Particle acceleration at relativistic shock waves... ... and cosmic rays...

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Cosmic rays from relativistic shocks

→ energy budget: do relativistic sources contribute to the cosmic ray flux?

→ microphysics: how does relativistic shock acceleration operate (→ maximum energy)?
Cosmic rays from relativistic shocks

\( \dot{N}_0 \tau_{\text{conf}} E_{\text{cr}} \sim 10^{48} E_{18}^{-1} \text{ erg} \) (assumes \( V_c = 10^{67} \text{ cm}^3 \))

→ to match the flux at energies \( >10^{15} \text{ eV} \) and \( <10^{18} \text{ eV} \):

<table>
<thead>
<tr>
<th>MW rate</th>
<th>confinement time at E</th>
<th>E injected in cr at E</th>
<th>flux matching E</th>
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</table>

→ for the long gamma-ray burst population:

\( \dot{N}_{\text{GRB}} \sim 10^{-4} \text{ yr}^{-1}, \ E_{\text{GRB}} \sim 10^{51} \text{ erg}, \ \tau_{\text{conf}} \gtrsim 10^{2} \text{ yr} \)

... however, rare sources: \( \dot{N}_{\text{GRB}} \tau_{\text{conf}} \ll 1 \) at \( \sim 10^{18} \text{ eV} \)?

→ for low luminosity gamma-ray bursts/trans-relativistic SNe:

\( \dot{N}_{\text{LLGRB}} \sim 10^{-3.5 \pm 0.5} \text{ yr}^{-1}, \ E_{\text{LLGRB}} \sim 10^{50} \text{ erg} \)

⇒ relativistic supernovae and GRBs may potentially contribute to the CR flux at high energies (e.g. Milgrom + Usov 96, Dermer 02, Budnik et al. 08, Wang et al. 08, Calvez et al. 09, Chakraborti et al. 11, see also Eichler & Pohl 10, 11)

... main uncertainties: source rate, confinement time, injected E distribution

→ for pulsar winds: potentially interesting, but what is \( E_{\text{cr}} \)?

Relativistic Fermi acceleration - ultra vs non-relativistic

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<td><em>no Bohm scattering</em> in self-generated field: precursor size ( \sim r_{\text{L,max}}/\gamma_{\text{sh}}^3 )</td>
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Relativistic Fermi acceleration - energy gain, kinematics

Energy gain:

\[ \frac{\Delta E_{\text{up}}}{E_{\text{up}}} = \gamma_{\text{bext}}^2 (1 + \beta_{\text{bext}} \cos \theta_{\text{down-up}}) \left(1 - \beta_{\text{bext}} \cos \theta_{\text{up-down}}\right) - 1 \]

with relative up-down Lorentz factor: \( \gamma_{\text{bext}} \approx \gamma_{\text{sh}} / \sqrt{2} \)

\[ \Rightarrow \text{distance between particle and shock wave after time } t: \quad (1 - \beta_{\text{sh}})ct \approx c t/(2\gamma_{\text{sh}}^2) \]

\[ \Rightarrow \text{particle caught back once its parallel velocity drops below } \beta_{\text{sh}} \]

\( \Leftrightarrow \text{deflection by } 1/\gamma_{\text{sh}} \)

\[ \Rightarrow \text{energy gain } \sim \gamma_{\text{sh}}^2 \text{ at first interaction, then } \sim 2 \]

\[ \Rightarrow \text{precursor length scale } \sim r_L/(2\gamma_{\text{sh}}^3) \]

note: for parallel shock waves, precursor length scale \( \sim \) infinite as some particles may escape along field lines

Relativistic Fermi acceleration - ultra vs non-relativistic

Non-relativistic shock waves

\[ \beta_{\text{sh}} \ll 1, \quad \gamma_{\text{sh}} \approx 1 \]

• diffusive shock acceleration
• parallel, oblique or perpendicular configuration
• scattering in large scale turbulence
• self-amplification of turbulence
• possibly Bohm scattering in self-amplified field

Ultra-relativistic shock waves

\[ \beta_{\text{sh}} \approx 1, \quad \gamma_{\text{sh}} \gg 1 \]

• non diffusive (upstream) because \( \beta_{\text{sh}} \sim \beta \sim 1 \)

