Cosmic rays and magnetic fields in galaxies

Christoph Pfrommer

in collaboration with

R. Pakmor, V. Springel
Heidelberg Institute for Theoretical Studies, Germany

Jul 1, 2015 / Ringberg Castle: Cosmic Magnetic Fields
Introduction

1. Introduction
   - Puzzles
   - Galactic winds
   - Cosmic ray physics

2. Galactic winds
   - Physics
   - Simulations
   - Open questions

3. Cooling flow problem
   - Radio and $\gamma$-ray emission
   - Cosmic-ray heating
   - Conclusions
Puzzles in galaxy formation

- Galactic winds
- Cooling flow problem
- Cosmic ray physics

- dwarf galaxy
- spiral galaxy
- giant elliptical galaxy

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

20% of baryons

Moster+ (2010)

Christoph Pfrommer
Cosmic rays and magnetic fields in galaxies
Puzzles in galaxy formation

- Galactic winds
- Cooling flow problem
- Cosmic ray physics

- Dwarf galaxy
- Spiral galaxy
- Giant elliptical galaxy

- \( \log(\text{stellar mass}/\text{halo mass}) \)
- \( \log(\text{halo mass}) \)

- 20% of baryons
- Feedback

- Moster+ (2010)
Puzzles in galaxy formation

- Galactic winds
- Cooling flow problem
- Cosmic ray physics

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

- Dwarf galaxy
- Spiral galaxy
- Giant elliptical galaxy

20% of baryons

Active galactic nuclei

Feedback by

Moster+ (2010)

Christoph Pfrommer

Cosmic rays and magnetic fields in galaxies
How are galactic winds driven?

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

Super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA
How are galactic winds driven?

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

observed energy equipartition between cosmic rays, thermal gas and magnetic fields

→ suggests self-regulated feedback loop with CR driven winds
Why are CRs important for wind formation?
Radio halos in disks: CRs and magnetic fields exist at the disk-halo interface

- CR pressure drops less quickly than thermal pressure ($P \propto \rho^\gamma$)
- CRs cool less efficiently than thermal gas
- CR pressure energizes the wind $\rightarrow$ “CR battery”
- Poloidal (“open”) field lines at wind launching site $\rightarrow$ CR-driven Parker instability
Cosmic-ray driven winds – literature

- **previous theoretical works:**

- **previous 3D simulations:**
CRs scatter on magnetic fields $\rightarrow$ isotropization of CR momenta

**CR streaming instability:** Kulsrud & Pearce 1969

- If $\nu_{cr} > \nu_A$, CR current provides steady driving force, which amplifies an Alfvén wave field in resonance with the gyroradii of CRs
- Scattering off of this wave field limits the (GeV) CRs’ bulk speed $\sim \nu_A$
- Wave damping: transfer of CR energy and momentum to the thermal gas
CRs scatter on magnetic fields → isotropization of CR momenta

**CR streaming instability:** Kulsrud & Pearce 1969

- if $v_{\text{cr}} > v_A$, CR current provides steady driving force, which 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

→ CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves
CR transport

- total CR velocity $\mathbf{v}_{\text{cr}} = \mathbf{v} + \mathbf{v}_{\text{st}} + \mathbf{v}_{\text{di}}$ (where $\mathbf{v} \equiv \mathbf{v}_{\text{gas}}$)
- CRs stream down their own pressure gradient relative to the gas, CRs diffuse in the wave frame due to pitch angle scattering by MHD waves (both transports are along the local direction of $\mathbf{B}$):

$$\mathbf{v}_{\text{st}} = -\mathbf{v}_A \frac{\nabla P_{\text{cr}}}{|\nabla P_{\text{cr}}|} \quad \text{with} \quad \mathbf{v}_A = \sqrt{\frac{B^2}{4\pi \rho}}, \quad \mathbf{v}_{\text{di}} = -\kappa_{\text{di}} \frac{\nabla P_{\text{cr}}}{P_{\text{cr}}},$$
CR transport

