# Particle Acceleration and Turbulence Generation in Collisionless Shocks

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Shock Waves, Turbulence, and Particle Acceleration
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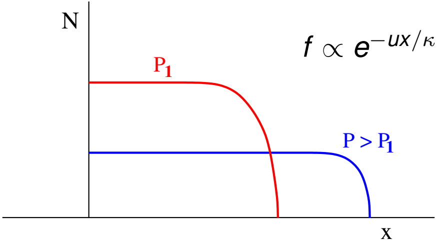
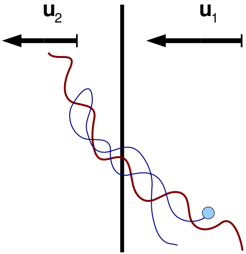
# Particle acceleration at collisionless shocks




- Higher energy particles diffuse further upstream




- Particles scattered/confined by *self-generated* waves
- transport equation:

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial x}\left(uf - \kappa(x,p)\frac{\partial f}{\partial x}\right) = \frac{\partial}{\partial p^3}\left(p^3 f \frac{\partial u}{\partial x}\right) + Q$$

# DSA - The diffusion approximation

Bell, Blandford & Ostriker, Krymskii, Axford et al.

- Steady-state test particle solution:

$$f_+(p) = ap^{-q} + q\int_0^p \frac{\mathrm{d}p'}{p}\left(\frac{p'}{p}\right)^q f_-(p')$$

where $q = 3r/r - 1$

- Produces power-law spectrum (independent of $\kappa$.)
- Maximum energy in Bohm limit ($\sim 5\mu$G field) $\ll 10^{15.5}$eV
- Steady CR spectrum requires $U_{cr}/\rho u_{sh}^2 \sim 10\%$
- $\delta B^2/B_0^2 \gg 1$ ?

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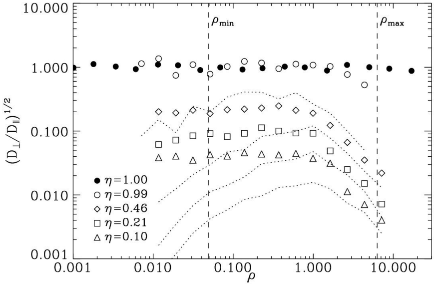


Casse et al. 2002

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# Turbulence generation & Magnetic field amplification

Inside a cosmic ray precursor, several instabilities can operate

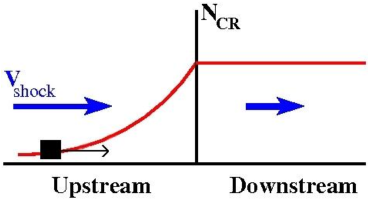
- streaming instability (Bell 1978)
- Drury instability (Drury 1984)
- Firehose instability (Quest & Shapiro 1996)
- Non-resonant instability (Lucek & Bell 2000, Bell 2004)
- small-scale dynamo (Beresnyak et al 2009)

Instabilities can also operate downstream

- Nonlinear Richtmeyer-Meshkov instability (Giacalone & Jokipii 2007)
- charge exchange current driven instability (Ohira et al. 2009)

# Numerical sims of nonresonant instability-Bell 04

- box in upstream plasma frame
- Parallel shock configuration
- CRs stream at $\approx$ shock speed
- $L_{box} \ll r_g \ll \kappa(p_{min})/u$
- periodic boundary conditions
- $\mathbf{j}_{cr} || \mathbf{B}_0$
- $\mathbf{j}_{cr} \cdot \mathbf{E} = \mathbf{u} \cdot (\mathbf{j}_{cr} \times \delta\mathbf{B})$

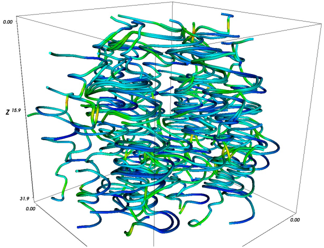



- $j_{cr}(\mathbf{x}, t) = \text{const.}$
  although see
  Lucek & Bell 2001,
  Zirakashvili et al 2008,
  Niemiec et al. 2009,
  Riquelme & Spitkovsky 2009

# Test particle transport in amplified field

- Take a snapshot of field in early stages of non-linear development, $kL_{box} \lesssim 1$
- determine statistical properties of field lines and diffusion

