The Physics of Cosmic Rays

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Galaxies are Pervaded by Magnetic Fields & Relativistic Particles

Synchrotron radiation from M51 (MPIfR/NRAO)

Galactic molecular clouds illuminated by $\gamma$-rays H.E.S.S. collaboration
How is Energy Partitioned Between Gas, Magnetic Fields, and Cosmic Rays?

- How do $< 10^{-9}$ of interstellar particles acquire as much energy as the background gas?

- What controls the cosmic ray energy spectrum and composition?

- How do cosmic rays couple thermally and dynamically to the background gas despite being virtually collisionless?

- How do cosmic rays regulate the extreme environments in which they are accelerated?
The Plan of This Talk

• Brief review of cosmic ray properties
• Cosmic ray hydrodynamics & applications
  – Galactic winds
  – Heating interstellar gas
• The lab connection
• Future opportunities


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Some Early Milestones in Cosmic Ray Astrophysics

• **1912** Hess shows the cosmic origin of atmosphere ionization.

• **1927** Clay shows the ionizing flux is latitude dependent, suggesting that “cosmic rays” are charged particles, deflected by the geomagnetic field.

• **1934** Baade & Zwicky propose that cosmic rays originate in supernovae.

• **1949** Hall & Hiltner detect a pervasive Galactic magnetic field through its effect on starlight polarization.

• **1949** E. Fermi proposes his theory of cosmic ray acceleration
Energy Spectrum

• A broken power law:
  \[ N(E) \sim E^{-2.7}, \ 3 < E_{\text{PeV}} < 3 \]
  \[ \sim E^{-3.0}, \ 3 < E_{\text{PeV}} < 100 \]

• Strong solar cycle modulation below \(~ 10 \text{ GeV}\)

• Energy density \(~ 1 \text{ eV cm}^{-3}\), near equipartition with magnetic & thermal/turbulent energy density of interstellar gas.

• Most of the pressure comes from \(~ \text{GeV}\) particles
(An)Isotropy

Left: The distribution of cosmic ray arrival directions is highly isotropic, up to the knee.
Right: Weak fluctuations at TeV energies have been discovered recently & challenge theory.

Hillas 1984

Abbasi et al. 2010
Composition and Lifetime

- Mostly protons
  - Heavier nuclei may dominate at higher energies
- Electrons ~1-2% by number
- Elemental composition similar to solar system
- Enriched in light elements (due to spallation)

- Confinement time ~ 15 Myr up to .4 GeV/nucleon.
- Confinement times decrease with increasing E.
Now Remote Sensing of Cosmic Ray Nuclei

Left: Fermi & VERITAS γ-ray detections from the starburst galaxy M82, fit to a model in which a primary cosmic ray spectrum interacts with the ISM before being advected out by a wind. *From Yoast-Hull et al. 2012.* Right: Galactic molecular clouds illuminated by γ-rays.
Central Molecular Zone of the Milky Way: Soft $\gamma$ Excess

Spectrum can be fit with “extra” soft protons, but energy requirements are huge. “Extra” soft electrons overproduce radio. Point sources? Exotic physics? From Yoast-Hull et al. 2014.
Far-Infrared Radio Correlation

- Tight correlation between FIR luminosity (measure of SFR) & synchrotron luminosity ($\sim U_B \times U_{crl}$)
- Appears to hold at least to $z \sim 2$
- Suggests a powerful self-regulation mechanism.
Properties & Implications

Properties

• Near interstellar composition

• Broken power law spectrum

• Nearly isotropic, anisotropy increases with energy

• Long confinement times

• “Universal” $U_B, U_{crl}, SFR$ relationships

Implications

• Source material is interstellar, not supernova ejecta.

• Acceleration & propagation of galactic component produce a power law spectrum.

• Particles are scattered & well trapped by the Galactic magnetic field.

• Particles diffuse with an energy dependent path length that steepens the source spectrum.

• Robust particle acceleration & dynamo processes driven by star formation; possible self-regulation.
Cosmic Ray Orbits: *DNS is Infeasible*

**Left scale:** distance in cm

**Right scale:** proton energy with gyroradius at that scale in Galactic magnetic field

A few astronomical scales are also indicated.
Elements of Field-Particle Interaction

- Orbits
  - Gyromotion
  - Drifts
  - Mirroring
  - Resonant scattering

- Collective behavior
  - Resonant instabilities
  - Nonresonant instabilities (new)

Test particle dynamics plus statistical mechanics

Plasma physics
Drifts and Mirroring

Gruntman 1997

- Magnetic moment $\frac{p^2}{B}$ is invariant under slow changes in $B$

- A particle with gyroradius $r_g$ in a $B$ field which varies on scale $L \gg r_g$ drifts across fieldlines at speed $v_{\text{drift}} \sim v \frac{r_g}{L}$. 

Silas.psfc.mit.edu
Gyroresonant Pitch Angle Scattering

Gyroresonant fluctuations (Doppler shifted frequency $k v_{\parallel} = \omega_{cr}$) scatter in pitch angle.

