The Issue With Diffusive Shock Acceleration

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Non-Relativistic Collisionless Shocks

Prominent sites of non-thermal particles and emission

Heliospheric
- Earth's bow shock
- Interplanetary shocks

Stellar bow shocks
- Novae

Extra-Galactic
- Radio SNe
- AGN lobes

Galactic
- Supernova remnants

Intra-cluster shocks
A universal acceleration mechanism

**Fermi mechanism** (Fermi, 1949): random elastic collisions lead to energy gain

In shocks, particles gain energy at any interaction (Krymskii77; Blandford & Ostriker; Bell; Axford+78)

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On the Origin of the Cosmic Radiation

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A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

For strong shocks: Mach number $M = \frac{v_{sh}}{c_s} \gg 1 \rightarrow R = 4$ and $q = 4$ (in energy, $q_E = 2$)

$$R = \frac{4M^2}{M^2 + 3}; \quad q = \frac{3R}{R - 1}$$
Non-Linear Diffusive Shock Acceleration

- The momentum spectral index depends only on the compression ratio:
  \[ q = \frac{3R}{R - 1} \quad \text{and} \quad R = \frac{\gamma + 1}{\gamma - 1} \]

- The CR pressure makes the adiabatic index smaller and hence \( R \) larger.

- Particles “feel” different compression ratios: spectra should become concave.

- If acceleration is efficient, at energies >1 GeV: \( q < 4 \) (flat spectra!)

(e.g., Jones-Ellison91, Malkov-Drury01 for reviews)
What Do Observations Say?
Gamma-Rays from SNRs

SNR spectra are expected to be \textit{flatter than \(E^{-2}\)}; instead, they are \textit{steeper}!

Too steep to be leptonic: \textit{hadronic} emission

Not consistent with \textit{non-linear DSA theory}!
Extra-galactic SNe

- Fast shocks in young SNRs
- Radio emission requires (e.g., Chevalier-Fransson06)

\[ f(E) \propto E^{-3} \rightarrow q_E \approx 3; q \approx 5 \]

Radio slope
\[ \alpha = \frac{q_E - 1}{2} \]

Non-linear theory (\( q_E < 2 \))

Adapted from Bell+11
A Theoretical Challenge

- Shocks in partially-neutral media (Blasi+12; Morlino+13; Ohira14, …)
- Oblique trans-relativistic shocks (Kirk+96; Morlino+07; Bell+11, …)
- Geometry effects (Malkov-Aharonian19, Hanusch+19)
- Ion “losses” due to magnetic field amplification (Bell+19)

Feedback of amplified magnetic fields (Bell78; Zirakashvili-Ptuskin08; DC+09; DC11,12,…)

None of these ideas has been tested from first principles!

The large velocity of scattering centers $v_{\text{waves}} \approx v_A(\delta B)$ leads to an effective ratio:

$$R_{cr} \approx \frac{u_1 \pm v_{A,1}}{u_2 \pm v_{A,2}} \lesssim R_{\text{gas}}$$
Astroplasmas from first principles

**Full-PIC approach**
- Define electromagnetic fields on a grid
- Move particles via Lorentz force
- Evolve fields via Maxwell equations
- Computationally very challenging!

**Hybrid approach**: Fluid electrons - Kinetic protons
(Winske-Omidi; Burgess+; Lipatov02; Giacalone+; DC-Spitkovsky+; Haggerty-DC,…)
- massless electrons for more macroscopical time/length scales
Hybrid Simulations of Collisionless Shocks

**dHybrid code** (Gargaté et al, 2007; DC & Spitkovsky 2014, Haggerty & DC, in prog.)
A Revised Theory of Non-Linear DSA

- Unprecedentedly-long hybrid sims with \(d\text{HybridR}\), including relativistic ion dynamics (Haggerty-DC, soon)
- \(R\) increases with time, up to \(~7!\)
- \(R\sim6-7\) inferred in Tycho (Warren+05)
- \(R \approx 7 \rightarrow q_{\text{expected}} \approx 3.5\)
- CR spectra fitted with \(q \approx 4.2\)
- Evidence for decoupling between \(R_{\text{gas}} \approx 7\) vs \(R_{\text{cr}} \approx 3.5\)

DC, Haggerty, Blasi, in prog.
Velocity of the CR Scattering Centers

CR feel an effective compression:

\[ R_{cr} = \frac{u_1 + w_1}{u_2 + w_2} \]

We can measure the effective CR speed \( \langle v_{cr} \rangle = u + w \)

Upst: \( w_1 \ll u_1 \approx 21.5v_A \approx 0.9v_{sh} \)

Downst: \( u_2 \approx 3.5v_A; w_2 \approx 2.3v_A \)

\[ R_{gas} \approx \frac{v_{sh}}{u_2} \approx 6.7; \quad R_{cr} \approx \frac{u_1}{u_2 + w_2} \approx 3.6 \]

Slope \( q = \frac{3R_{cr}}{R_{cr} - 1} \) fits the spectrum!

DC, Haggerty, Blasi, in prog.
Conclusions

Hybrid simulations with relativistic ions

Acceleration efficiency $\sim 10\%$ for large $M$

Evidence of CR-modified shocks: upstream precursor and increased $R_{\text{gas}} \approx 7$

CRs feel a $R_{cr} < R_{\text{gas}}$ due to net velocity of amplified magnetic structures downstream (different from anything in the literature,…)

First-principle explanation for the observed steep DSA spectra, e.g., in SNRs

More scalings with shock parameters are being worked out
Hybrid Simulations with Relativistic Ions: dHybridR

- Hybrid limit requires $v_{\text{bulk}} \ll c$

- DSA: $f(p) \propto p^{-4}$; $4\pi p^2 f(p) \, dp = f(E) \, dE$

- $f(E) \propto E^{-1.5}$ (non rel.) $\Rightarrow$ $f(E) \propto E^{-2}$ (relativ.)

- Long-term evolution
  
  - $E_{\text{max}}(t) \propto t$
  
  - Efficiency 10-12%
**Evidence of a CR Precursor**

The CR pressure *slows* the upstream flow down and *heats* it up.

- B damping leads to *non-adiabatic* heating
- \( \sim \) *equipartition* between gas and B pressures
- Compression \( \sim 1.3 \) upstream and \( R_{TOT} > 4 \) overall!