020)
Radio synchrotron harps: testing CR propagation

Haywood+ (Nature, 2019)
Radio synchrotron harps: testing CR propagation

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Radio synchrotron harps: testing CR propagation

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CR diffusion

- Thomas, CP, Enßlin (2020)
Radio synchrotron harps: testing CR propagation

Haywood+ (Nature, 2019)

CR streaming and diffusion

Thomas, CP, Enßlin (2020)
Simulations – flowchart

observables:
- X-ray, Hα, HI, ... emission
- stellar spectra

physical processes:
- thermal energy
- radiative cooling
- supernovae
- shocks
- AGN

loss processes
gain processes
observables
populations

CP+ (2017a)
Simulations with cosmic ray physics

observables:
- X-ray, Hα, HI, ... emission
- stellar spectra

physical processes:
- radiative cooling
- supernovae
- shocks
- AGN
- Coulomb losses

- thermal energy
- cosmic ray energy

loss processes
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CP+ (2017a)
Simulations with cosmic ray physics

observables:
- X-ray, Hα, HI, ...
- stellar spectra

physical processes:
- thermal energy
- shocks
- supernovae
- AGN
- Coulomb losses
- CR streaming & diffusion

loss processes
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observables
populations

CP+ (2017a)

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Cosmic rays in galaxy formation
Simulations with cosmic ray physics

observables:
- X-ray, Hα, HI, ... emission
- stellar spectra
- radio synchrotron
- gamma-ray emission

physical processes:
- thermal energy
- radiative cooling
- shocks
- supernovae
- AGN
- Coulomb losses
- CR streaming & diffusion
- heat conduction
- hadronic losses
- gain processes

observables: physical processes:
cosmic ray energy

CP+ (2017a)

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Cosmic rays in galaxy formation
Gamma-ray emission of the Milky Way
Galactic wind in the Milky Way?
Fermi gamma-ray bubbles

Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.
1. Galaxy formation in idealized halos

CP, Pakmor, Simpson, Springel (2017b)

*Simulating gamma-ray emission in star-forming galaxies*

MHD + CR advection + anisotropic diffusion, \( \{10^{10}, 10^{11}, 10^{12}\} \) \( M_\odot \)
Simulation of Milky Way-like galaxy, $t = 0.5$ Gyr

$t = 0.5$ Gyr, $M_{200} = 10^{12} M_\odot$, anisotropic CR diffusion

\[ \rho [M_\odot \text{ pc}^{-3}] \]

\[ \varepsilon_{\text{cr}} [\text{erg cm}^{-3}] \]

\[ \sqrt{B^2} [\mu\text{G}] \]

CP+ (2017b)
Simulation of Milky Way-like galaxy, $t = 1.0$ Gyr

Simulation of Milky Way-like galaxy, $t = 1.0$ Gyr, $M_{200} = 10^{12} M_\odot$, anisotropic CR diffusion

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$\sqrt{B^2} [\mu \text{G}]$

CP+ (2017b)
Cosmic ray driven wind: mechanism

\[ \nabla P_{\text{cr}} + \nabla P_{\text{th}} > \rho \nabla \Phi \]

**CR streaming in 3D simulations:** Uhlig, CP+ (2012), Ruszkowski+ (2017)

CR-driven winds: dependence on halo mass

Jacob+ (2018)
CR-driven winds: suppression of star formation

![Graph showing the relationship between $M_*$/(f_{bar} M_{vir})$ and $M_{vir}$ (in $M_{\odot}$). The graph compares different scenarios such as no CRs, CRs, CRs, iso. diff., CRs, aniso. diff., and an empiric model, with a Behroozi+2013 model as a reference.](image)

Jacob+ (2018)
2. Cosmological galaxy formation
The galaxy formation model

- primordial and metal line cooling
- sub-resolution model for star formation (Springel+ 03)
- mass and metal return from stars to ISM
- cold dense gas stabilised by pressurised ISM
- thermal and kinetic energy from supernovae modelled by isotropic wind – launched outside of SF region
- black hole seeding and accretion model (Springel+ 05)
- thermal feedback from AGN in radio and quasar mode
- uniform magnetic field of $10^{-10}$ G seeded at $z = 128$

Simulation suite (Buck+ 2019)

- 2 galaxies, baryons with $5 \times 10^4 \ M_\odot \sim 5 \times 10^6$
- resolution elements in halo, $2 \times 10^6$ star particles
- 4 models with different CR physics for each galaxy:
  - no CRs
  - CR advection
  - + CR anisotropic diffusion
  - + CR Alfvén wave cooling
Cosmic rays in cosmological galaxy simulations

Auriga MHD models: CR transport changes disk sizes

Buck, CP, Pakmor, Grand, Springel (2019)
Cosmic rays in cosmological galaxy simulations

Auriga MHD models: CR transport modifies the circum-galactic medium

Buck, CP, Pakmor, Grand, Springel (2019)
Puzzles in galaxy formation: galaxy clusters

- Dwarf galaxy
- Spiral galaxy
- Giant elliptical galaxy

20% of baryons

Active galactic nuclei

Feedback by active galactic nuclei

Log(stellar/halo mass) vs. Log(halo mass)

Moster+ (2010)
Jet simulation: gas density, CR energy density, $B$ field

Ehlert, Weinberger, CP+ (2018)
Perseus cluster – heating vs. cooling: theory

CR and conductive heating balance radiative cooling:
\[ H_{cr} + H_{th} \approx C_{rad} \]: modest mass deposition rate of \( 1 \, M_\odot \, \text{yr}^{-1} \)

Ehlert, Weinberger, CP+ (2018)
CR and conductive heating balance radiative cooling:
\[ H_{\text{cr}} + H_{\text{th}} \approx C_{\text{rad}} \]: modest mass deposition rate of \( 1 \, \text{M}_\odot \, \text{yr}^{-1} \)

Simulated CR heating rate matches 1D steady state model
Conclusions for cosmic ray physics in galaxies

CR hydrodynamics:

- moment expansion similar to radiation hydrodynamics
- novel theory of CR transport mediated by Alfvén waves and coupled to magneto-hydrodynamics
- synchrotron harps: CR streaming dominates over diffusion
Conclusions for cosmic ray physics in galaxies

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- moment expansion similar to radiation hydrodynamics
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- synchrotron harps: CR streaming dominates over diffusion

**CR feedback in galaxy formation:**
- CR feedback drives galactic winds & slows down star formation
- CRs modify disk sizes and the circumgalactic medium
- CR heating may balance radiative cooling in cluster cooling flows
CRAGSMAN: The Impact of Cosmic RAys on Galaxy and CluSter ForMAtion

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Cosmic rays in galaxy formation
Cosmic ray transport:
- Thomas & Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays*, 2019, MNRAS.

Cosmic ray feedback in galaxy clusters:
- Jacob & Pfrommer, *Cosmic ray heating in cool core clusters I: diversity of steady state solutions*, 2017a, MNRAS.
- Jacob & Pfrommer, *Cosmic ray heating in cool core clusters II: self-regulation cycle and non-thermal emission*, 2017b, MNRAS.
- Ehlert, Weinberger, Pfrommer, Pakmor, Springel, *Simulations of the dynamics of magnetised jets and cosmic rays in galaxy clusters*, 2018, MNRAS.
Cosmic ray feedback in galaxies:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh*, 2017a, MNRAS.
- Jacob, Pakmor, Simpson, Springel, Pfrommer, *The dependence of cosmic ray driven galactic winds on halo mass*, 2018, MNRAS.