ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany

37th International
Cosmic Ray Conference
12–23 July 2021

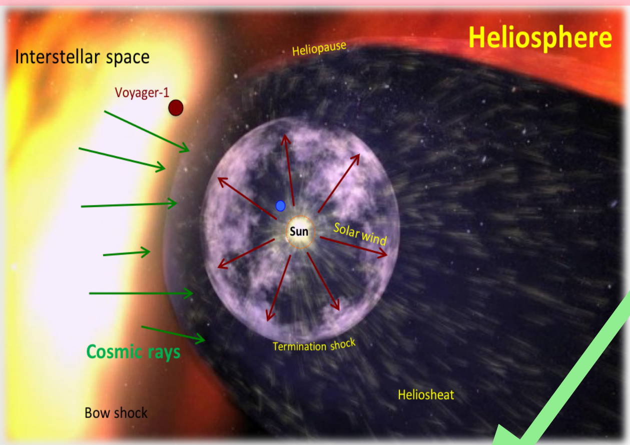
Cosmic Rays and the ISM

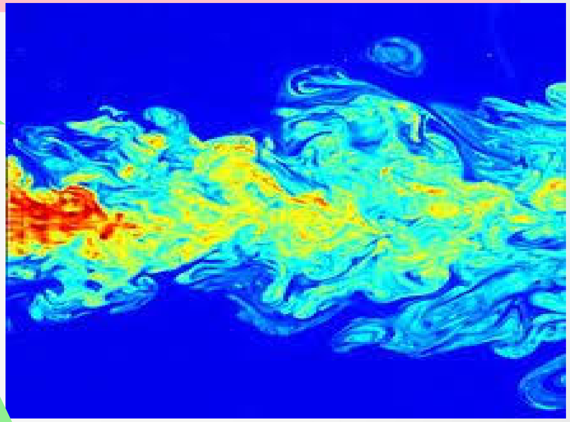
Session 14

Conveners: S. Recchia, P. Serpico and G. Giacinti

Cosmic rays are active players

CRs shape any possible aspect of their life and their environment, from sources up to their travel toward the intergalactic spaces





Cosmic rays are active players

CRs affect their own life...

- **Excitation of plasma instabilities - acceleration**
  - confinement in the accelerator
  - maximum energy
  - injection...

- **Excitation of plasma instabilities - escape the accelerator**
  - how accelerated particles becomes CRs
  - self-confinement in the source region
  - suppressed diffusion, source grammage...

Cosmic rays are active players

CRs affect their own life...

- **Excitation of plasma instabilities - galactic propagation**
  - ✗ what is the CR Galactic diffusion coefficient?
  - ✗ how do CRs escape galaxies?
  - ✗ ...

- **Coupling with the ISM - galactic propagation**
  - ✗ advect with self-generated Alfvén waves
  - ✗ advect with CR-induced winds
  - ✗ ...

Cosmic rays are active players

CRs affect the ISM at many scales

CR-Induced magnetic instabilities
CR coupling with the ISM

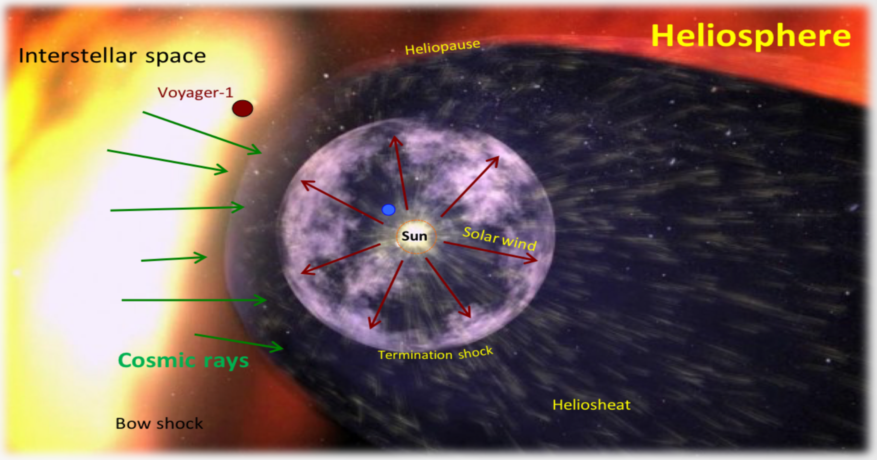
- shaping B field at different scales
- modify the acceleration sites - CR-modified shocks
- CR bubbles around sources
- dynamics and chemistry of molecular clouds
- outflows and feedback on star formation
- feedback on galactic evolution
- ...