• nearly always perpendicular (=superluminal)
• scattering in small scale turbulence (\( l \ll r_L \))
• self-generation of e.m. microturbulence
• no Bohm scattering in self-generated field:
  precursor size \( \sim r_{L, \text{max}}/\gamma_{\text{sh}}^3 \)
**Ultra-relativistic superluminal shock waves**

\[ B_{\perp|sh} = \gamma_{sh} B_{\perp|u} \]
\[ B_{\parallel|sh} = B_{\parallel|u} \]

\[ \Rightarrow \text{ultra-relativistic shock waves are mostly perpendicular (superluminal)} \]

Note: behind the shock: \( \langle E_p \rangle \) close to \( \langle E_e \rangle \)
\[ \gamma_e \text{ close to } \gamma_p \frac{m_e}{m_i} \text{ (depending on } \sigma, \gamma_{sh}) \]

\( \Leftarrow \text{efficient heating, indicated by PIC simulations} \)

Sironi & Spitkovsky 11

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**Relativistic Fermi acceleration - ultra vs non-relativistic**

**Non-relativistic shock waves**
\[ \beta_{sh} \ll 1, \gamma_{sh} \approx 1 \]
- *diffusive* shock acceleration
- parallel, oblique or perpendicular configuration
- scattering in large scale turbulence
- self-amplification of turbulence
- possibly Bohm scattering in self-amplified field

**Ultra-relativistic shock waves**
\[ \beta_{sh} \approx 1, \gamma_{sh} \gg 1 \]
- *non diffusive* (upstream) because \( \beta_{sh} \approx \beta \ll 1 \)
- nearly always perpendicular (=superluminal)
- scattering in small scale turbulence \( (l \ll r_L) \)
- self-generation of e.m. microturbulence
- no Bohm scattering in self-generated field:
  \[ \text{precursor size } \sim r_{l,\max}/\gamma_{sh}^{\frac{3}{2}} \]
Relativistic Fermi acceleration - oblique shock waves

Ultra-relativistic shock waves are generically superluminal:
- the intersection between a magnetic field line and the shock front moves faster than c
- if a particle is tied to a field line, this particle cannot return to the shock front...

Scattering from turbulence:
- large scale turbulence does not help:
  the particle cannot execute more than 1 1/2 cycle...
  up → down → up → down then advection to -∞ (ML et al. 06, Niemiec et al. 06)

large scale: w.r.t. typical Larmor radius (downstream frame) of accelerated particles of Lorentz factor $\gamma_p \sim \gamma_{sh}$

conditions for successful relativistic Fermi acceleration: $\delta B \gg B_0, \quad \ell_c \ll r_L$

for reference: $r_L \sim 10^{12} \text{ cm} \left( \frac{B_0}{1 \mu \text{G}} \right)^{-1} \left( \frac{\gamma_{sh}}{300} \right) \quad \ell_c \sim 10^{20} \text{ cm} \quad \text{in ISM}$

Relativistic Fermi acceleration - ultra vs non-relativistic

Non-relativistic shock waves

- $\beta_{sh} \ll 1, \gamma_{sh} \sim 1$
- *diffusive* shock acceleration
- *parallel, oblique or perpendicular* configuration
- *scattering in *large scale* turbulence
- *self-amplification of turbulence*
- *possibly Bohm scattering* in self-amplified field

Ultra-relativistic shock waves

- $\beta_{sh} \sim 1, \gamma_{sh} \gg 1$
- *non diffusive* (upstream) because $\beta_{sh} \sim \beta \sim 1$
- *nearly always perpendicular* (=superluminal)
- *scattering in *small scale* turbulence ($l \ll r_L$)
- **self-generation of e.m. microturbulence**
- *no Bohm scattering* in self-generated field:
  precursor size $\sim r_{max}/\gamma_{sh}^3$
Micro-instabilities at a relativistic shock front

→ shock reflected and shock accelerated particles move in upstream background field with Lorentz factor $\gamma_{sh}^2$, along shock normal, forming an unmagnetized beam of Lorentz factor $\gamma_{sh}^2$ and opening angle $1/\gamma_{sh}$

→ neutral beam instabilities: (e.g. Bret 09)