- total CR velocity $\mathbf{v}_{\text{cr}} = \mathbf{v} + \mathbf{v}_{\text{st}} + \mathbf{v}_{\text{di}}$ (where $\mathbf{v} \equiv \mathbf{v}_{\text{gas}}$)

- CRs stream down their own pressure gradient relative to the gas, CRs diffuse in the wave frame due to pitch angle scattering by MHD waves (both transports are along the local direction of $\mathbf{B}$):

$$\mathbf{v}_{\text{st}} = -v_A \frac{\nabla P_{\text{cr}}}{|\nabla P_{\text{cr}}|} \quad \text{with} \quad v_A = \sqrt{\frac{B^2}{4\pi \rho}}, \quad \mathbf{v}_{\text{di}} = -\kappa_{\text{di}} \frac{\mathbf{v}_{\text{st}} \cdot \nabla P_{\text{cr}}}{P_{\text{cr}}},$$

- energy equations with $\varepsilon = \varepsilon_{\text{th}} + \rho v^2/2$ (neglecting CR diffusion):

$$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot \left[ (\varepsilon + P_{\text{th}} + P_{\text{cr}}) \mathbf{v} \right] = P_{\text{cr}} \nabla \cdot \mathbf{v} + |\mathbf{v}_{\text{st}} \cdot \nabla P_{\text{cr}}|$$

$$\frac{\partial \varepsilon_{\text{cr}}}{\partial t} + \nabla \cdot (\varepsilon_{\text{cr}} \mathbf{v}) + \nabla \cdot \left[ (\varepsilon_{\text{cr}} + P_{\text{cr}}) \mathbf{v}_{\text{st}} \right] = -P_{\text{cr}} \nabla \cdot \mathbf{v} - |\mathbf{v}_{\text{st}} \cdot \nabla P_{\text{cr}}|$$
**CR transport**

- total CR velocity \( \mathbf{v}_{cr} = \mathbf{v} + \mathbf{v}_{st} + \mathbf{v}_{di} \) (where \( \mathbf{v} \equiv \mathbf{v}_{\text{gas}} \))

- CRs stream down their own pressure gradient relative to the gas, CRs diffuse in the wave frame due to pitch angle scattering by MHD waves (both transports are along the local direction of \( \mathbf{B} \)):

\[
\mathbf{v}_{st} = -v_A \frac{\nabla P_{cr}}{|\nabla P_{cr}|} \quad \text{with} \quad v_A = \sqrt{\frac{B^2}{4\pi\rho}}, \quad \mathbf{v}_{di} = -\kappa_{di} \frac{\nabla P_{cr}}{P_{cr}},
\]

- energy equations with \( \varepsilon = \varepsilon_{\text{th}} + \rho \mathbf{v}^2/2 \) (neglecting CR diffusion):

\[
\frac{\partial \varepsilon}{\partial t} + \nabla \cdot \left[ (\varepsilon + P_{\text{th}} + P_{cr}) \mathbf{v} \right] = P_{cr} \nabla \cdot \mathbf{v} + |\mathbf{v}_{st} \cdot \nabla P_{cr}|
\]

\[
\frac{\partial \varepsilon_{cr}}{\partial t} + \nabla \cdot (\varepsilon_{cr} \mathbf{v}) + \nabla \cdot \left[ (\varepsilon_{cr} + P_{cr}) \mathbf{v}_{st} \right] = -P_{cr} \nabla \cdot \mathbf{v} - |\mathbf{v}_{st} \cdot \nabla P_{cr}|
\]

\[\Longleftrightarrow \quad \frac{\partial \varepsilon_{cr}}{\partial t} + \nabla \cdot \left[ \varepsilon_{cr} (\mathbf{v} + \mathbf{v}_{st}) \right] = -P_{cr} \nabla \cdot (\mathbf{v} + \mathbf{v}_{st})\]
Cosmological moving-mesh code AREPO (Springel 2010)
Simulations – flowchart