Orbits follow fieldlines and short wavelength fluctuations average out.

J. Everett

![Diagram of orbits and gyroresonant fluctuations](image)
Crossfield Diffusion

Horizontal motion due to fieldline motion

Particle moves to another fieldline

Perpendicular diffusion in many propagation codes
Diffusion Coefficients

• Define the running diffusion tensor

\[ D_{ij}(t) \equiv \frac{1}{2N} \sum_{n=1}^{N} \frac{[x_{i,n}(t) - x_{i,n}(0)][x_{j,n}(t) - x_{j,n}(0)]}{t} \]

• Correct for crossfield motion

\[ x_{gc} = x + \frac{\nu \times \vec{b}}{\omega_g}. \]

\[ \Delta x \equiv x_{gc} - x_f \]

• Define the corrected running diffusion tensor

\[ D_{ij}^c \equiv \frac{1}{2N} \sum_{n=1}^{N} \frac{\Delta x_i(t) \Delta x_j(t)}{t} \]
Summary of Results

Upper bound:
Eddy rate
$L^2/t_{orb}$

Lower bound:
$r_g^2/t_{sca}$
Gyroresonant Scattering by Hydromagnetic Waves: Statistical Description

Elastic scattering in the wave frame

\[ \left. \frac{df}{dt} \right|_{\text{scattering}} = \frac{\partial}{\partial \mu_w} \left( \frac{1 - \mu_w^2}{2} \right) \nu \frac{\partial f}{\partial \mu_w}, \]

where \( \mu_w \equiv \mathbf{p} \cdot \mathbf{B} / \mathbf{pB} \) in the wave frame and

\[ \nu \equiv \frac{\pi}{4} \omega_{cr} k \frac{\delta B_k^2}{B^2} \]

is the scattering frequency due to power at the resonant \( k \equiv \omega_{cr} / \mu_w \nu. \)
Convection – Diffusion Equation

\[
\frac{\partial f}{\partial t} + u \cdot \nabla f = \frac{\nabla \cdot u}{3} p \frac{\partial f}{\partial p} + \nabla \cdot D_{||} \hat{b}b \nabla f + \frac{1}{p^2} \frac{\partial}{\partial p} \frac{p^2 D_{pp}}{\partial p} \frac{\partial f}{\partial p},
\]

where

Velocity of wave frame \( u \equiv u_{\text{plasma}} + \frac{\nu_+ - \nu_-}{\nu_+ + \nu_-} v_A, \)

Spatial diffusion \( D_{||} \equiv \frac{\nu^2}{\nu_+ + \nu_-}, \)

Second order Fermi acceleration \( D_{pp} \equiv \frac{4}{3} \gamma^2 m^2 v_A^2 \frac{\nu_+ \nu_-}{\nu_+ + \nu_-}, \)

and “+” and “−” denote wave propagation direction.
Momentum and Energy Transfer

- Gyroresonant, streaming cosmic rays transfer momentum to co-propagating waves & absorb momentum from counter-propagating waves.
- Super-Alfvenic streaming $v_D > v_A$ destabilizes co-propagating Alfven waves ($v_A = B/(4\pi \rho)^{1/2}$).
- Growth rate $\Gamma_{cr}$ for $E^{-\alpha}$ spectrum:

$$\Gamma_{cr}(E) \sim \omega_{cp} \frac{n_{cr}}{\gamma^{\alpha-1} n_i} \left(\frac{v_D}{v_A} - 1\right).$$

Typically fast under interstellar conditions
Damping Transfers Wave Energy & Momentum to the Background

- Ion – neutral friction
  - *Important in HI, H₂ gas*
- Nonlinear energy transfer to thermal ions
  - *Important in hot gas*
- Distorted by wandering of background field
  - *Important when small scale turbulence is present*

In a steady state, damping balances growth, determining the streaming rate, wave amplitude, & dissipation rate.
Relate Streaming Anisotropy to Density Gradient

\[-v^\hat{b} \cdot \nabla f = (\nu_+ + \nu_-) \frac{\partial f}{\partial \mu} + v_A(\nu_+ - \nu_-)m\gamma \frac{\partial f}{\partial p}.\]

Cosmic ray density/pressure gradient drives anisotropy, as particles stream down their gradient.

Resonant, co-propagating waves absorb cosmic ray momentum.

Waves transfer momentum & energy to the background gas, accelerating & heating it.
Cosmic Ray Hydrodynamics

Cosmic ray generated waves dominate the scattering

- Cosmic rays are advected at $v_A$ relative to fluid, but also diffuse along magnetic field.
- Cosmic ray pressure gradient along $B$ accelerates and heats the background gas.

Externally driven turbulence dominates the scattering

- Cosmic rays advect with fluid and diffuse along magnetic field.
- Cosmic rays undergo second order Fermi acceleration by the turbulence.

Which is correct? Self-confinement prevails at least for the bulk (few GeV) particles, where streaming instability is strongest.
Which Picture to Adopt?