Cosmic rays are active players

CRs affect the ISM at many scales

CR locality

- local bubble
- nearby SNRs, ^{60}Fe
- Voyager, CR composition
- nearby PeVatron?
- life on Earth
- space travels
- ...



Cosmic ray-induced instabilities and implications

Mohamad Shalaby
Benedikt Schroer
Sarah Recchia

CR-induced instabilities - implications

Sources of CR scattering in the ISM...

- **CR scattered by "resonant" magnetic inhomogeneities** $k \sim 1/R_L$
- **Alfvénic turbulence**
  - injected on large scales (~10-100 pc)
  - cascade to resonant scale
  - problem with anisotropic cascade [Goldreich & Sridhar 1995]
  - not able to scatter CRs?
- **Other...**
  - compressible MHD turbulence [Lazarian, several works]
  - magnetic mirroring by clouds [Chandran 2000]
  - ... [Evoli & Yan 2014] [Fornieri et al. 2021]

CR-induced instabilities - implications

Self-generated turbulence - active role of CRs

- **Streaming CRs can excite plasma (Alfvénic) turbulence**

- **CR gradient**
  - resonant streaming instability $k \sim 1/R_L$
  - transfer momentum to waves
- **CR current**
  - non-resonant instability **[Bell 2004]**
  - waves on scales $<< R_L$
  - grow to $\approx R_L$
- **Wave damping**
  - Ion-neutral friction
  - Turbulent damping (pre-existing Alfvénic turbulence)
  - Non-linear dampings
  - ...

Galactic CR propagation
Confinement in the source region

CR acceleration
Confinement in the source region
escape from galaxies ...

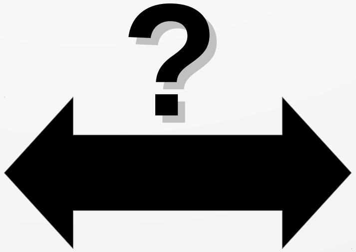
CR-induced instabilities - implications

CR escape from sources - a challenging problem

- a self consistent theory of acceleration and escape is missing
  - active role of CRs - non linearity
  - broad range of spatial scales and propagation regimes involved
  - difficult with simulations
  - CR source grammage

SOURCE

- strong B amplif. $\delta B \sim B_0$
- Bohm diffusion $\lambda \sim R_L$
- $P_{CR} > P_B$



ISM

- $\delta B \ll B_0$
- $\lambda \gg R_L$
- $P_{CR} \sim P_B$

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

A New Cosmic-Ray-driven Instability

Mohamad Shalaby

- CR strongly couple via kinetic instabilities

- New instability:
  - much higher rate
  - new CR transport
  - can't be suppressed by ion-neutral friction (damping)
  - potential role in the ionization of molecular clouds by MeV CRs

- CR impact/regulate galactic outows and ISM chemistry

- CR transport mode strongly impact CGM gas and magnetic field distribution

ONLINE ICRC 2021 THE ASTROPARTICLE PHYSICS CONFERENCE Berlin | Germany
37th International Cosmic Ray Conference 12–23 July 2021

Tracing the origin of low diffusivity and CR bubbles around sources

Benedikt Schroer, O. Pezzi, D. Caprioli, C. Haggerty and P. Blasi

- CRs leave their sources mainly along the local magnetic field present in the region around the source and in doing so they excite both resonant and non-resonant modes through streaming instabilities. The excitation of these modes leads to enhanced particle scattering and in turn to a large pressure gradient that causes the formation of expanding bubbles of gas and self-generated magnetic fields.

- By means of hybrid particle-in-cell simulations, we demonstrate that, by exciting this instability, CRs excavate a cavity around their source where the diffusivity is strongly suppressed.

- This phenomenon is general and is expected to occur around any sufficiently powerful CR source in the Galaxy. Our results are consistent with recent gamma-ray observations where emission from the region around supernova remnants and stellar clusters have been used to infer that the diffusion coefficient around these sources is ~10-100 times smaller than the typical Galactic one.

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

Damping of Alfvén waves in a partially ionized medium and the grammage of CRs in the proximity of supernova remnants

S.Recchia, D. Galli, L. Nava, M. Padovani, S. Gabici, A. Marcowith, V. Ptuskin, G. Morlino

- We investigate the escape of CRs from supernova remnants embedded in a partially ionized medium and the self-confinement in the source region, as due to the CR streaming instability.

