Particle acceleration by the shock waves propagating in a non-uniform medium

Shota Yokoyama, Yutaka Ohira

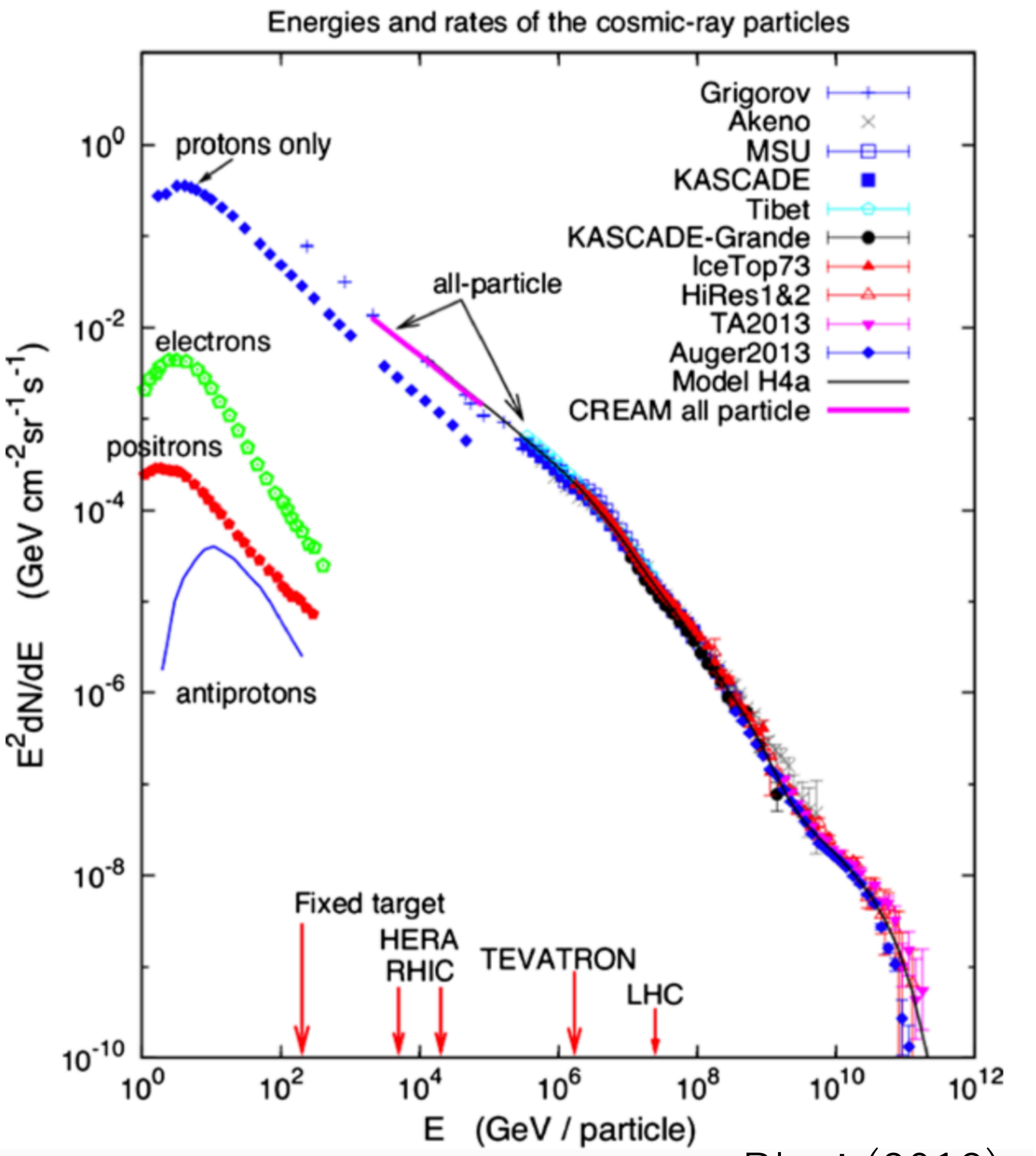
Department of Earth and Planetary Science, The University of Tokyo

Cosmic Rays (CRs)

- CRs observed on the earth have wide range of power-law energy spectrum.
- Such a power-law is explained by Diffusive Shock Acceleration (DSA).

$$\frac{dN}{dE} \propto E^{-2}, s \rightarrow 2 \; (M_1 \rightarrow \infty)$$

- In particular, Galactic CRs are believed to be accelerated by DSA in supernova remnants (SNRs)