• What is the spectrum of interstellar/intergalactic turbulence down to sub-AU scales?
• How does the streaming instability work in the presence of background magnetic turbulence?
• Have all the linear & nonlinear damping mechanisms been identified?

Nature of the coupling & direction of energy flow depend on this.
Some Implications of Self-Confinement

• Cosmic rays provide hydrostatic support to the galactic disk.

• Cosmic ray buoyancy drives escape of the galactic magnetic field.

• Cosmic ray pressure gradient drives a galactic wind.

• Cosmic rays contribute to heating and convective instability in galaxies & galaxy clusters.

• Cosmic rays modify collisionless shocks
Top left: Soft x-ray sky,
Bottom left: Magnetic flux tube geometry.
Top right: Domains of flow, with mass loss rates
Bottom right: Gas temperature with & without cosmic ray heating.

Cosmic Ray Heating of Diffuse Interstellar Gas

Left: Galactic Hα emission, showing a thick layer of warm ionized gas. Right: Model of thermal equilibrium, including cosmic ray heating (Wiener et al. 2013)
Cosmic Ray Coupling to Clouds

Top left: Model cloud setup. Top Right: Cosmic ray & wave pressure vs. depth. Bottom right: Transition from advection to diffusion, followed by free streaming -> No force on the bulk of the cloud.
Fermi Bubbles

Gamma-ray emitting bubbles in the inner Milky Way, discovered by Fermi $\gamma$-ray observatory.

Cosmic ray energy density in a pressure inflated cavity assuming isotropic diffusion (left) and field aligned diffusion (right).

Model cavity formation by a short lived AGN jet (Guo et al. I, II)

The Origin of Cosmic Rays

Fermi’s prescription:

$$F(E) \sim E^{-(1 + \frac{\tau_{\text{acc}}}{\tau_{\text{esc}}})}$$

$\tau_{\text{acc}}$ is acceleration time, $\tau_{\text{esc}}$ is escape time.

Neither is specified in Fermi’s original model.
Acceleration at Shocks

Self-confinement of cosmic rays to a shock front leads to rapid acceleration.

First order Fermi Process: net energy gain per loop

\[ \frac{\tau_{\text{acc}}}{\tau_{\text{esc}}} \sim 1 \]

Chandra-Newton image of RCW 86
Nonresonant Instabilities

- When $U_{cr}/U_B > c/v_D$ there is a new, nonresonant instability driven by the electron current that compensates the cosmic ray current.
- Conditions are met at shocks, and possibly in young galaxies.
Rapid Growth to Nonlinear Amplitude

Linear growth rates (Zweibel & Everett 2010)

Simulations suggest that the magnetic field can be amplified, producing the observed thin synchrotron rims, increasing the acceleration rate, producing a new saturated state.
Acceleration in Contracting Islands

Top: Particle orbits in shrinking magnetic islands formed by magnetic reconnection (Drake et al 2006).

Bottom: Initial spectrum (steep) and later spectrum (flat) as particles interact with a large ensemble of islands (Drake et al 2012).

Small $\tau_{\text{acc}}/\tau_{\text{esc}}$ give flat spectrum of solar system particles; fast acceleration mechanism in flares.
Lab Studies: Ion Heating in an RFP Plasma

- Thermal heating of impurity ions is anisotropic ($T_\perp > T_\parallel$)
- Thermal heating has a charge/mass dependence
- Majority ions develop a high-energy tail

Courtesy D. Den Hartog
Dramatic ion heating occurs during the sawtooth reconnection event.

**Zooming in on dynamics at reconnection event:**

- Energy stored in the equilibrium magnetic field drops suddenly
- Large fraction of released energy is transferred to ions
  - Heating time (100 µs) is much faster than i-e collision time (10 ms)
  - \( T_i > T_e \)
- Power flow from equilibrium magnetic field to ions is large
  - \( P_{mag} \approx 10 \text{ kJ}/100 \mu s = 100 \text{ MW} \)
  - \( P_{ohmic} \approx 5 \text{ MW} \)

Courtesy D. Den Hartog
Experimental Study of Diffusion

- Unstable TORPEX plasma develops turbulent magnetic structure.
- Energetic particles injected by an internal source.
- Trajectories can be followed & mapped (Gustafson et al 2012 PRL).
Summary and Prospects

- Cosmic rays carry ~1/3 of the energy in the interstellar medium in galaxies.

- *If self-confined by plasma instabilities*, cosmic rays transfer energy & momentum to the background, heating the gas & driving outflows.

- New opportunities are arising from
  - a wealth of new cosmic ray & lab data.
  - advances in simulation
  - improved understanding of magnetized turbulence & how it interacts with energetic particles.
Goals

• Understand how the cosmic ray energy budget, spectrum, and composition are regulated.

• Improve the theory of cosmic ray hydrodynamics, incorporating new developments in magnetized turbulence & how it interacts with particles.

• Include cosmic rays in theories of astrophysical plasma processes such as shocks, reconnection, and dynamos.