- If self-confinement is effective, a sizable fraction of the CR grammage could be produced in the source region rather than in the whole time spent by CRs in the Galactic disk, as typically assumed. This would have important implications for the interpretation of quantities such as the B/C ratio, and would require a profound modification of the current paradigm of the Galactic CR transport.

- We solve the 1D CR and Alfvén wave transport equation in the source proximity, taking into account the generation of waves by resonant streaming instability and various damping processes, most notably ion-neutral friction. From that, we estimate the moment of escape of CRs of a given energy from a SNR, their residence time in a region of ~ 100pc around the source, and the corresponding grammage.

- We find that, for the typical environment met in the WNM and WIM phases of the ISM, ion-neutral friction limits the effect of self-confinement and the resulting CR source grammage is negligible compared to that inferred from observations, contrary to what was previously suggested in the literature.

Cosmic ray interaction with the ISM and with molecular clouds

Ellis Owen
Chad Bustard

CR interaction with the ISM and MCs

CRs are the main ionization agents of MC
… effects on cloud collapse (and star formation)

- How do CRs penetrate into clouds? **[Phan et al. 2018]**
- How do CRs propagate between and within clouds?
- Role of self-generated turbulence at the borders and within clouds, and role of damping (ion-neutral friction)
- Dynamical and chemical impact of CRs on clouds
- gamma-ray observations

CRs transport in the complex, multi-phase ISM

- diffusion?
- magnetic mirroring ? **[Chandran, 2000]**
- turbulent reacceleration

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

Empirical assessment of cosmic ray propagation in magnetised molecular cloud complexes

Ellis Owen, A.Y.L. On, S.P. Lai and K. Wu

- This poster introduces a method to empirically estimate the diffusion coefficient of cosmic rays propagating through molecular cloud complexes, using polarized optical and near infra-red observations.

- We apply this method to the IC 5146 Galactic molecular cloud complex, and use the resulting empirical diffusion coefficient to compute the distribution of cosmic rays and their impacts through the IC 5146 filaments.

- We find that cosmic rays can drive ionization in the dense filaments of this system, but their heating power is inconsequential. We further consider the effect of cosmic ray irradiation levels that would be comparable to those inferred for nearby starburst galaxies.

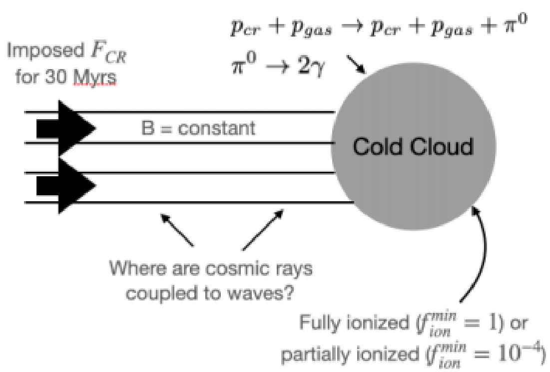
- We conclude that cosmic rays could drive a strong heating power and significantly raise the Jeans' masses of filaments in the molecular cloud complexes of starburst galaxies, where they could moderate or suppress ongoing star-formation or distort the local stellar initial mass function.

Cosmic Ray Transport, Energy Loss, and Influence in the Multiphase ISM

Chad Bustard (Kavli Institute for Theoretical Physics), Ellen G. Zweibel (University of Wisconsin-Madison)
Reference: Bustard and Zweibel 2021, ApJ 913, 106 (https://arxiv.org/abs/2012.06585)

Why is this important:

- Focused, high-resolution simulations are needed to understand how cosmic rays navigate and influence small-scale, multiphase gas structures under-resolved in galaxy-scale simulations.



