Stationary study of diffusive shock acceleration (DSA) of cosmic rays in supernova remnants (SNR)

Internship Project

Quentin Rouch

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Dr. Laurent Gremillet (CEA)

Astrophysical Workshop - Kinetic Physics of Astrophysical Plasmas
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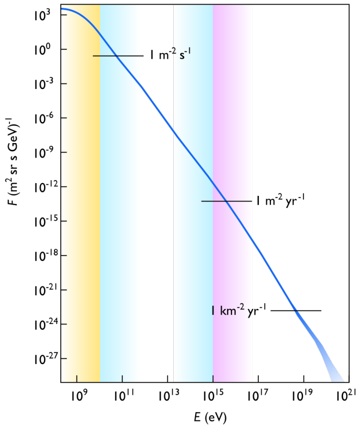
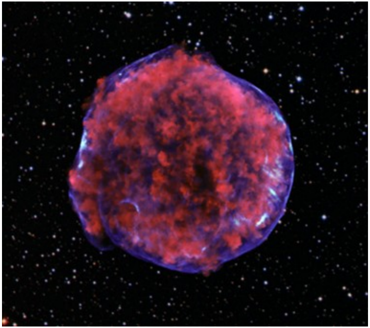
The Origin of Extreme Energies



Energy distribution of cosmic ray protons



Tycho SNR (X-ray)

Stationary Non-Linear DSA

Proton acceleration up to $\sim$ 100 TeV

Methodology : The Baseline Model

Particle Transport

Standard Parker Equation

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Isotropic Assumption

Diffusive Regime (Fick's Law)

Key Processes Captured :

- Spatial advection and diffusion
- Adiabatic energy gain at the shock

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Saturated Turbulence

Minimal Diffusion ($\kappa_{Bohm} \propto p$)

Limitation :

A "floor model" that completely ignores the non-linear growth of magnetic turbulence.

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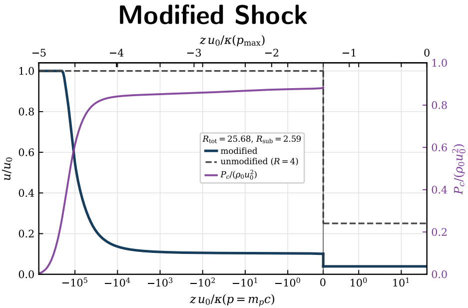
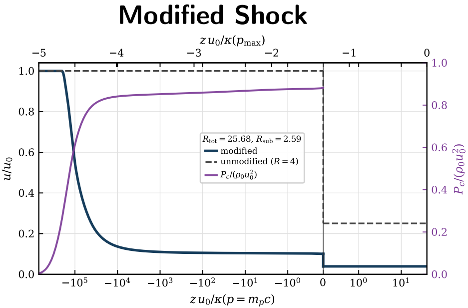
Quasi-isotropic diffusive closure

$$\underbrace{\bar{u}\frac{\partial \bar{f}_0}{\partial z}}_{\text{Advection}} = \underbrace{\frac{\partial}{\partial z}\left(\kappa_{Bohm}(p)\frac{\partial \bar{f}_0}{\partial z}\right)}_{\text{Isotropic Diffusion}} + \underbrace{\frac{1}{3}\frac{\mathrm{d}\bar{u}}{\mathrm{d}z}p\frac{\partial \bar{f}_0}{\partial p}}_{\text{Energy Gain}} + \underbrace{Q(z,p)}_{\text{Injection}}$$

Results


Modified Shock
$z\,u_0/\kappa(p_{\max})$
−5
−4
−3
−2
−1
0
1.0
0.8
0.6
0.4
0.2
0.0
u/u_0
$R_{\rm tot} = 25.68$, $R_{\rm sub} = 2.59$
modified
unmodified ($R = 4$)
$P_c/(\rho_0 u_0^2)$
-10^5
-10^4
-10^3
-10^2
-10^1
-10^0
0
10^0
10^1
$z\,u_0/\kappa(p = m_p c)$
$P_c/(\rho_0 u_0^2)$

