Cosmic Ray (CR) transport and acceleration in turbulence

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Introduction and basic formalism and interaction mechanism.

Cosmic Ray (CR) scattering by numerically tested models of turbulence.

Nonlinear theory and numerical testings

Perpendicular transport

Implications for various astrophysical problems

Instabilities and Back-reaction of CRs (small scale)
What are Cosmic rays?

Cosmic rays: energetic charged particles from space.
Origin of cosmic rays

• Pinpointing direct source is impossible (except for, perhaps, the ultra high energy cosmic rays)
  – Individual cosmic rays move along random paths in the turbulent magnetic fields.
  – Observed to come from all directions in the night sky (at any point they are isotropic in arrival direction.)

• Indirect methods (\(r_L < \) size of SNR, gamma ray emissions, etc) indicate that most cosmic rays < \(10^{15}\) eV are from shock waves driven by supernova explosions
Flux of primaries: 1 cgs ...... 1/cm²·sec
Isotropy: δ = 10⁻⁴
Energy: 10⁹eV − − − 10²⁰eV
Composition: Hydrogen to Uranium
Age: (from Lithium Beryllium and Boron) —— 5gm /cm²

\[ T = 3 \times 10^6 \text{years} \]

Summary

Cosmic rays fill the galactic disc.
\[ \Phi = N \nu \sim n c = 1 \]
\[ N = 10^{-10}/\text{cm}^3 \]

- \( B = 3 \times 10^{-6} \text{gauss} \)
- \( H = 100 \text{parsecs} \sim 3 \times 10^{21} \text{cm} \)
- \( R = 10^4 \text{ parsecs} \)
- \( n^* = 1/\text{cm}^3 \)
- \( v_A = 10^6 \text{ cm/sec} \)
- \( E_{cr} \sim E_B \sim E_p \sim 1 \text{ev}/\text{cm}^3 \)
Importance of CR propagation

- CMB synchrotron foreground
- Identification of dark matter
- Diffuse γ-ray emission
- Diffuse Galactic 511 keV radiation
Cosmic Rays and turbulence

M. Duldig 2006

Extended Big Power Law

Armstrong et al. 1995, Chepurnov & Lazarian 2009

Fig. 5.— WHAM estimation for electron density overplotted on the figure of the Big Power Law in the sky figure from Armstrong et al. (1995). The range of statistical errors is marked with the gray color.
Importance of wave-particle interaction: Fermi II

Stochastic Acceleration:

Magnetic “clouds”

Fermi (49)

Gamma ray burst

Solar Flare
Importance to Fermi I acceleration

- Shock Acceleration
  
  Krymsky 77, Axford et al 77, Bell 78, Blandford & Ostriker 78, Drury 83

  Shock front

  Pre-shock region

  Turbulence generated by streaming

  Diffusion of CRs

  Post-shock region

  Turbulence generated by shock

Tycho’s remanent
More data are available for model fitting.
Big simulation itself is not adequate!

Big numerical simulations fit results due to the existence of "knobs" of free parameters (see, e.g., http://galprop.stanford.edu/).

Self-consistent picture can be only achieved on the basis of theory with solid theoretical foundations and numerically tested.
Basic equations

In case of negligible acceleration, Fokker-Planck equation can be used to describe the particles’ evolution:

\[
\frac{\partial F}{\partial t} + v \mu \frac{\partial F}{\partial Z} - \Omega \frac{\partial F}{\partial \phi} = S + \frac{1}{p^2} \frac{\partial}{\partial x} \left( p^2 D_{xy} \frac{\partial F}{\partial y} \right)
\]

S : Sources and sinks of particles
2nd term on rhs: diffusion in phase space specified by Fokker-Planck coefficients \( D_{xy} \)
Fokker Planck (FP) diffusion coefficients

Cosmic Rays ↔ Magnetized medium

More details can be found in the book Schlickeiser (2002)
FP coefficients can be used to find transport and acceleration properties.

Propagation
\[ \nu = 2D_{\mu\mu}/(1 - \mu^2) \]
\[ \lambda_\parallel = \frac{3}{4} \int d\mu \frac{\nu(1 - \mu^2)^2}{D_{\mu\mu}} \]

Stochastic Acceleration
\[ A(E) = \frac{\partial [\nu p^2 D(p)]}{4p^2 \partial p}, \quad D(p) = \frac{1}{2} \int_{-1}^{1} D_{pp} d\mu \]

\[ D_{\mu\mu} \xleftrightarrow{} \delta B, \]
\[ D_{pp} \xleftrightarrow{} \delta E = \delta \nu \cdot B_0 / c \]

• Where do \( \delta B, \ \delta \nu \) come from? MHD turbulence!
• The diffusion coefficients are primarily determined by the statistical properties of turbulence.
The result is intuitive.

\[ \delta \theta \sim \frac{\delta B}{B} \]

Non resonance.

\[ l_L \ll \frac{1}{k} \]

\[ l_L \gg \frac{1}{k} \]

What is size of \( \delta B/B \) for \( \lambda = 1 \) parsec?

\[ D_\theta = \frac{c}{\lambda} \sim 10^{-8} \sim \Omega \left( \frac{\delta B}{B} \right)^2 \sim 3 \times 10^{-2} \left( \frac{\delta B}{B} \right)^2 \]

\[ \frac{\delta B}{B} \sim 10^{-3} \]
Resonance mechanism

Gyroresonance

\[ \omega - k_{\parallel} v_{\parallel} = n\Omega, \quad (n = \pm 1, \pm 2 \ldots), \]
Which states that the MHD wave frequency (Doppler shifted) is a multiple of gyrofrequency of particles (\(v_{\parallel}\) is particle speed parallel to \(B\)).

So, \(k_{\parallel,\text{res}} \sim \Omega/v = 1/r_L\)