ISM observables:
- X-ray, Hα, HI, ... emission
- Stellar spectra

Physical processes in the ISM:
- Radiative cooling
- Stellar populations
- Supernovae
- Shocks
- AGN
- Thermal energy

C.P., Enßlin, Springel (2008)
Simulations with cosmic ray physics

ISM observables:

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

Physical processes in the ISM:

- radiative cooling
- supernovae
- shocks
- AGN
- Coulomb losses

- thermal energy
- cosmic ray energy

- gain processes
- loss processes
- observables
- populations

C.P., Enßlin, Springel (2008)
Simulations with cosmic ray physics

ISM observables:
- X-ray, $H\alpha$, HI, ...
- Stellar spectra

Physical processes in the ISM:
- Thermal energy
- Radiative cooling
- Super-novae
- Shocks
- AGN
- Coulomb losses
- Cosmic ray energy
- Heat conduction
- CR streaming

C.P., Enßlin, Springel (2008)
Simulations with cosmic ray physics

ISM observables:
- X-ray, H\(\alpha\), HI, ...
- stellar spectra
- radio synchrotron
- gamma-ray emission

Physical processes in the ISM:
- thermal energy
- gain processes
- loss processes
- Coulomb losses
- AGN
- CR streaming
- shocks
- supernovae
- hadronic losses
- radiative cooling
- heat conduction

C.P., Enßlin, Springel (2008)
 Simulation setup

Pfrommer, Pakmor, Springel, in prep.

*note*: MHD + CR physics with isotropic CR diffusion
CR driven winds: density and vertical velocity

- CR pressure launches super wind that escapes from the halo
- forming disk collimates the wind into a biconical morphology with a time-varying opening angle
**CR driven winds: density and vertical velocity**

- CR pressure launches super wind that escapes from the halo
- forming disk collimates the wind into a biconical morphology with a time-varying opening angle
CR driven winds: density and vertical velocity

- CR pressure launches super wind that escapes from the halo
- forming disk collimates the wind into a biconical morphology with a time-varying opening angle
Cosmic ray driven wind: mechanism

**CR streaming:** Uhlig, C.P.+ (2012)

CR driven winds: temperature and $X_{cr} = P_{cr}/P_{th}$

- CR pressure dominates over thermal one in halo ($\gamma = 4/3$ vs. $5/3$)
- CR-induced Alfvén waves heat and energize the wind → acceleration through additional energy deposition
CR driven winds: temperature and $X_{\text{cr}} = P_{\text{cr}}/P_{\text{th}}$

- CR pressure dominates over thermal one in halo ($\gamma = 4/3$ vs. $5/3$)
- CR-induced Alfvén waves heat and energize the wind → acceleration through additional energy deposition
CR driven winds: temperature and $X_{\text{cr}} = P_{\text{cr}}/P_{\text{th}}$

CR pressure dominates over thermal one in halo ($\gamma = 4/3$ vs. $5/3$)

CR-induced Alfvén waves heat and energize the wind
→ acceleration through additional energy deposition
CR driven winds: $B$ field, face and edge-on view

- disk: magnetic shear amplification aligns $B$ with velocity field
- halo: X-shaped $B$ morphology due to time varying collimation
- narrower wind $\rightarrow$ faster outflow $\rightarrow$ lower density channel
CR driven winds: $B$ field, face and edge-on view

- disk: magnetic shear amplification aligns $B$ with velocity field
- halo: X-shaped $B$ morphology due to time varying collimation
- narrower wind $\rightarrow$ faster outflow $\rightarrow$ lower density channel
Halo $B$ field: observations vs. simulations

