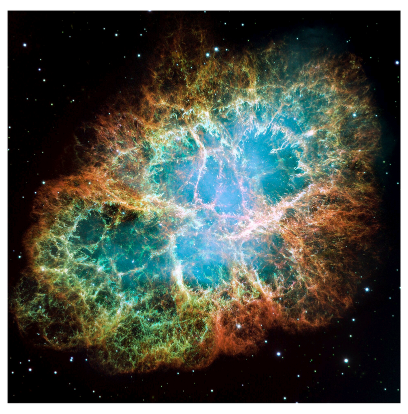
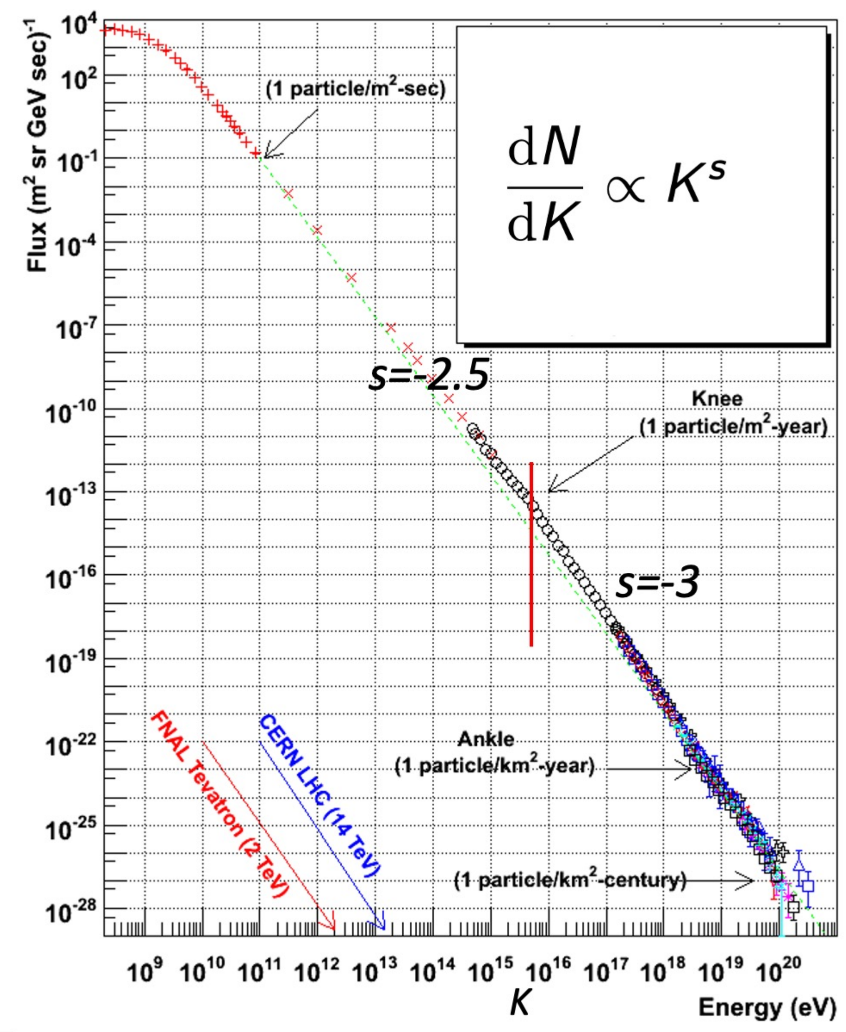


Reinterpretation of the Fermi acceleration of cosmic rays in terms of the ballistic surfing acceleration in supernova shocks

