LOFAR’s role in unveiling the physics of galactic winds and AGN feedback

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in collaboration with

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(cosmic ray-driven winds)

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Puzzles in galaxy formation

Driving galactic winds
AGN feedback

Puzzles in galaxy formation

Bright-end of luminosity function:
astrophysical solutions:
AGN/quasar feedback, . . .

Faint-end of luminosity function:
dark matter (DM) solutions:
warm DM, interacting DM, DM from late decays, large annihilation rates, . . .

Somerville+1999 astrophysical solutions:
preventing gas from falling into DM potential wells:
increasing entropy by reionization, blazar heating . . .

preventing gas from forming stars in galaxies:
suppress cooling (photoionization, low metallicities), . . .
pushing gas out of galaxies:
supernova/quasar feedback → galactic winds

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Puzzles in galaxy formation

Bright-end of luminosity function:

- astrophysical solutions: AGN/quasar feedback, ...

Somerville+1999
Puzzles in galaxy formation

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Somerville+1999

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Puzzles in galaxy formation

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- astrophysical solutions:
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  preventing gas from forming stars in galaxies:
    suppress cooling (photoionization, low metallicities), ... 
  pushing gas out of galaxies:
    supernova/quasar feedback $\rightarrow$ galactic winds
Galactic super wind in M82

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Galactic wind in the Milky Way?
Diffuse X-ray emission in our galaxy

Snowden et al., 2007
Galactic wind in the Milky Way?
Fermi gamma-ray bubbles

Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.
How to drive a wind?

- **standard picture:** wind driven by thermal pressure
- **energy sources for winds:** supernovae, AGN
- **problem with the standard picture:** fast radiative cooling
- **alternative channels:**
  - radiation pressure on dust grains
  - cosmic rays (CRs, relativistic protons with $\gamma_{ad} = 4/3$)
Radio halos in edge-on disk galaxies
CRs and magnetic fields exist at the disk-halo interface → wind launching site?

why are CRs important for wind formation?

- CR pressure drops less quickly than thermal pressure \((P \propto \rho^\gamma)\)
- CRs cool less efficiently than thermal gas
- most CR energy loss goes into thermal pressure

Tüllmann+ (2000)
Interactions of CRs and magnetic fields

- CRs scatter on magnetic fields $\rightarrow$ isotropization of CR momenta

- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{cr} > v_{waves}$ with respect to the gas, CR excite Alfvén waves
  - scattering off this wave field limits the CRs’ bulk speed $\ll c$
  - wave damping: transfer of CR energy and momentum to the thermal gas
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$\rightarrow$ CRs exert a pressure on the thermal gas by means of scattering off Alfvén waves
Interstellar medium (ISM) simulations – flowchart

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

Physical processes in the ISM:
- radiative cooling
- thermal energy
- supernovae
- shocks
- AGN

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

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

Physical processes in the ISM: thermal energy, radiative cooling, shocks, supernovae, AGN, Coulomb losses, cosmic ray energy

C.P., Enßlin, Springel (2008)

LOFAR's role for galactic winds and AGN feedback
ISM simulations with extended cosmic ray physics

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

Physical processes in the ISM:
- radiative cooling
- supernovae
- shocks
- AGN
- Coulomb losses
- CR streaming

Energy flow:
- thermal energy
- cosmic ray energy

C.P., Enßlin, Springel (2008)
ISM observables:

- X-ray, Hα, HI, ... emission
- Stellar spectra
- Radio synchrotron
- Gamma-ray emission

Physical processes in the ISM:

- Radiative cooling
- Stellar populations
- Super-novae
- Shocks
- AGN
- Coulomb losses
- Cosmic ray energy
- Heat conduction
- CR streaming

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


*Galactic winds driven by cosmic-ray streaming*
CR streaming drives winds

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Gas mass loss within the virial radius

- after initial phase (∼ 2.5 Gyr), only winds driven by CR streaming overcome the ram pressure of infalling gas and expel gas from the halo
- mass loss rate increases with CR injection efficiency $\zeta_{\text{SN}}$ (left) and towards smaller galaxy masses (right)
Mass loss and star formation histories

For a $10^9 h^{-1} M_\odot$ halo:

- no CRs
- streaming ($\zeta_{SN} = 0.3$)
- streaming ($\zeta_{SN} = 0.1$)
- advection only ($\zeta_{SN} = 0.3$)
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Puzzles in galaxy formation
Driving galactic winds
Mass loss and star formation
AGN feedback
Cosmic-ray heating