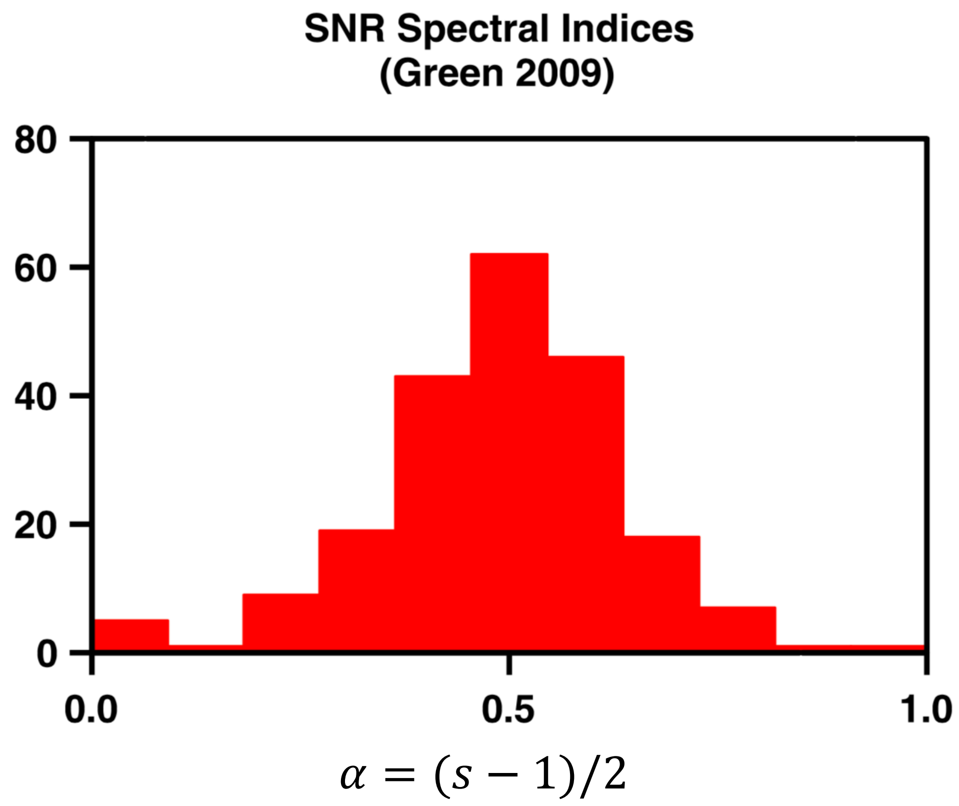
Blasi (2013)

The observation

- The spectral index of synchrotron radiation α is observed for various SNRs.
- α is related to the spectral index of accelerated particles, s, with

$$\alpha = \frac{s-1}{2}$$

- The deviation from $\alpha = 0.5$ $(s = 2)$ cannot be explained by the standard DSA in strong shocks such as in SNRs.



Reynolds (2011)

Purposes & Methods

- To understand the origin of the deviation from $s = 2$, we introduce a **density fluctuation** in the interstellar medium (ISM) to the standard DSA.

- We model the motion of particles as isotropic scatterings in the fluid rest frame and adopt Monte Carlo simulations.

- The fluctuation in the ISM is described by linearized fluid equations, and our simulation utilizes the analytical solution for them.