- integrate particle trajectories




$$\frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = q\mathbf{v} \times \mathbf{B}$$

$$\frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t} = \mathbf{v}$$

for a set of isotropic particle distributions

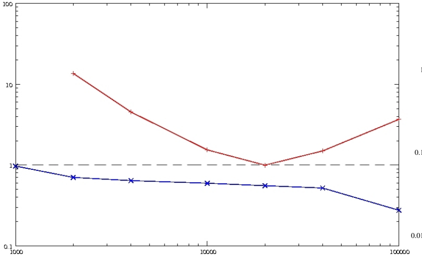
Determine asymptotic behaviour of $\dfrac{< \Delta x_i^2 >}{2\Delta t}$

# Diffusion coefficients

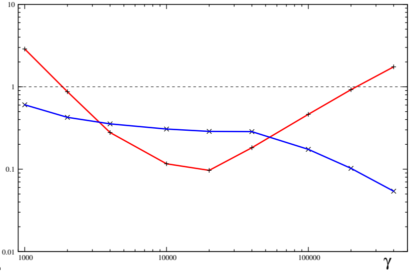
Comparison of diffusion coefficients to Bohm limit in the pre-amplified field $B_0 = 3\mu\mathrm{G}$

$\kappa_{\|}/\kappa_{Bohm}$, $\kappa_{\perp}/\kappa_{Bohm}$

$\delta B^2/B_0^2 \sim 5$



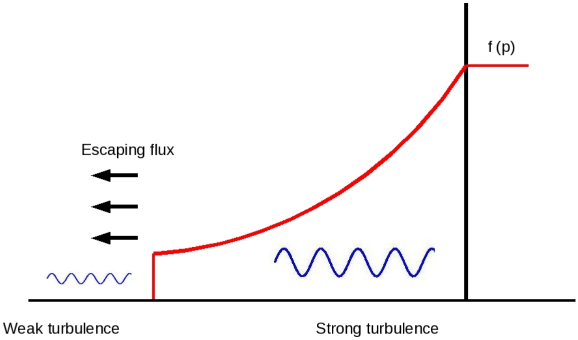

$\delta B^2/B_0^2 \sim 25$




BR, O'Sullivan, Duffy, Kirk (2008) MNRAS

# Cosmic-ray modified shock with free escape boundary

- Scattering waves are self-generated




- At a certain distance upstream, magnetic turbulence too weak to confine particles ($\kappa \to \infty$)
- magnetic field growth (amplification) driven in transition region
- Bohm diffusion in saturated field $B \sim \xi_{\rm cr} \rho u_{\rm sh}^3 / c$

# Steady-state solutions

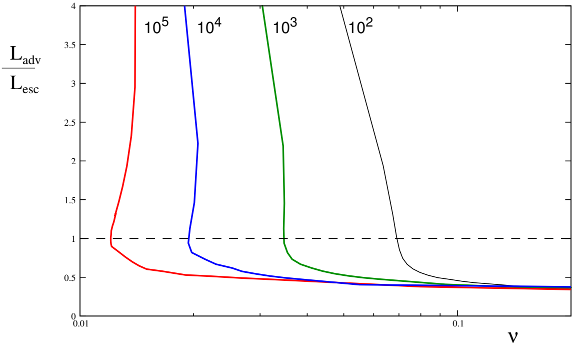
- solve hydrodynamic + transport equations numerically
- Boundary condition: $f(L_{\rm esc}) = 0 \;\; , \quad L_{\rm esc} \equiv \kappa(p^*)/u_0$
- diffusive current at escape boundary drives growth of waves

$$j_{\rm cr}(-L_{\rm esc}) = -4\pi e \int_{p_0}^{\infty} \kappa \frac{\partial f}{\partial x} p^2 \mathrm{d}p$$

- nonresonant mode growth dominates provided:

$$\zeta M_A^2 \equiv \frac{j_{cr} p^*}{e \rho_0 u_0^2} M_A^2 > 1$$

# Maximum momentum




$u_{sh} = 5000\text{km s}^{-1}$

$n_0 = 1\ \text{cm}^{-3}$

BR, Kirk & Duffy, 2009

$$\nu = \frac{4\pi}{3}\frac{mc^2}{\rho_0 u_0^2}p_0^4 f_0(p_0), \qquad L_{\rm adv} \equiv u_{\rm sh}/\Gamma_{\rm max} \sim L_{\rm esc}$$

- steady state maximum energy function of injection parameter
  $\rightarrow$ self regulating system

# Summary

- turbulence generation/magnetic field amplification a natural consequence of efficient DSA

- Future simulations will answer many questions

- time asymptotic solutions to modified shock problem and boundary conditions investigated

- particle accelerating shocks appear to be self-organising /self-regulating systems