Temperature structure

- Halo temperatures scale as $kT \propto v_{\text{wind}}^2 \sim v_{\text{esc}}^2$
- $10^9 \rightarrow 10^{10} M_\odot$: transition of isotropic to bi-conical wind; in these cones, CR wave heating overcomes radiative cooling
- $10^{10} \rightarrow 10^{11} M_\odot$: broadening of hot temperature structure due to inability of CR streaming to drive a sustained wind; instead, fountain flows drive turbulence, thereby heating larger regions

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Gas temperature: simulation \((10^{10} \, M_\odot)\) vs. observation

\(t = 4.9\) Gyr, streaming

M82

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CR-driven winds: analytics versus simulations
Wind speeds and mass loading factors

- Winds speeds increase with galaxy mass as $v_{\text{wind}} \propto v_{\text{circ}} \propto M_{200}^{1/3}$ until they cutoff around $10^{11} \, M_{\odot}$ due to a fixed wind base height (set by radiative physics).

- Mass loading factor $\eta = \dot{M}/\text{SFR}$ decreases with galaxy mass.
Conclusions on cosmic-ray driven winds in galaxies

- galactic winds are naturally explained by CR streaming (energy source, known plasma physics, observed scaling relations)
- CR streaming heating can explain observed hot wind regions above disks
- substantial mass losses of low mass galaxies → opportunity for understanding the physics at the faint end of galaxy luminosity function

outlook: MHD simulations, better understanding of plasma physics, cosmological settings, ...
Messier 87 at radio wavelengths

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

- **expectation:** low frequencies sensitive to fossil electrons 
  \((E \sim 100 \text{ MeV}) \rightarrow \) time-integrated activity of AGN feedback!
Messier 87 at radio wavelengths

- *Observations of M87*
  - Cosmic-ray heating
  - Conclusions

- **Puzzles in galaxy formation**
  - Driving galactic winds
  - AGN feedback

- **Messier 87 at radio wavelengths**

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

  \( \nu = 140 \text{ MHz (LOFAR/de Gasperin+ 2012)} \)

- **expectation:** low frequencies sensitive to fossil electrons \( (E \sim 100 \text{ MeV}) \) → time-integrated activity of AGN feedback!

- **LOFAR:** halo confined to same region at all frequencies and no low-\( \nu \) spectral steepening → puzzle of “missing fossil electrons”
solutions:

- special time: M87 turned on
  \sim 40 \text{ Myr ago} after long silence
  \iff conflict order unity duty cycle inferred from stat. AGN feedback studies (Birzan+ 2012)
Solutions to the “missing fossil electrons” problem

solutions:

- special time: M87 turned on \( \sim 40 \) Myr ago after long silence
  \( \Leftrightarrow \) conflicts order unity duty cycle inferred from stat. AGN feedback studies (Birzan+ 2012)

- Coulomb cooling removes fossil electrons
  \( \Rightarrow \) efficient mixing of CR electrons and protons with dense cluster gas
  \( \Rightarrow \) predicts \( \gamma \) rays from CRp-p interactions

\[
p = \frac{\tilde{p}}{m_e c}
\]

\[
\tau = \frac{E}{\dot{E}} \text{[Myr]}
\]

\[
B = 10 \mu G \\
B = 20 \mu G
\]

C.P. (2013)
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)
    $= \text{CRp index}$
    $= \text{CRe injection index as probed by LOFAR}$
  (3) spatial extension is under investigation (?)

→ confirming this triad would be smoking gun for first $\gamma$-ray signal from a galaxy cluster!

Rieger & Aharonian (2012)
Estimating the CR pressure in M87

- X-ray data $\rightarrow n$ and $T$ profiles
- assume $X_{cr} = P_{cr}/P_{th}$ (self-consistency requirement)
- $F_{\gamma} \propto \int dV P_{cr} n$ enables to estimate $X_{cr} = 0.31$
  (allowing for Coulomb cooling with $\tau_{Coul} = 40$ Myr)

$\rightarrow$ in agreement with non-thermal pressure constraints from dynamical potential estimates (Churazov+ 2010)
Cosmic-ray heating vs. radiative cooling (1)

**CR Alfvén-wave heating:**

\[ H_{cr} = -v_A \cdot \nabla P_{cr} = -v_A \left( X_{cr} \nabla_r \langle P_{th} \rangle \Omega + \frac{\delta P_{cr}}{\delta l} \right) \]

