Theory and Simulations of Particle Acceleration in Collisionless Non-relativistic Shocks

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Shocks in the Universe

Enhance their dynamical importance (see the next section).

We found that most clusters and groups with $T_x > 1$ keV have shocks within 0.5 $h/c_0^1$ Mpc from the centers at present. The area distribution of these cluster shocks, shown in the upper right panel of Figure 5, fits best to $dS(M, z) d\log M/c_0^18/ \sqrt{M_{\text{ch}}/c_1^18}$ with $M_{\text{ch}}/c_25^1$ in the range of $M_{\text{d}}/c_10^1$. Their mean Mach number is $c_24^4$. The cluster shocks, however, actually account for only a very small fraction of identified shock surfaces. We emphasize that the statistics for the cluster shocks would have been affected by the finite resolution, $\Delta l = 9.7^1 h/c_0^1$ kpc, as well as by the exclusion of physical processes such as radiative cooling and feedback from galaxies and stars that influence conditions inside cluster cores. Still, it is significant that, compared with the distribution of binary merger shocks studied Fig. 4.

Three-dimensional shock surfaces in a volume of $(25^1 h/c_0^1)^3$ Mpc$^3$ around the same complex as in Fig. 3. The color bar shows the values of Mach numbers of shock surfaces.

<table>
<thead>
<tr>
<th>$z$</th>
<th>$S_{\text{ext}}$</th>
<th>$S_{\text{int}}$</th>
<th>$h M_{\text{d}}/c_0^1$</th>
<th>$h M_{\text{d}}/c_0^1$</th>
<th>$h v_{\text{sh}}/c_0^1$</th>
<th>$h c_s/\sqrt{c_0^1}$</th>
<th>$h c_s/\sqrt{c_0^1}$</th>
<th>$h /c_0^1$</th>
<th>$h /c_0^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>4.4 2.1 8.0 3.2</td>
<td>123 226 15.3 82</td>
<td>1.05 6.78</td>
<td>0.2 4.4 2.3 8.1</td>
<td>3.3 123 230 15.3</td>
<td>83 1.12 7.15</td>
<td>0.5 4.5 2.8 8.0</td>
<td>3.3 122 231 15.3</td>
<td>83 1.25 7.86</td>
</tr>
<tr>
<td>1.0</td>
<td>5.0 3.7 7.5 3.4</td>
<td>114 214 15.3 76</td>
<td>1.48 8.87</td>
<td>1.5 5.7 5.0 7.0</td>
<td>3.4 107 196 15.3</td>
<td>69 1.79 10.3</td>
<td>2.0 6.8 6.6 6.5</td>
<td>3.4 100 177 15.3</td>
<td>62 2.14 10.9</td>
</tr>
</tbody>
</table>

TABLE 1

Mean Flow Quantities of External/Internal Shocks at Several Different Epochs

Lengths in units of $(1 + z)c_0^1$ Mpc, speeds in km s$^{-1}$, and density compared to the mean comoving density of gas $h/c_26$ gas$^1$. sn1006

Snr1006 CME

CME

Cygnus A

Ryu+03

Tsurutani&Rodriguez'81

SN1006
Particle Acceleration

X-ray image by Chandra [Bamba+2003]

In-situ obs. by Geotail [Shimada+1999]
"Standard Model"

- Diffusive Shock Acceleration (DSA)
  - established in late 70's [e.g., Bell '78]
  - predicts a universal power-law: $N \propto E^{-2}$
  - simple; comparison with observations is relatively easy
Questions

1. What fraction of the total energy is converted into accelerated particles?

2. What is the maximum particle energy achievable?

Key Issues
- Injection
- Nonlinear Feedback
- Particle Transport
Energetics

Energy conversion efficiency $\sim 10\%$ ? (needed for SNRs)

Not bad at CME-driven shocks. But, the maximum energy is much smaller.

Mewaldt+ (2006)
Positive Feedback

DSA is an intrinsically efficient process!

Recall that the standard DSA theory predicts the spectrum of the form:

\[ f(p) \propto p^{-q} \quad q = \frac{3r}{r - 1} \]

(r is the shock compression ratio)
Possible Negative Feedback?

• Injection
  If the injection occurs predominantly at the subshock, the reduction of Mach number in the precursor may lower the injection rate.