Results



- Strong CR pressure (P_c) generates a broad precursor

Results

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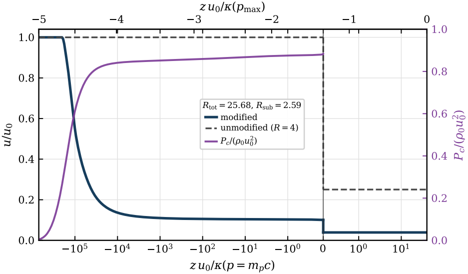

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- Subshock is weakened ($R_{sub} \approx 2.6$)

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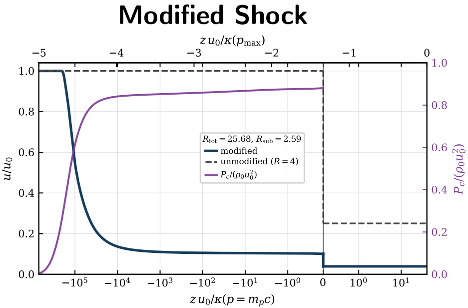

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- Total compression rate increases ($R_{tot} \approx 25.7$)

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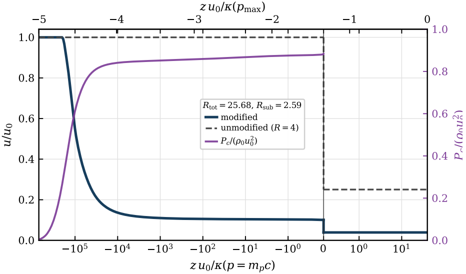
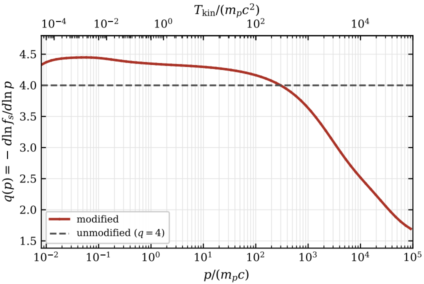


Spectral slope at the shock



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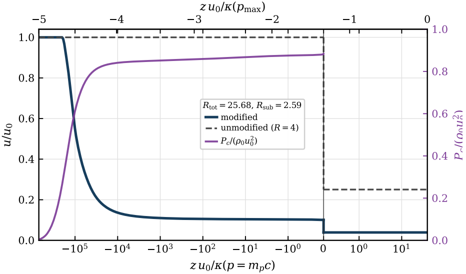

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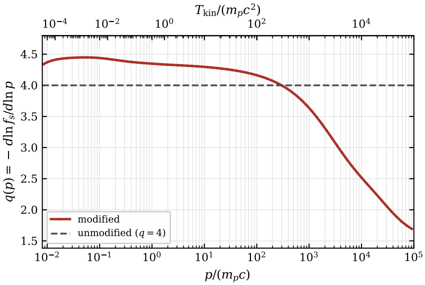

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- Low p : Soft spectrum ($q > 4$) due to weak R_{sub}.

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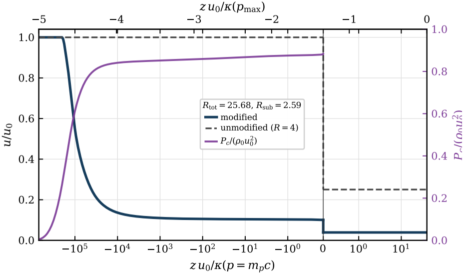

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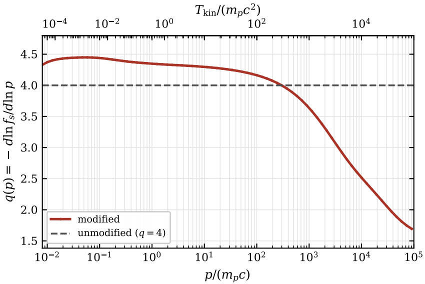

- Low p : Soft spectrum ($q > 4$) due to weak R_{sub}.
- High p : Hard spectrum ($q < 4$) due to high R_{tot}.

Perspectives : Transport & Turbulence advanced Models

Particle Transport

From: Parker Eq. (Isotropic diffusion)

To: **Anisotropic M1 Closure**

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$$f(z,p) \approx f_0(z,p) + f_1(z,p) + \ldots$$

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To: Dynamic Wave Spectrum

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Magnetic waves spectrum evolution :

Turbulence is amplified by the Bell instability driven by the cosmic ray current

Thank you for your attention!

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