- Alfvén velocity \( v_A = B/\sqrt{4\pi \rho} \) with \( B \sim B_{eq} \) from LOFAR and \( \rho \) from X-ray data
- \( X_{cr} \) calibrated to \( \gamma \) rays
- \( P_{th} \) from X-ray data
- Pressure fluctuations \( \delta P_{cr}/\delta l \) (e.g., due to weak shocks of \( \mathcal{M} \sim 1.1 \))
Cosmic-ray heating vs. radiative cooling (1)

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**Radiative cooling:**

\[ C_{\text{rad}} = n_e n_t \Lambda_{\text{cool}}(T, Z) \]

- cooling function \( \Lambda_{\text{cool}} \) with \( Z \sim Z_\odot \),
  all quantities determined from X-ray data
Cosmic-ray heating vs. radiative cooling (2)

Global thermal equilibrium on all scales in M87

- \( C_{\text{rad}}, H_{\text{CR}} \) [ergs cm\(^{-3}\) s\(^{-1}\)]
- \( H_{\text{CR}}, P_{\text{smooth}} + \delta P \)
- \( H_{\text{CR}}, P_{\text{smooth}} \)
- \( C_{\text{rad}}(0.7 \ Z_\odot \lesssim Z \lesssim 1.3 \ Z_\odot) \)

Radial extent of radio halo:

\[ 10^{-28}, 10^{-27}, 10^{-26}, 10^{-25} \]
isobaric perturbations to global thermal equilibrium
CRs are adiabatically trapped by perturbations
Local stability analysis (1)

- isobaric perturbations to global thermal equilibrium
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- 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
improve statistics: observe other AGNs, which are interacting with cooling cluster gas

improve magnetic field estimates: Faraday rotation studies (M87 and others)

detailed spectral flow modeling: understanding prevailing core dynamics and electron aging
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
- local thermal stability analysis predicts observed temperature floor at $kT \simeq 1$ keV

outlook: simulate steaming CRs coupled to MHD, cosmological cluster simulations, ...
Cosmic ray-driven winds in galaxies:


AGN feedback by cosmic rays:

Additional slides
Critical length scale of the instability

\[ \lambda_{\text{crit}} = r \]

unstable wavelength larger than system

thermally unstable

stabilized by CR streaming

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CR streaming (1)

- total CR velocity $v_{cr} = v_{gas} + v_{st}$
- CRs stream down their own pressure gradient relative to the gas:
  \[ v_{st} = -\lambda c_s \frac{\nabla P_{cr}}{|\nabla P_{cr}|} \]

- CR transport equation $\rightarrow$ evolution equation for CR number and energy density:
  \[
  \frac{\partial n_{cr}}{\partial t} = -\nabla \cdot \left[ (v_{gas} + v_{st}) n_{cr} \right]
  \\
  \frac{\partial \varepsilon_{cr}}{\partial t} = (v_{gas} + v_{st}) \cdot \nabla P_{cr} - \nabla \cdot \left[ (v_{gas} + v_{st}) (\varepsilon_{cr} + P_{cr}) \right]
  \]
CR streaming (2)

- Lagrangian time derivative
  \[
  \frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{v}_{\text{gas}} \cdot \nabla
  \]

- specific CR energy, \( \tilde{\varepsilon}_{\text{cr}} \), and CR particle number, \( \tilde{n}_{\text{cr}} \),
  \[
  \varepsilon_{\text{cr}} = \tilde{\varepsilon}_{\text{cr}} \rho \quad \text{and} \quad n_{\text{cr}} = \tilde{n}_{\text{cr}} \rho
  \]

- CR evolution equations:
  \[
  \rho \frac{d\tilde{n}_{\text{cr}}}{dt} = -\nabla \cdot [\mathbf{v}_{\text{st}} \rho \tilde{n}_{\text{cr}}]
  \]
  \[
  \rho \frac{d\tilde{\varepsilon}_{\text{cr}}}{dt} = \mathbf{v}_{\text{st}} \cdot \nabla P_{\text{cr}} - P_{\text{cr}} \mathbf{v}_{\text{gas}} - \nabla \cdot [\mathbf{v}_{\text{st}} (\rho \tilde{\varepsilon}_{\text{cr}} + P_{\text{cr}})]
  \]
  - energy loss term (wave damping)
  - adiabatic changes due to converging/diverging gas flow
  - energy change due to CR streaming in/out of a volume element
Test: Gadget-2 versus 1-d grid solver
Evolution of the specific CR energy due to streaming in a medium at rest

Uhlig+2012
Resolution study

- our results winds driven by CR streaming are converged with respect to particle resolution \((\text{left})\) and time step of the explicit streaming solver \((\text{right})\)