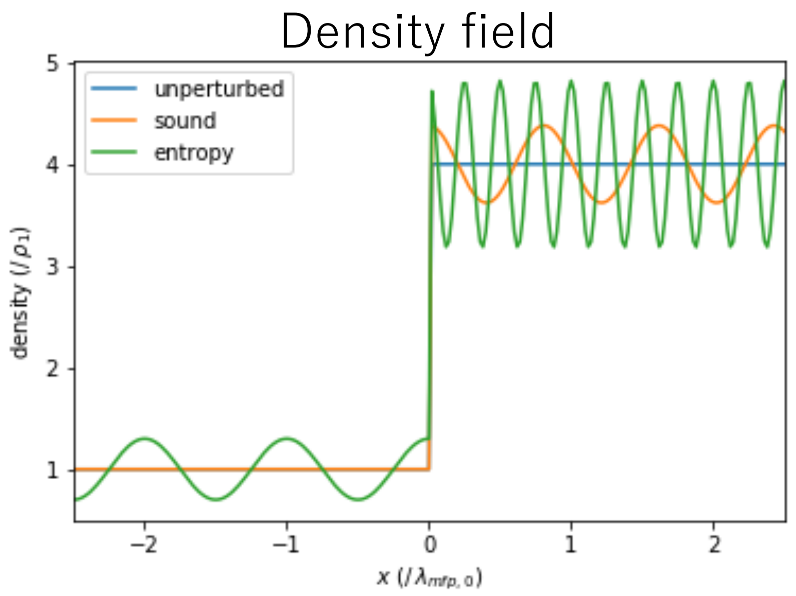
Density and Velocity Fields

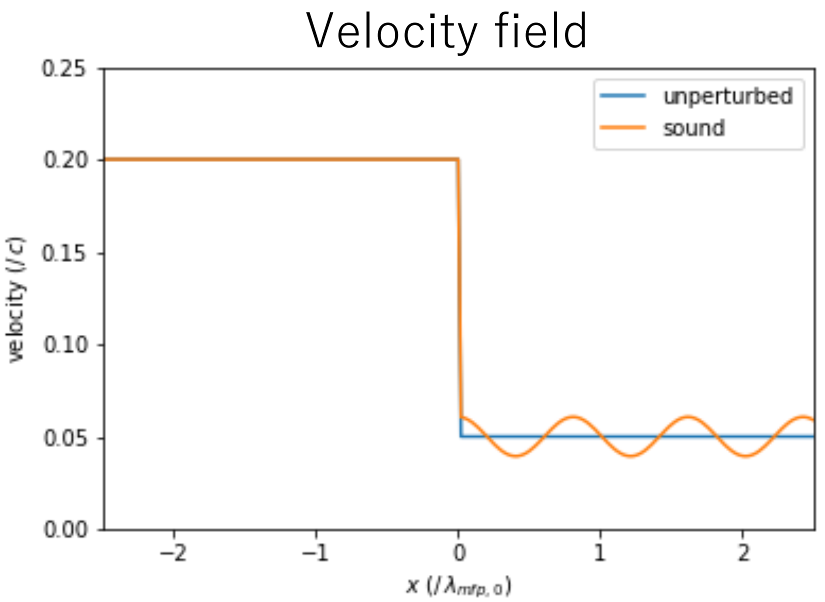
- If a monochromatic density fluctuation enters the shock in parallel to the shock normal, a **sound wave** and an entropy wave are generated in the downstream (McKenzie & Westphal, 1968).

For M >> 1,

$$\lambda_{sound} \simeq 0.81\,\lambda_{\delta\rho_1}, \qquad \lambda_{entropy} = (1/4)\,\lambda_{\delta\rho_1}$$

$$\frac{\delta u_2}{u_1} \simeq 0.18\,\frac{\delta\rho_1}{\rho_1}, \qquad \delta x_{sh} \simeq 0.24\,\lambda_{\delta\rho_1}\frac{\delta\rho_1}{\rho_1}$$





Monte Carlo simulation

- Particles are displaced in the shock rest frame by $\vec{v}\Delta t$ for each step.
- Particles are isotropically scattered in the local rest frame of fluid.
- The scattering time is assumed to be proportional to the particle energy, $t_{sc} \propto E$.