Weibel/filamentation (Gruzinov & Waxman 99, Medvedev & Loeb 99, Lyubarsky & Eichler 06, Wiersma & Achterberg 04, 07, 08; ML & Pelletier 10, 11; Rabinak et al. 10, Shaitsultanov et al. 11)

Cerenkov resonance with plasma eigenmodes: ML & Pelletier 10, 11

oblique two stream with electrostatic modes $\omega_p = k_x v_{beam}$

Whistler waves $\omega_{WH} = k_x v_{beam}$

→ charged current instabilities:

Buneman mode (ML & Pelletier 11) ... efficient source of electron heating

Bell instability... for parallel shocks (Bell 04, Reville et al. 06, ML & Pelletier 10)

→ main limitation: very short precursor, length $\sim r_{L,0}/\gamma_{sh}^3 \sim \gamma_{sh}^{-1} c/\omega_{ci}$

Phase diagram for relativistic shock acceleration

at high magnetisation, e.m. precursor → wakefield heating /acceleration e.g. Hoshino et al. 92, Gallant et al. 92, Lyubarsky 06, Hoshino 08

GRB int. shocks blazar shocks?

PIC simulations (Sironi & Spitkovsky 11)

too short precursor... no micro-instabilities... no Fermi acceleration...

micro-instabilities grow ⇒ Fermi acceleration...

GRB in ISM

ML & Pelletier 10, 11
Relativistic shock acceleration to UHE?

- Relativistic Fermi acceleration - ultra vs non-relativistic

Non-relativistic shock waves

\[ \beta_{sh} \ll 1, \gamma_{sh} \approx 1 \]

- **Small** energy gain per cycle \( \sim \beta_{sh} \ll 1 \)
- **Small** escape probability \( \sim \beta_{sh} \ll 1 \)
- Powerlaw spectrum, index \( s \approx 2 \)
- Magnetized turbulence seeded by accelerated particles...
  - **On large** scales \( \sim r_L \gg c/\omega_p \)
- Maximal energy:
  \[ E_{\text{max}} \sim \beta_{sh} Z e B_{\text{amp}} R \]

Ultra-relativistic shock waves

\[ \beta_{sh} \approx 1, \gamma_{sh} \gg 1 \]

- **Large** energy gain per cycle \( \sim 2 \) if magnetization is low enough
- **Large** escape probability \( \sim 0.3 \text{ - } 0.4 \)
- Powerlaw spectrum, index \( s \approx 2.3 ? \)
- Magnetized turbulence seeded by accelerated particles...
  - **On microscopic** scales \( \sim r_L / \gamma_{sh}^3 \gg c/\omega_p \)
- Maximal energy:
  \[ E_{\text{max}} \sim \gamma_{sh} Z e B_{0} R \approx 10^{17} \text{ eV} \]

- Magnetic self-generation in the precursor does not help push particles to UHE: filamented microturbulence \( \leftrightarrow \) inefficient scattering...
  \[ E_{\text{max}} \sim \gamma_{sh} Z e B_{0} R \approx 3 \times 10^{15} \text{ eV} \]

- PIC simulations (Sironi & Spitkovsky 11)

- Too short precursor...

- Acceleration appears efficient at the termination shock of pulsar winds... shock-driven reconnection \( \rightarrow \) scattering + acceleration? (e.g. Lyubarsky 03)

- GRB int. shocks blazar shocks?

- GRB in ISM
at low magnetization (e.g., ISM), relativistic shock acceleration develops; accelerated particles build the microturbulence in which they scatter and get accelerated...

some crucial differences wrt non-relativistic diffusive shock acceleration:

- acceleration is not diffusive upstream, but shock drift
- ultra-relativistic shock waves are very nearly perpendicular
- the precursor is strongly limited in extent: $r_{L,max}/\gamma_{sh}^{3/2}$
- Bohm scattering in the self-amplified cannot take place
- $E_{max} \sim \gamma_{sh} Z e B_0 R$

acceleration at mildly relativistic shock waves is yet another story:

- superluminal nature not generic
- precursor size may come close to $r_{L,max}$
- near Bohm scattering in the self-amplified cannot be excluded
- large $E_{max}$?