NGC 891, Krause (2009)
CR streaming vs. diffusion: estimates

- CRs cannot be transported faster than the Alfvén speed over macroscopic distances:

\[ V_{\text{diff}} \equiv \kappa \frac{|
abla P_{\text{cr}}|}{\varepsilon_{\text{cr}} + P_{\text{cr}}} < V_A \]

\[ \Rightarrow \text{limit on diffusion coefficient } \kappa \text{ (varies spatially and temporarily)} \]
CR driven winds: $v_A$ and $v_{\text{diff}}/v_A$

- **3 Gyr**: stationary outflow with thick CR disk $\rightarrow v_{\text{diff}}/v_A < 1$
  (using a Galactic diffusion coefficient $\kappa \approx 10^{28} \text{ cm}^2 \text{ s}^{-1}$.)

---

Christoph Pfrommer

Cosmic rays and magnetic fields in galaxies
CR driven winds: $v_A$ and $v_{\text{diff}}/v_A$

- 3 Gyr: stationary outflow with thick CR disk $\rightarrow v_{\text{diff}}/v_A < 1$
  (using a Galactic diffusion coefficient $\kappa \simeq 10^{28}$ cm$^2$ s$^{-1}$)
- $< 2$ Gyr: small CR injection regions $\rightarrow v_{\text{diff}}/v_A \gg 1$!
CR streaming vs. diffusion: estimates

- CRs cannot be transported faster than the Alfvén speed over macroscopic distances:

\[ V_{\text{diff}} \equiv \kappa \left| \nabla P_{\text{cr}} \right| \left( \frac{1}{\varepsilon_{\text{cr}} + P_{\text{cr}}} \right) ! < V_A \]

⇒ limit on diffusion coefficient \( \kappa \) (varies spatially and temporarily)
CR streaming vs. diffusion: estimates

- CRs cannot be transported faster than the Alfvén speed over macroscopic distances:
  \[ v_{\text{diff}} \equiv \kappa \frac{\nabla P_{\text{cr}}}{\varepsilon_{\text{cr}} + P_{\text{cr}}} < v_A \]
  \[ \Rightarrow \text{limit on diffusion coefficient } \kappa \text{ (varies spatially and temporarily)} \]

- what happens during CR injection at a supernova remnant?
  \[ v_{\text{diff}} \sim \frac{\kappa}{4L_{\text{cr}}} \sim 10^3 \text{ km s}^{-1} \kappa_{28} L_{\text{cr,10 pc}}^{-1} \sim 100v_A \]
CR streaming vs. diffusion: estimates

- CRs cannot be transported faster than the Alfvén speed over macroscopic distances:

\[ v_{\text{diff}} \equiv \kappa \frac{|\nabla P_{\text{cr}}|}{\varepsilon_{\text{cr}} + P_{\text{cr}}} < v_A \]

⇒ limit on diffusion coefficient \( \kappa \) (varies spatially and temporarily)

- what happens during CR injection at a supernova remnant?

\[ v_{\text{diff}} \sim \frac{\kappa}{4L_{\text{cr}}} \sim 10^3 \text{ km s}^{-1} \quad \kappa_{28}L_{\text{cr,10 pc}}^{-1} \sim 100v_A \]

⇒ flux-limited CR diffusion: prohibitively expensive because of von-Neumann-type time step constraint \( (\Delta t \propto \Delta x^2 / \kappa) \), even for implicit solvers

⇒ simulate CR streaming!
Modeling CR streaming
A challenging hyperbolic/parabolic problem

- **streaming equation** (no heating):

\[
\frac{\partial \varepsilon_{\text{cr}}}{\partial t} + \nabla \cdot \left[ (\varepsilon_{\text{cr}} + P_{\text{cr}}) \mathbf{v}_{\text{st}} \right] = 0
\]

\[
\mathbf{v}_{\text{st}} = -\text{sgn}(\mathbf{B} \cdot \nabla P_{\text{cr}}) \mathbf{v}_{\text{A}}
\]