S5.16

K. Stasiewicz, Space Research Centre, Polish Academy of Sciences, Warsaw, e-mail: kstasiewicz@cbk.waw.pl

Observed spectrum of cosmic rays

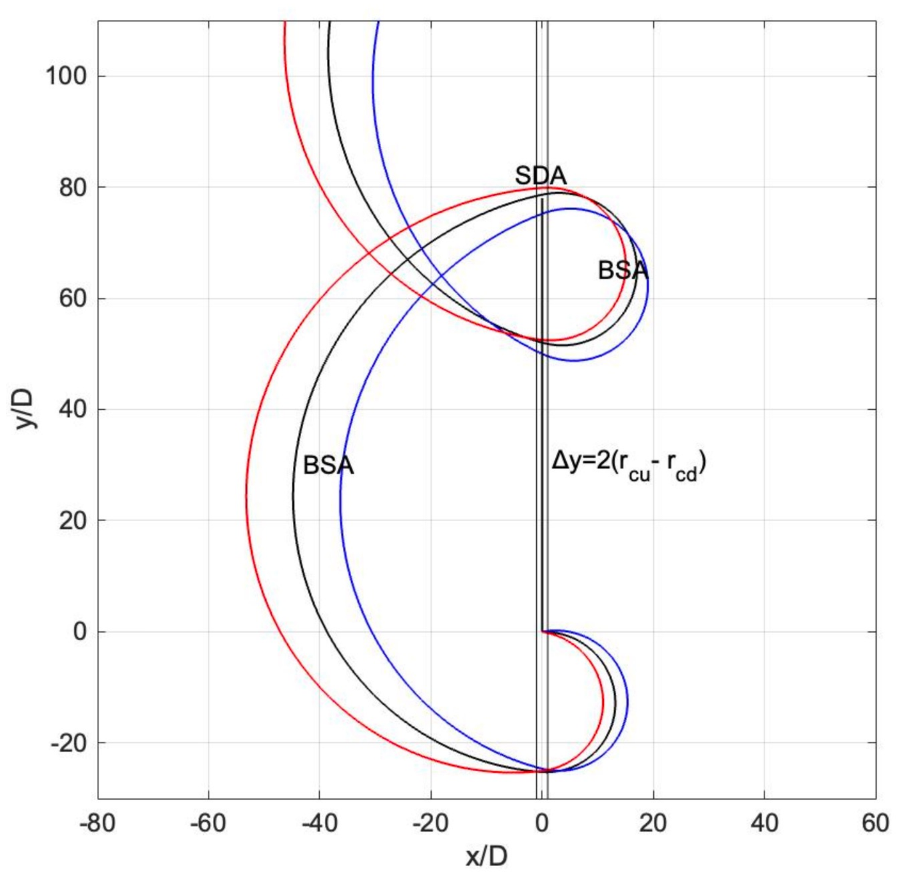


ABSTRACT

Aims. The applicability of first-order Fermi acceleration in explaining the cosmic ray spectrum has been reexamined using recent results on shock acceleration mechanisms from the Multiscale Magnetospheric mission in Earth's bow shock. It is demonstrated that the Fermi mechanism is a crude approximation of the ballistic surfing acceleration (BSA) mechanism. While both mechanisms yield similar expressions for the energy gain of a particle after encountering a shock once, leading to similar power-law distributions of the cosmic ray energy spectrum, the Fermi mechanism is found to be inconsistent with fundamental equations of electrodynamics.
Methods. The BSA mechanism has been investigated solely using the momentum equation in test-particle simulations with the electromagnetic fields of a model shock described in https://doi.org/10.1093/mnrasl/slad071.
Results. It is found that the spectral index of cosmic rays is determined by the average magnetic field compression rather than the density compression, as in the Fermi model. It is shown that the knee observed in the spectrum at an energy of 5×10^{15} eV could correspond to ions with a gyroradius comparable to the size of shocks in supernova remnants. The BSA mechanism can accurately reproduce the observed spectral index $s = -2.5$ below the knee energy, as well as a steeper spectrum, $s = -3$, above the knee. The acceleration time up to the knee, as implied by BSA, is on the order of 300 years.
Conclusions. First-order Fermi acceleration does not represent a physically valid mechanism and should be replaced by ballistic surfing acceleration in applications or models related to quasi-perpendicular shocks in space. It is noted that BSA, which operates outside of shocks, was previously misattributed to shock drift acceleration (SDA), which operates within shocks.

Key words. Cosmic rays – Shock waves – Acceleration of particles – Supernova remnants

Ballistic surfing acceleration
physical mechanism



$$\frac{d\boldsymbol{p}}{dt} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}),$$

$$\Delta K = q \int \boldsymbol{E} \cdot \boldsymbol{v}\, dt.$$

$$c_B = \frac{B_d}{B_u}$$

After one gyration across the shock the energy gain implied by Eq. (3) is $\Delta K \approx 2qE_y(r_{cu} - r_{cd})$. For relativistic particles with kinetic energy $K \approx pc$ and gyroradius $r_c = p_\perp/qB$, the energy gain is

$$\Delta K \approx 2qE_y \frac{1}{\pi} \int_0^\pi (r_{cu} - r_{cd}) \sin\theta\, d\theta = K \frac{(c_B - 1)}{c_B} \frac{V_u}{c} \quad (4)$$

where $V_u = E_y/B_u$ is the upstream convection velocity, and the integral is the average over pitch angles, assuming isotropic dis-