• Turbulent Heating
  Turbulence driven by streaming CRs in the precursor becomes so strong, so that one expects turbulent dissipation may reduce the overall efficiency.
Injection

- Thermal Distribution
- Injection
- Fermi Acceleration
- high energy cutoff due to:
  1) escape
  2) radiation loss
  3) shock age
- log(Particle Number)
  - 0.1 keV
  - 1 MeV
  - 10-100 TeV?
- log(Particle Energy)
- X-ray
- standard theory
- concave spectrum due to shock modification?
The Injection Problem

The seed population must have sufficiently large energy so that they
• easily traverse the shock: \( v \gg V_{\text{shock}} \)
• scatter by waves for isotropization

\[
\frac{\omega - k v_{||}}{\Omega/\gamma} = 1
\]

for \( \omega \ll \Omega/\gamma \)

\[
k r_g \sim 1
\]

relatively easy for ions, but serious difficulty for electrons
Protons

Russell & Hoppe (1983)
Protons

Sugiyama (2011)
Electrons

Only relativistic electrons can satisfy the resonance condition with low-frequency MHD waves

\[ \omega - kv_\parallel = \Omega/\gamma \]

Possible solutions to the electron injection problem:

✧ **Generation of high-frequency (whistler) waves**

or

✧ **Pre-acceleration to > 100keV**
**Generation of whistlers**

**Q**: How to generate whistlers?

**A**: Consider mirrorly reflected energetic electrons. 

Amano & Hoshino (2010, PRL)
Oka+2006 argued that the electron acceleration efficiency at the bow shock is regulated by a whistler critical Mach number $M_{\text{crit}}^w$. This by chance corresponds to the critical Mach number of ours (within a numerical factor ~1).

Note: $\alpha \sim \beta_e \sim 1$
First Principles Approach

To understand possible pre-acceleration mechanisms:
• Shock internal structure
• Kinetic instabilities
• Plasma waves

must be considered. This involves extremely complicated nonlinear physics. Fully kinetic Particle-In-Cell simulation is the only option to investigate the mechanisms.

Caveat:
Any (!) simulations employ artificial parameters such as
• ion-to-electron mass ratio: \( m_i/m_e \)
• plasma-to-cyclotron frequency ratio: \( \omega_{pe}/\Omega_{ce} \propto v_A \)

Unfortunately, plasma instabilities are sometimes sensitive to these parameters.
Shock Surfing Acceleration

Plausible mechanism at very high Mach number shocks:
- **2D**: Amano&Hoshino(2009), Matsumoto+(2012)

![Graph showing particle number and Ke/K0 ratio vs. solitary wave](image)

Hoshino&Shimada (2002)
Spontaneous Reconnection

$\log_{10}(N_e/N_0)$

Upstream Flow Energy

Generation of B-field

Magnetic Reconnection

Particle Acceleration

$Ma=45, \ mi/me=225$

Matsutomo, Amano, Kato, Hoshino (Science, 2015)
Magnetic Field Amplification

Extremely fast decay of X-ray hot spots
Uchiyama+(2007, Nature)

Magnetic field amplification by CR streaming instability
Lucek&Bell(2000), Bell(2004)
Non-adiabatic Heating

Wave kinetic equation (for shear Alfvén wave)

\[
\frac{\partial}{\partial t} \left( \frac{\delta B^2}{4\pi} \right) + \frac{\partial}{\partial x} \left[ \left( \frac{\delta B^2}{4\pi} \right) \left( \frac{3}{2} u - v_A \right) \right] = u \frac{\partial}{\partial x} \left( \frac{\delta B^2}{8\pi} \right) + v_A \frac{\partial}{\partial x} P_c - L
\]

is coupled with the CR diffusion-convection and hydrodynamic equations.

Work done by CR pressure gradient (wave generation)

\[
\frac{\rho^{\gamma^{-1}}}{\gamma - 1} u \frac{\partial}{\partial x} \left( \frac{P_g}{\rho^\gamma} \right) = L
\]

Dissipation of wave energy leading to entropy production

Assumption of a specific form of dissipation: \( L = \alpha v_A \frac{\partial P_c}{\partial x} \)

[e.g., McKenzie & Voelk, 1982]
Non-adiabatic heating substantially reduces the subshock Mach number! The acceleration efficiency is degraded from the standard NLDSA solution, but yet resides above the test-particle limit.

T. Saito (Ph.D thesis)
Conclusions

• Particle acceleration efficiency of 10-20% (in terms of energy conversion rate) seems to be possible.
• Conventional understanding is that nonlinearity enhances the efficiency, in an essentially unlimited manner.
• There must be something that would suppress otherwise the unlimited acceleration.
• The injection and turbulence have yet remained the key issues in the shock acceleration theory.