What we do:

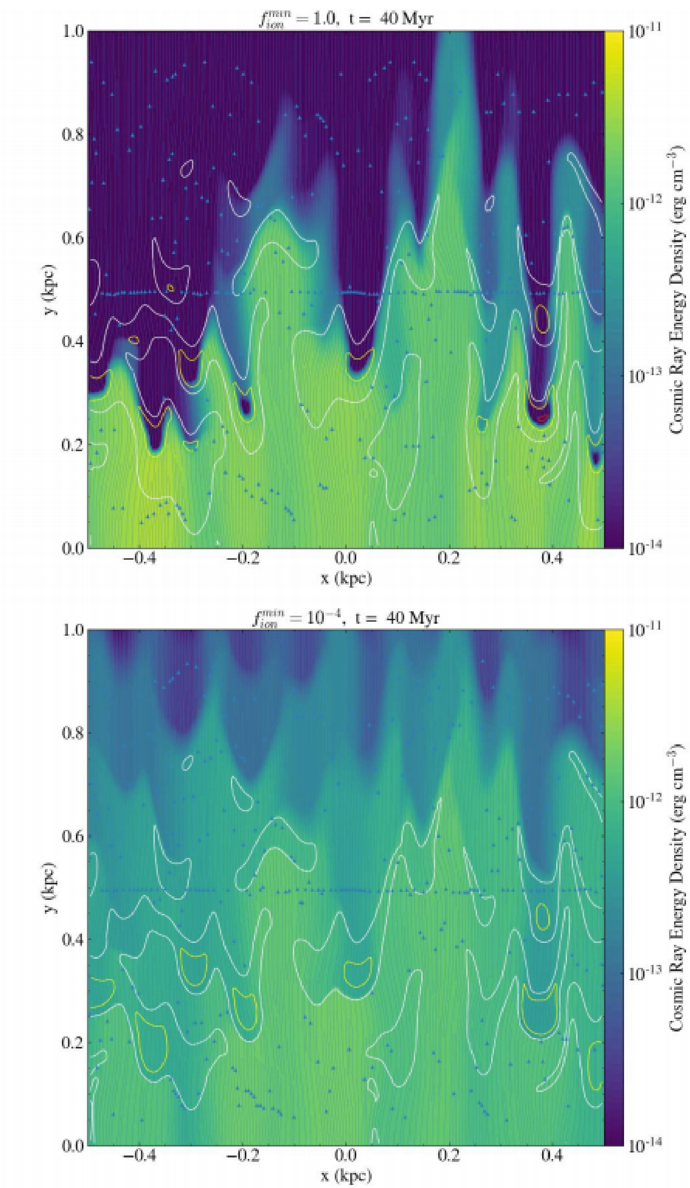
- We use MHD+CR simulations to probe cosmic ray interactions with individual cold clouds and series of clumps, taking into account fast cosmic ray transport in partially neutral gas — "ionization-dependent transport."

Some results:

- Cosmic ray momentum and energy transfer are concentrated at cloud interfaces for partially neutral clouds; variations in Alfven speed induce cosmic ray "bottlenecks" that allow cosmic ray pressure gradients to form and accelerate the clouds. Bottlenecks at partially neutral clouds are only well-captured if the cloud interface is well-resolved — a condition unlikely to be satisfied in large-scale simulations.

- There are clear spatial differences in gamma-ray emission if ionization-dependent transport is included or neglected, but the total gamma-ray luminosity is, interestingly, largely unchanged.

- Weak magnetic fields are easily influence by pressure perturbations, and field line draping around cold clouds funnels cosmic rays through the intercloud medium, rather than into cold clouds. This has implications for the acceleration of cold clouds in galactic winds that we plan to study further.



Turbulent Reacceleration of Streaming Cosmic Rays: Fluid Simulations

Chad Bustard (Kavli Institute for Theoretical Physics), S. Peng Oh (University of California - Santa Barbara)

Why is this important:

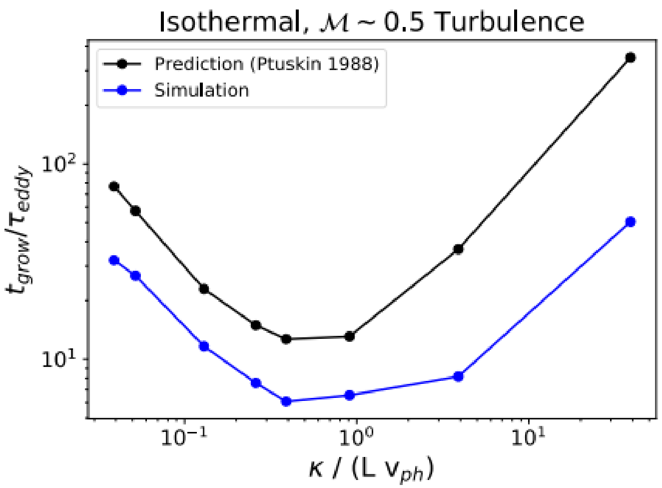
- While frequently invoked to explain primary-to-secondary ratios at ~GeV energies, the physical underpinnings of reacceleration for self-confined (E < 300 GeV) cosmic rays are unclear: resonant reacceleration fails because cosmic rays only co-move with forward waves excited through the streaming instability (both forward and background waves are required for reacceleration). *Non-resonant reacceleration of streaming cosmic rays has not been explored.*