- CR streaming \(\sim\) CR advection with the Alfvén speed

- at local extrema, CR energy can overshoot and develop unphysical oscillations

- **idea**: regularize equations, similar to adding artificial viscosity
  \(\rightarrow\) diffusive at extrema, advective at gradients
**AREPO MHD simulations of CR driven galactic winds**

**the good:** CR diffusion successfully launches super winds that

- expel a large fraction of gas from the halo
- heat the halo gas and circumgalactic medium → X-rays?
- enrich halo/circumgalactic medium with X-shaped $B$ fields
- suppress subsequent star formation
AREPO MHD simulations of CR driven galactic winds

**the good**: CR diffusion successfully launches super winds that

- expel a large fraction of gas from the halo
- heat the halo gas and circumgalactic medium $\rightarrow$ X-rays?
- enrich halo/circumgalactic medium with X-shaped $B$ fields
- suppress subsequent star formation

**the bad**: constant (Galactic) diffusivity too simplified:

- adequate for stationary outflow with thick CR disk
- fails for non-equilibrium conditions during disk formation
AREPO MHD simulations of CR driven galactic winds

the good: CR diffusion successfully launches super winds that

- expel a large fraction of gas from the halo
- heat the halo gas and circumgalactic medium $\rightarrow$ X-rays?
- enrich halo/circumgalactic medium with X-shaped $B$ fields
- suppress subsequent star formation

the bad: constant (Galactic) diffusivity too simplified:

- adequate for stationary outflow with thick CR disk
- fails for non-equilibrium conditions during disk formation

the ugly: CR streaming is a challenging hyperbolic/parabolic problem
Puzzles in galaxy formation

- Introduction
- Galactic winds
- Cooling flow problem
- Radio and $\gamma$-ray emission
- Cosmic-ray heating
- Conclusions

**Puzzles in galaxy formation**

- Dwarf galaxy
- Spiral galaxy
- Giant elliptical galaxy

- $\log(\text{stellar / halo mass})$
- $\log(\text{halo mass})$
- $20\%$ of baryons
- Active galactic nuclei
- Feedback by stellar

- Moster+ (2010)

Christoph Pfrommer

Cosmic rays and magnetic fields in galaxies
Feedback heating: M87 at radio wavelengths

\[ \nu = 1.4 \text{ GHz (Owen+ 2000)} \]

- high-\(\nu\): freshly accelerated CR electrons
- low-\(\nu\): fossil CR electrons \(\rightarrow\) time-integrated AGN feedback!
Feedback heating: M87 at radio wavelengths

- high-$\nu$: freshly accelerated CR electrons
- low-$\nu$: fossil CR electrons $\rightarrow$ time-integrated AGN feedback!
- LOFAR: same picture $\rightarrow$ puzzle of “missing fossil electrons”
- solution: electrons are fully mixed with the dense cluster gas and cooled through Coulomb interactions

$\nu = 1.4$ GHz (Owen+ 2000)

$\nu = 140$ MHz (LOFAR/de Gasperin+ 2012)
The gamma-ray picture of M87

- **high state** is time variable
  → jet emission

- **low state**:
  1. steady flux
  2. $\gamma$-ray spectral index (2.2) $\approx$ CRp index $\approx$ CRe injection index as probed by LOFAR
  3. spatial extension is under investigation (?)