$$K_1 = hK_0; \quad h = 1 + (1 - 1/c_B)V_u/c.$$

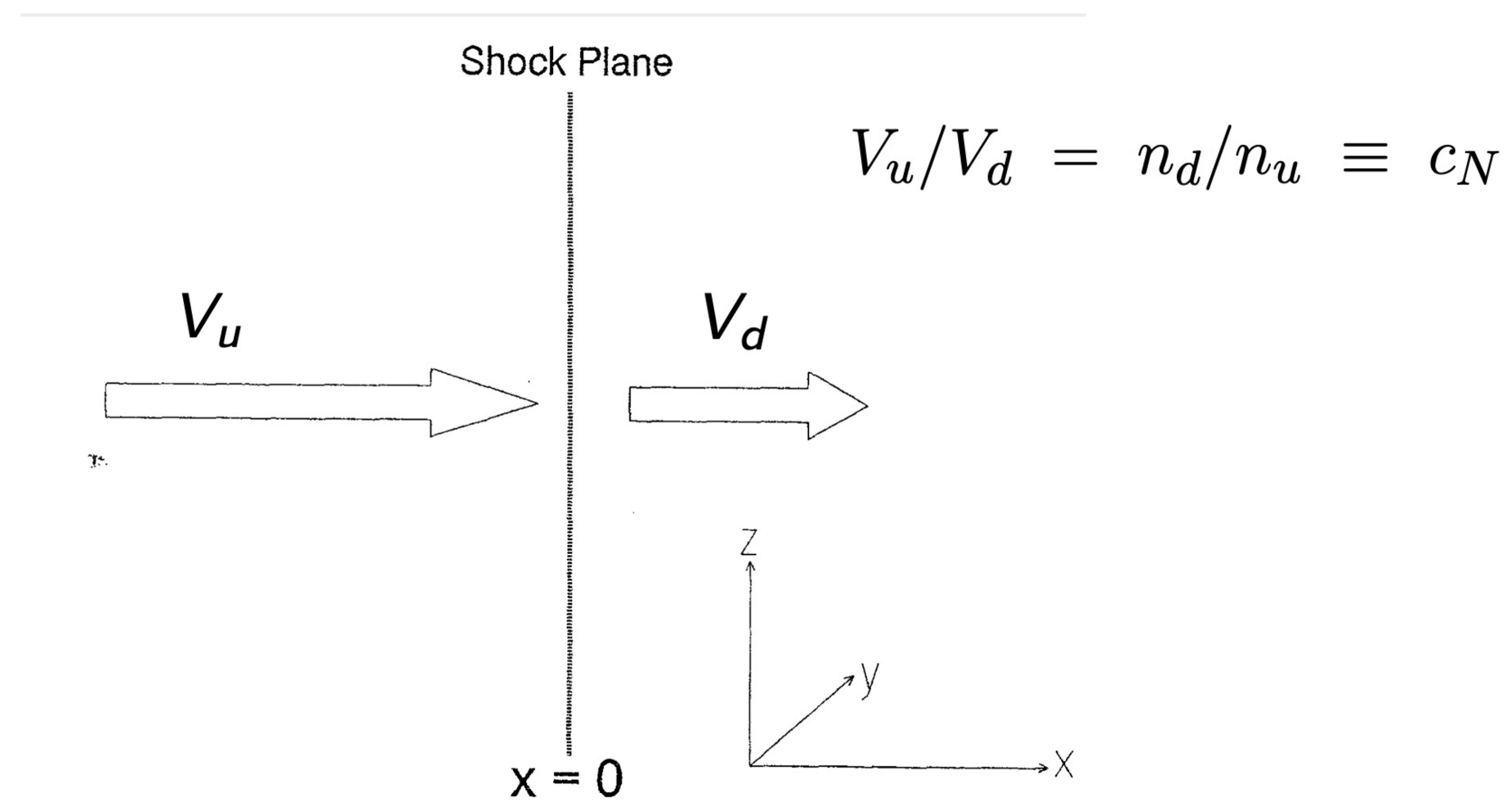
$$\frac{dN}{dK} \propto K^s$$

Spectral index predicted by BSA

$$s = \frac{\ln P}{\ln h} - 1 = -\frac{2c_B - 1}{c_B - 1}$$

$$c_B = 3; \quad s = -2.5$$

Fermi / DSA (diffusive shock acceleration)
non-physical mechanism



Energy gain based on the Lorentz transformation between upstream and downstream reference frames. NON-PHYSICAL !
commonly referred to as the first-order Fermi acceleration:

$$\Delta K_F = K \frac{(c_N - 1)}{3} \frac{V_u}{c}. \quad (5)$$

with $c_B > 1$, as illustrated in Fig. 3. Let P be the probability that particles remain in the shock region after one interaction or gyration. Then, after j interactions there are $N = N_0 P^j$ particles with energies $K = K_0 h^j$. Eliminating j, one obtains $N/N_0 = (K/K_0)^{\ln P/\ln h}$, where N is the number of particles that reached energy K and can be accelerated further. Using Longair (2011) value for probability, $P \approx 1 - V_u/c$, we find the spectrum of

Spectral index predicted by Fermi/DSA

$$s_F = \frac{\ln P}{\ln h_F} - 1 = -\frac{c_N + 2}{c_N - 1}.$$

$$c_N = 3; \quad s = -2.5$$

Incidentally correct

Explanation for the knee energy

Although BSA would function effectively at arbitrarily high energy, the acceleration in the upstream region will be counteracted by deceleration in the downstream region as the diameter of the orbit on the compressed side approaches the shock length L, see Fig. 3. The condition $2r_{cd} \sim L$ would result in a knee in the spectrum located at energy

$$K_L \sim \frac{qc}{2} \langle LB_d \rangle. \quad (10)$$

2010). The observed knee energy, $K_L \approx 5 \times 10^{15}$ eV, is derived from Eq. (10) for $\langle LB_d \rangle \sim 1$ nT pc, which could correspond to, for example, $B_d \approx 1$ nT on the inner (compressed) side of a spherically expanding supernova shock and $L \sim 1$ pc. Shocks with length $L < 1$ pc inside supernova remnants with an effective compression $c_B = 3$ would lead to $s = -2.5$, which could explain the energy spectrum below the knee.