Parameter sets

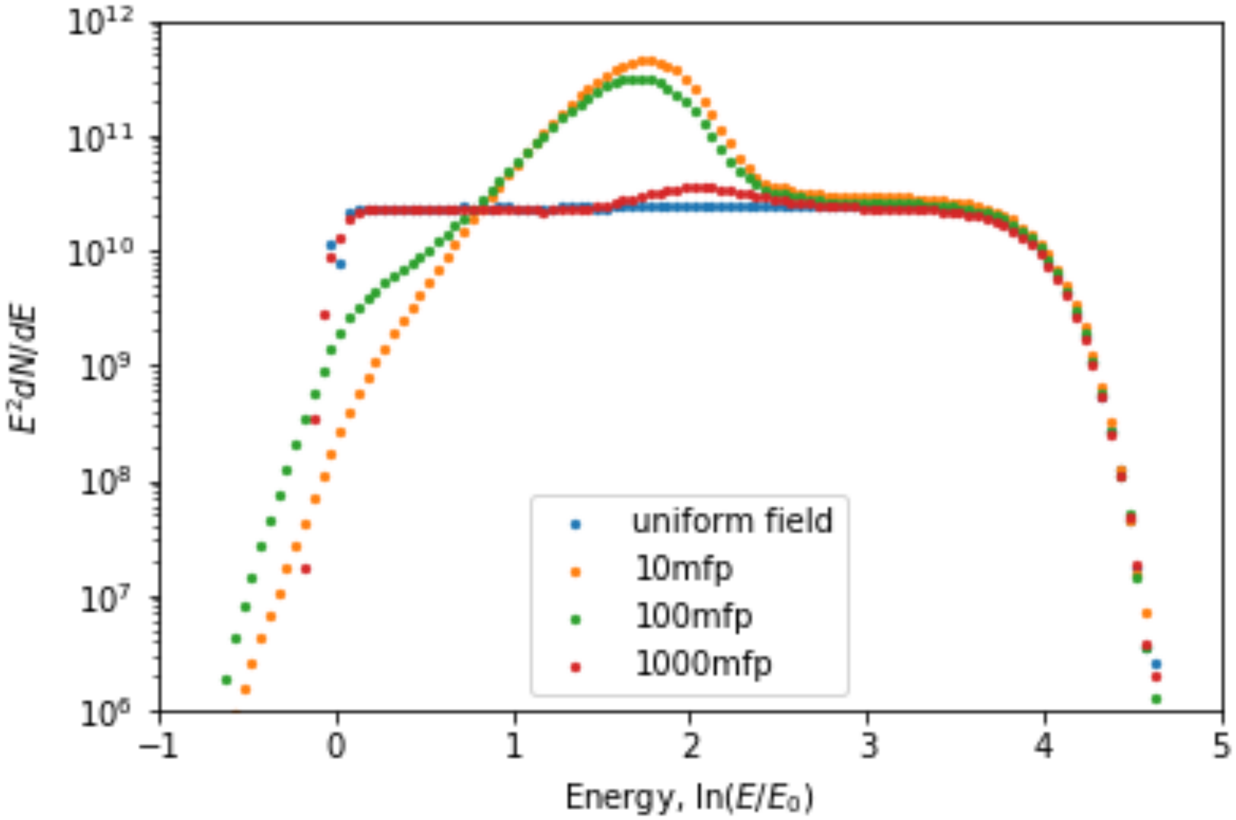
Lorentz factor of injection particles	Γ_0	10
Shock velocity	$u_{\rm sh}/c$	0.20
Upstream Mach number	M_1	100
Amplitude of the upstream density fluctuation	$\delta\rho_1/\rho_1$	0.30
Wavelength of the upstream density fluctuation	$\lambda_{\delta\rho 1}/\lambda_{\rm mfp}$	10, 100, 1000

Result 1

- When the fluctuation is absent (blue), our simulation is consistent with the standard DSA.

- If there is a fluctuation, the spectrum is modified.
- The modification is remarkable when the wavelength is comparable to the mean free paths of particles.