What we do:

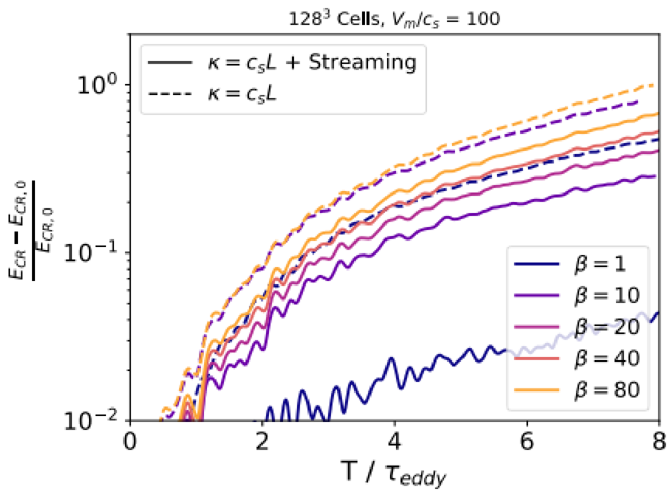
- We estimate the non-resonant reacceleration rate for streaming cosmic rays in subsonic, compressive turbulence, and we run Athena++ MHD simulations with driven turbulence to confirm our results

Some results:

- Non-resonant reacceleration of streaming CRs is greatly stunted by streaming energy loss
- Canonical equations for reacceleration rates should be significantly modified for E < 300 GeV (self-confined CRs)



Simulations with pure diffusion (no streaming) recover analytic growth rates *(Ptuskin 1988)* within a factor of 2, at least with $\kappa \lessapprox \kappa_{crit}$



Adding in streaming, even with $\kappa = \kappa_{crit}$, gives slow growth unless β is large

$$\frac{\partial E_{cr}}{\partial t} \sim -v \cdot \nabla P_{cr} + v_A \cdot \nabla P_{cr}$$

$$\frac{t_{grow,crit}}{t_{loss}} \sim \frac{1}{\sqrt{\beta} M_s^2}$$

↓

Unless $\beta \gg 1$, energy loss prevails over energy gain from subsonic turbulence

Cosmic ray feedback in galaxies

Thimon Thomas
Philipp Girichidis
Roland Crocker

CR feedback in galaxies

CRs coupled to ISM through (CR-generated) turbulence
… exchange of momentum and energy

- help launch galactic winds
- expel material from disks
- formation of galactic halos
- contribute to galactic evolution
- regulate star formation

non-linearity and some (open) problems...

- CR feedback is a non-linear problem
- include self-consistently the CR transport in outflow models
- self-generated advection and diffusion
- production of secondaries? Observed spectra?

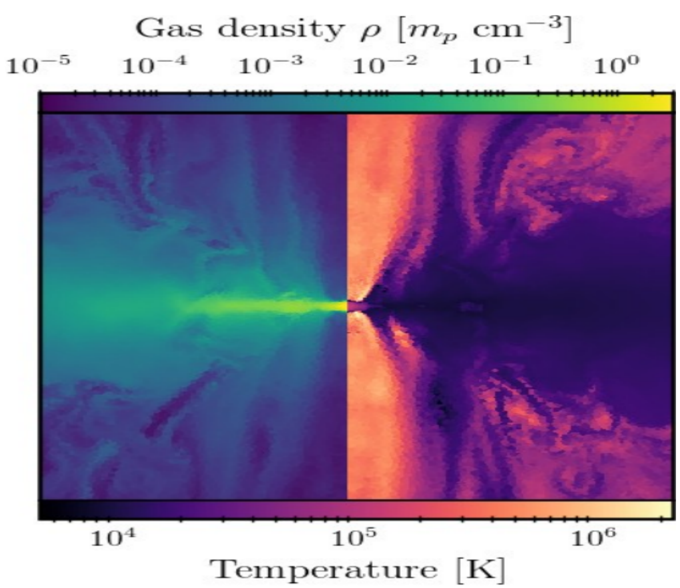
Cosmic ray transport and feedback in galaxies

