Cosmic-Ray Transport between the Knee and the Ankle with CRPropa

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Motivation

Direct observation of CRs at their sources is impossible

- Indirect information based on:
  - Neutral messengers ($\nu$, $\gamma$)
  - Transport modelling

All observables (spectrum, composition, arrival direction) are influenced during the transport

- Three-dimensional modeling including interactions

Impossible to simulate all particle individually on long time scales

- Ensemble averaged description
Modelling the Transport

\[ \frac{\partial n(\vec{r}, p, t)}{\partial t} + \vec{u} \cdot \nabla n = \nabla \cdot (\kappa \nabla n) + \frac{1}{p^2} \frac{\partial}{\partial p} \left( p^2 \kappa_{pp} \frac{\partial n}{\partial p} \right) + \frac{p}{3} (\nabla \cdot \vec{u}) \frac{\partial n}{\partial p} + S \]

Advection
Spatial Diffusion
Momentum-diffusion
Adiabatic Effects
Sources

Partial (Fokker-Planck) Differential Equation (FPG) for particle density \( n \)

\[ \text{Stochastic Differential Equations (SDEs)} \]

\[ d\vec{x} = \vec{u} dt + \hat{D} d\vec{W} \]
\[ dp = -\frac{p}{3} (\nabla \cdot \vec{u}) dt + D_{pp} dw_p \]
Comparison

**Grid**
GalProp, DRAGON, PICARD, ...

**Advantages**
- Shorter computation times
- Widely used and well tested
- Good interaction implementation
- PICARD: Explicit stationary solver

**Disadvantages**
- Huge memory requirements
- Not possible to reweight
- No information on single particles
- Shocks hard to simulate

**SDE**
CRPropa, Kopp+ (´12), Miyake+ (´14), ...

**Advantages**
- Scales linearly with number of processors
- Reweighting is possible
- Not restricted to grid
- Backtracking is possible

**Disadvantages**
- Averaging of results necessary → Many pseudo particles
- Not all interactions implemented yet
Numerical Solution in CRPropa

**CRPropa 3.0** (Alves Batista+, 2016):
Open source Software for CRs with \((E > 10^{17} \text{ eV})\)

**CRPropa 3.1** (Merten+, 2017):
Extension to lower energies \((E > 10^{13} \text{ eV})\)

**Numerical Integration:** Euler-Maruyama-Scheme

\[
\begin{align*}
\mathbf{x}_{n+1} - \mathbf{x}_n &= (u_x \hat{e}_x + u_y \hat{e}_y + u_z \hat{e}_z) \cdot h \\
&\quad + \left(\sqrt{2\kappa_\parallel \eta_\parallel} \hat{e}_t + \sqrt{2\kappa_\perp \eta_\perp,1} \hat{e}_n + \sqrt{2\kappa_\perp \eta_\perp,2} \hat{e}_b\right) \cdot \sqrt{h} \\
p_{n+1} - p_n &= -p_n / 3 \left(\nabla \cdot \mathbf{u}\right) \cdot h
\end{align*}
\]

**Validation I:** Mag. field \(\mathbf{B} = B_0 \hat{e}_z\), wind \(\mathbf{u} = u_0 \hat{e}_x\) and aniso. diffusion \(\epsilon := \frac{\kappa_\perp}{\kappa_\parallel} = 0.1\)

**Validation II:** Spiral magnetic field, no wind and pure parallel diffusion \(\epsilon = 0\)

**New modules**
- DiffusionSDE
- AdiabaticCooling
- AdvectionField
  - Constant, Spherical, SphericalShock
- Source
  - UniformCylinder
- SNR
- Pulsar

\[
\begin{align*}
\text{SNR} &\quad \text{Pulsar}
\end{align*}
\]
Cosmic rays from the GTS

- **Assumption**: The galactic termination shock (GTS) is able to accelerate CR, e.g., Bustard+ (2017).

- **Question**: Can they diffuse back into the Galaxy?

- **Diffusion**: \( D = 5 \times 10^{28} C_\epsilon \cdot \left( \frac{R}{4 \text{ GV}} \right)^\delta \cdot \text{diag}(1, \epsilon, \epsilon) \, \text{cm}^2/\text{s} \)

- **Magnetic field**:
  Spherical symmetric **(model S)** and an Archimedian spiral **(model A)**

- **Wind Modell**:
  Continuous differentiable also at shock

- **Shock**:
  \( L_{\text{CR}} = 10^{40} \text{ erg/s}, \Delta T = 100 \text{ Myr}, \frac{dn}{dE} \propto E^{-2}, r_{\text{shock}} = 250 \text{ kpc} \)

- **Simulationvolume**: Free-Escape-Boundaries at \( r_{\text{obs}} = 10 \text{ kpc}, \quad r_b = 350 \text{ kpc} \)
CRs from the GTS (results)

- Ensemble loses energy in most cases (adiabatic cooling)
- Time scale and maximum luminosity depend on the diffusion index $\delta$
- Energy spectrum is time dependent
- Perpendicular diffusion mitigates the anisotropy problem
- Upper limit of the neutrino flux is below the observed IceCube flux

The CR flux in the shin region can be partly explained by the GTS.
Summary & Outlook

• CRPropa allows for anisotropic Diffusion in arbitrary magnetic background fields
• Consistent description of advection and corresponding adiabatic effects
• SDE method: Advantages at high energies compared with grid-based methods, e.g., intrinsic parallelization, backtracking, and reweighting.

• The GTS is an interesting source candidate for the CR flux in the shin region
• Magnetic field morphology has an important influence on observables
• 3D-modelling is necessary: Time evolution differs between 1D and 3D and anisotropy is only available in 3D

• Implementation of Momentum diffusion $\rightarrow$ Acceleration of CRs
• $(\delta b/B) \rightarrow$ Space dependent eigenvalues of the diffusion tensor
• Analyses the additional propagation towards the Earth
• Analyses the lost CRs from starburst galaxies