→ confirming this triad would be smoking gun for first $\gamma$-ray signal from a galaxy cluster!
**AGN feedback = cosmic ray heating (?)**

**hypothesis:** low state $\gamma$-ray emission traces $\pi^0$ decay within cluster

- cosmic rays excite Alfvén waves that dissipate the energy $\rightarrow$ heating rate

$$H_{cr} = -v_{st} \cdot \nabla P_{cr}$$

(Loewenstein, Zweibel, Begelman 1991, Guo & Oh 2008, Enßlin+ 2011)

- calibrate $P_{cr}$ to $\gamma$-ray emission and $|v_{st}| = |v_A|$ to radio/X-ray emission $\rightarrow$ spatial heating profile

---

Christoph Pfrommer

Cosmic rays and magnetic fields in galaxies
AGN feedback $=$ cosmic ray heating (?)

hypothesis: low state $\gamma$-ray emission traces $\pi^0$ decay within cluster

- cosmic rays excite Alfvén waves that dissipate the energy $\rightarrow$ heating rate

$$\mathcal{H}_{\text{cr}} = - \mathbf{v}_{\text{st}} \cdot \nabla P_{\text{cr}}$$

(Loewenstein, Zweibel, Begelman 1991, Guo & Oh 2008, Enßlin+ 2011)

- calibrate $P_{\text{cr}}$ to $\gamma$-ray emission and $|\mathbf{v}_{\text{st}}| = |\mathbf{v}_A|$ to radio/X-ray emission $\rightarrow$ spatial heating profile

$\rightarrow$ cosmic-ray heating matches radiative cooling (observed in X-rays) and may solve the famous “cooling flow problem” in galaxy clusters!
Local stability analysis (1)

- isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations
Local stability analysis (1)

- isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations
Local stability analysis (1)

- Isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations
Local stability analysis (1)

- isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations
Local stability analysis (2)

Theory predicts observed temperature floor at $kT \simeq 1$ keV

\begin{align*}
X_{\text{CR}} &= 0.31 \\
X_{\text{CR}} &= 0.031
\end{align*}

C.P. (2013)
Virgo cluster cooling flow: temperature profile
X-ray observations confirm temperature floor at $kT \simeq 1 \text{ keV}$
Emerging picture of CR feedback by AGNs

(1) during buoyant rise of bubbles:
CRs diffuse and stream outward
→ CR Alfvén-wave heating

CR streaming and diffusion
CR injection by bubble disruption
turbulent advection: adiabatic compression and CR energization
CR escape and outward streaming
→ CR Alfvén-wave heating
Emerging picture of CR feedback by AGNs

(1) during buoyant rise of bubbles: CRs diffuse and stream outward → CR Alfvén-wave heating

(2) if bubbles are disrupted, CRs are injected into the ICM and caught in a turbulent downdraft that is excited by the rising bubbles → CR advection with flux-frozen field → adiabatic CR compression and energizing: $P_{cr}/P_{cr,0} = \delta^{4/3} \sim 20$ for compression factor $\delta = 10$

(3) CR escape and outward streaming → CR Alfvén-wave heating
Prediction: flattening of high-\( \nu \) radio spectrum

\begin{center}
\begin{tabular}{c c}
\hline
\textbf{frequency} \( \nu \) [MHz] & \textbf{flux density} [Jy] \\
\hline
\hline
10 & \text{radio data} \\
100 & \\
1000 & \\
10000 & \\
\hline
\end{tabular}
\end{center}

- radio data
- continuous inj.
- continuous inj., switch off
- hadronically induced emission

\[ \nu [\text{MHz}] \]
\[ \text{flux density [Jy]} \]

\text{C.P. (2013)}

\text{Christoph Pfrommer}  
\text{Cosmic rays and magnetic fields in galaxies}
Conclusions on AGN feedback by cosmic-ray heating

- LOFAR puzzle of “missing fossil electrons” solved by mixing with dense cluster gas and Coulomb cooling
- Predicted $\gamma$ rays identified with low state of M87
  $\rightarrow$ estimate CR-to-thermal pressure of $X_{cr} = 0.31$
- CR Alfvén wave heating balances radiative cooling on all scales within the radio halo ($r < 35$ kpc)
- Local thermal stability analysis predicts observed temperature floor at $kT \simeq 1$ keV

**Outlook:** simulate steaming CRs coupled to MHD, cosmological cluster simulations, improve $\gamma$-ray and radio observations . . .