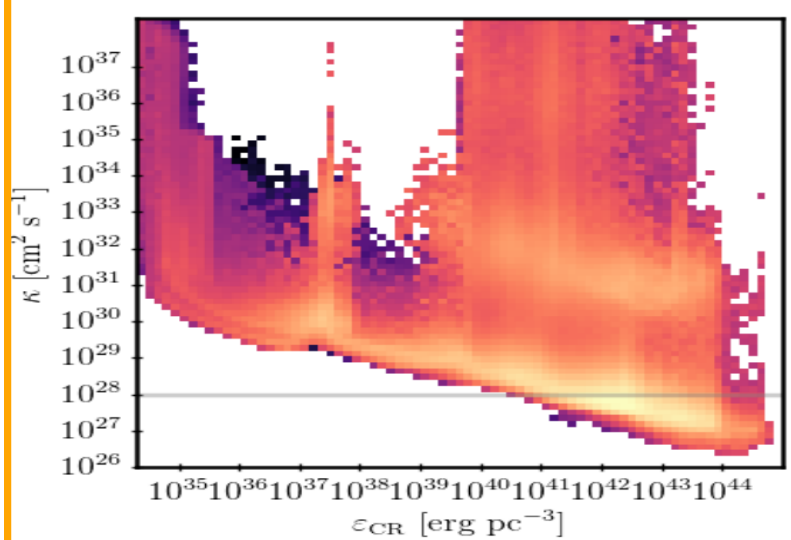
Thimon Thomas, C. Pfrommer and R. Pakmor

- We present the first of its kind galaxy formation simulation of a halo $M = 10^{11} M_{\odot}$ including two-moment CR hydrodynamics that consistently models the interaction between GeV CRs and gyroresonant Alfvén waves through the streaming instability.

- Star formation and CRs drive a powerful and turbulent galactic wind in the simulation with a resulting interesting spatio-temporal behaviour of CRs and Alfvén waves, e.g., with regions that are of devoid of Alfvén waves and a have high CR diffusion coefficient.

- A statistical evaluation of the realized GeV CRs propagation shows that it cannot be described by steady-state CR transport model (advection, diffusion, and/or streaming).





The CR diffusion coefficient has values k = 10^{27}-10^{29} cm^2/s with mass-weighted harmonic mean k = 10^{28} cm^2/s

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

Spectrally resolved cosmic rays in galaxy simulations

Philipp Girichidis

- We investigate the dynamical impact of CRs on the evolution of galaxies, in particular the star formation rate, the shape of the disc and the CR-driven outflows.
- The impact of CRs is highly relevant for the star formation history of galaxies and the mass loss due to winds and outflows. In order to explain the observed outflow properties and the low overall efficiency of star formation is a closely connected to CRs.
- We include CRs into magneto-hydrodynamical simulations by dynamically coupling them to the thermal and magnetic gas self-consistently. We include spectrally resolved CRs from 10 MeV up to TeV in the advection-diffusion approximation. The full spectrum in every computational cell allows us to accurately account for CR cooling and compute the CR pressure impact precisely. The energy-dependent diffusion can be properly addressed by varying diffusion coefficients.
- Our simulations show that spectrally resolved CRs reduce the star formation rate and at the same time increase the outflow rate from star forming regions in the galaxy. The spectral analysis shows that mainly the energy regime between 10 and 30 GeV drives galactic outflows.

Cosmic ray feedback across the sequence of star-forming galaxies

Roland M. Crocker and M. Krumholz

- The importance of cosmic rays as an agent of feedback in galaxies that form stars (like the Milky Way).

- The universe turns gas into stars with low efficiency. Exactly why this is remains somewhat contentious. We show that in galaxies like the Milky Way, cosmic rays provide at least part of the answer to the origin of this low efficiency.

- Introduced a model for how cosmic ray transport works in dense, partially- ionised, but largely neutral, star-forming gas; used this understanding of cosmic ray transport in a numerical investigation of the circumstances under which star-forming gas will be rendered unstable because of cosmic rays.

- Modern, star-forming galaxies like the Milky Way and nearby dwarfs are shown to inhabit a region of parameter space that means that they sit at the cusp of cosmic ray- driven instability; they cannot sustain much high star formation rate surface densities without their gas columns becoming unstable. In contrast, gas rich systems like starbursts – while gamma-ray bright – are not cosmic ray unstable – because hadronic losses render the cosmic ray pressure small in comparison with other ISM constituents.