$@\, t = 10^8\, \tau_{sc,0}$

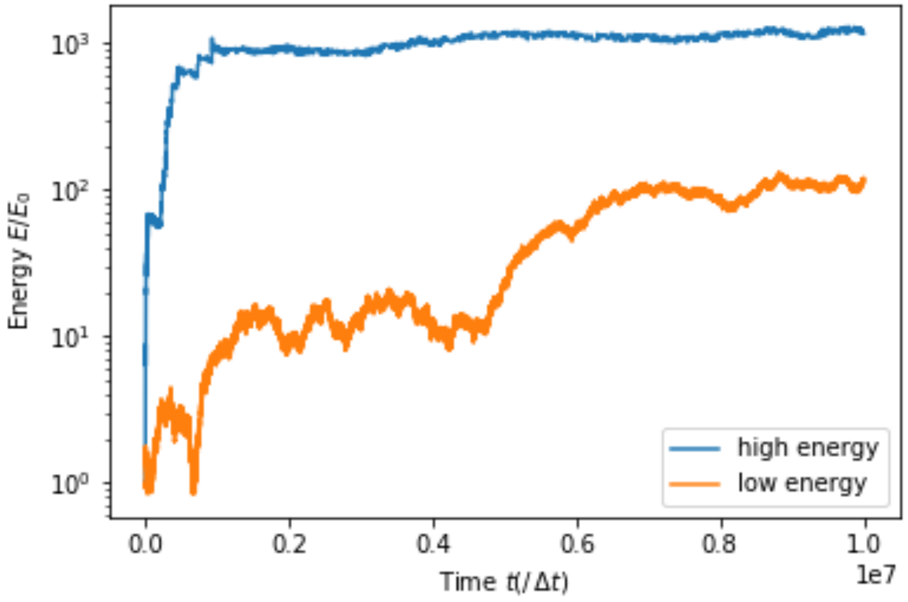


Result 2

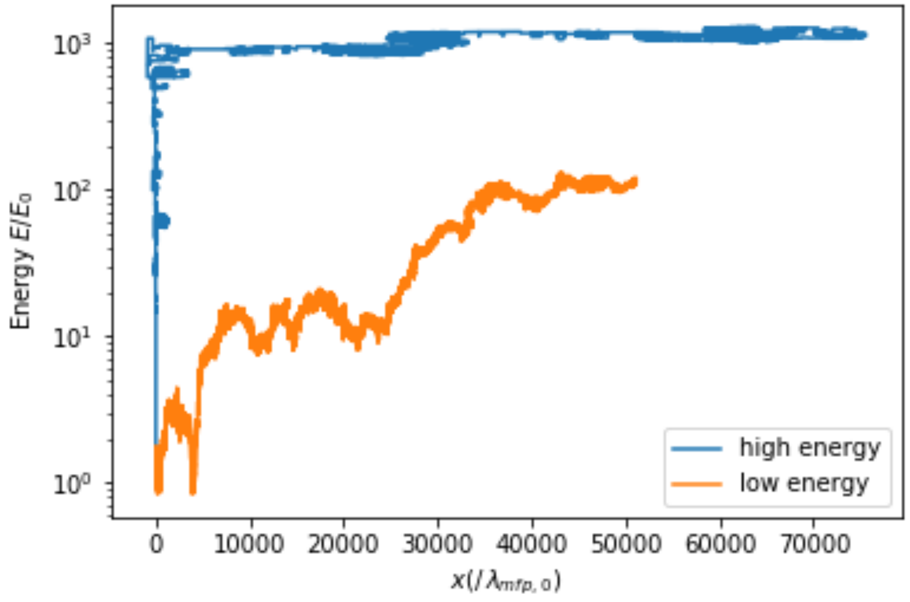
- High energy particles are accelerated mainly at the shock front (blue).
- Some particles are accelerated in the downstream region (orange).

➡ **Second order Fermi acceleration**

$t - E$



$x - E$



Order Estimate

- We estimate the contribution of 2nd order Fermi acceleration during DSA.
- The momentum gain by DSA for each crossing is

$$\frac{\Delta p_{DSA}}{p} = \frac{4}{3}\frac{u_1 - u_2}{v}$$

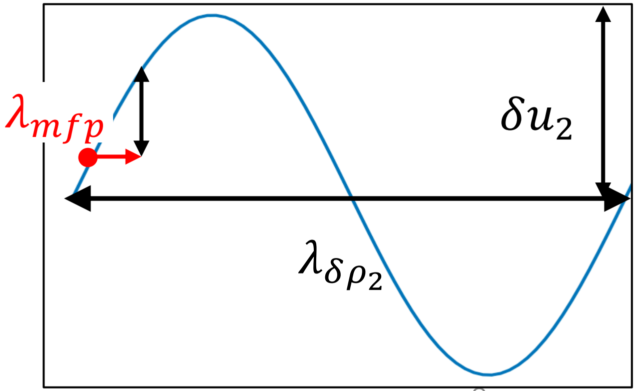
$$v \sim c, \qquad \kappa \sim \frac{1}{3}\lambda_{mfp} \cdot v$$

$$\lambda_{mfp} = v \cdot \tau_{sc}$$

- Mean residence time in downstream region is $\Delta t_2 = 4\kappa_2/u_2$.
- The momentum gain in Δt_2 by 2nd order Fermi acc. is $\Delta p_{2nd} \sim \sqrt{D_{pp}\Delta t_2}$.
- D_{pp} is estimated as

$$D_{pp} = \left\langle \frac{\Delta p \Delta p}{\Delta t} \right\rangle \sim \left(\frac{\lambda_{mfp}}{\lambda_{\delta\rho_2}} \cdot \frac{\delta u_2}{v} p \right)^2 \Big/ \tau_{sc} \sim \frac{\tau_{sc}\delta u^2}{\lambda_{\delta\rho_2}^2} p^2$$

The velocity change which particle feels in a scattering time is $\sim (\lambda_{mfp}/\lambda_{\delta\rho_2})$ times δu_2



Order Estimate

- The contribution of 2nd order Fermi acc. during DSA is estimated as

$$\frac{\Delta p_{2nd}}{\Delta p_{DSA}} \sim \frac{\lambda_{mfp}}{\lambda_{\delta\rho_2}} \cdot \frac{\delta u_2}{u_2} \cdot \sqrt{\frac{c}{u_2}}$$

- 2nd order acc. is efficient when the mean free path of particle is comparable to the spatial scale of downstream sound wave.
- In addition, the 2nd order acc. may become more important relative to DSA when the shock velocity is slower.

➡ Further simulations will be addressed in the subsequent study.

Summary & Future work

- It is verified that the density fluctuation modifies the energy spectrum of the standard DSA by the second order Fermi acceleration in the downstream region.

<u>Future work</u>

➢ Quantitative estimate of this modification.

➢ Extension to two or three dimensional fluctuations.

➢ Adopting non-linear effects such as dissipation of sound waves, cascade, etc..