Accelerating sources: non-linearity, observational constraints and locality

Jiro Shimoda
Nicolò Masi
Pierre Cristofari

Sources: non-linearity & constraints

CR acceleration at shocks (SNRs…)
… DSA and non-linear versions

- what is the maximum energy?
- how efficient is the acceleration?
- … the two questions are connected
- acceleration is typically a non-linear process
- CR-induced instabilities play a major role

# of PeVatrons?

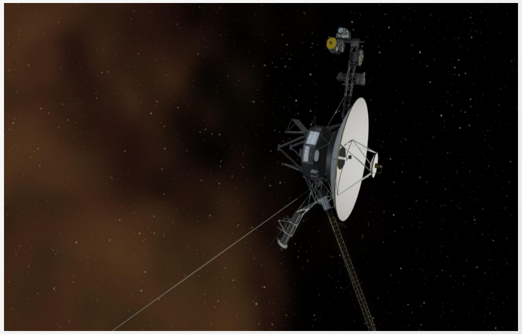
“Feedback” on the accelerator

- CR-modified shocks are predicted for efficient CR acceleration
- shock modification affect the CR spectrum and maximum energy
- … observation of shock modification?

Sources: local ISM and observations

Short-lived CR particles should come from neardy sources and mostly probe the local ISM conditions

- sub-GeV CRs
- multi-TeV leptons
- … unstable isotopes
- specific local source (spatial and temporal) distribution matters
- … stocasticity & anisotropies **[Session 06, Session 45]**



- Voyager data - outside solar system
- local bubble
- … recent nearby sources?

[^{60}Fe, Knie et al. 2004, Wallner et al. 2019]

[Local stellar cluster Breitschwerdt et al. 2016]

Powerful Diagnostics of Cosmic-Ray Modified Shock by Hα Polarimetry

Jiro Shimoda and J. Martin Laming

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

- Cosmic-Ray Modified Shocks (CRMSs) are one of an essential prediction of the diffusive shock acceleration.
- We must examine a velocity modification of plasma with ~ 10 % level around the SNR shock.
- The polarization direction of Hα responds sensitively whether the shock is modified.

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

Studying the low-energy excess in cosmic-ray iron: a possible evidence of a massive supernova activity in the solar neighborhood via primary 60Fe

Nicolò Masi et al.

- Since its launch the Alpha Magnetic Spectrometer-02 has delivered outstanding quality measurements of the spectra of cosmic-ray.
- The analysis of new iron spectrum by AMS-02 within the GALPROP–HELMOD framework, together with Voyager-1 and ACE-CRIS data, provided an updated local interstellar spectrum in the energy range from 1 MeV/n to 10 TeV/n: it revealed an unexpected bump both in iron and in the Fe/He, Fe/O and Fe/Si ratios at 1–3 GV.
- This was the first time such an excess was found in the spectrum of an element that is dominated by stable species: it will be fundamental to measure the spectra of other heavy CR species to see if a similar spectral feature is present.
- The new-found excess in the Fe spectrum around 2 GV is falling in line with other excesses in iron rare isotope ^{60}Fe, which is likely connected to the past SN activity in the Local Bubble.
- Starting from this LIS and the ^{60}Fe/^{56}Fe abundance measured by ACE-CRIS, 60Fe primary component was estimated, along with the prediction of the important SubFe/Fe ratio.
- To further constrain the ^{60}Fe yield from SNe and interpret the 1.5 ÷ 3 Myr ago progenitor event, it will be useful to study the possible associate production of the long-lived radioactive ^{26}Al isotope.

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

The low number of SNR pevatrons in the Galaxy

Pierre Cristofari, P. Blasi and E. Amato

- **What is this contribution about?**
  SNR pevatrons.

- **Why is it relevant / interesting?**
  Everybody searches for PeVatrons! Looking for sources of CRs...

- **What have we done?**
  We calculated (analytical) the spectrum of protons from SNe after propagation in the Galaxy (type Ia, II, and very energetic) and confront to the local spectrum of CRs.

- **What is the result?**
  The number of SNR PeVatron in the Galaxy should be limited (\sim 1% of 3/century), thus maybe we'll never see an active SNR PeVatron in gamma rays and that's ok...

Let's discuss…