On (shock) acceleration of ultrahigh energy cosmic rays

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**Acceleration – Hillas criterion**

- **a simple criterion:** to find which object *might* be a source of UHE cosmic rays:
  - A particle gets accelerated as long as it is confined in the source:
    \[ r_L \leq L \Rightarrow E \leq 10^{20} \text{ eV} Z B \mu_G L_{100 \text{ kpc}} \]

- **refined criterion:**
  - Compare acceleration timescale with energy loss timescale and escape timescale
  - \( t_{\text{acc}} \leq t_{\text{loss}}, t_{\text{esc}} \)
  - \( t_{\text{acc}} \) depends on acceleration mechanism
  - \( t_{\text{esc}} \) depends on magnetic field
  - \( t_{\text{loss}} \) depends on environment

- Requires an object by object study...

- Norman et al. 95

... magnetars, gamma-ray bursts and radiogalaxies are promising candidates...
Fermi acceleration at non-relativistic shock waves

- Fermi acceleration at supernovae shock waves: likely source of Galactic cosmic rays

SN1006

- Energy gain per cycle:
  \[ g \equiv \frac{\Delta E_{up}}{E_{up}} = \Gamma^2_{\text{rel}} (1 + \beta_{\text{rel}} \cos \theta_{\text{down} \rightarrow \text{up}}) (1 - \beta_{\text{rel}} \cos \theta_{\text{up} \rightarrow \text{down}}) - 1 \]

- Analytical predictions: test particle undergoing diffusive propagation on both sides of non-relativistic shock with energy gain \( g \) per cycle and downstream return probability \( P_{\text{ret}} \)
  - energy gain:
    \[ g \simeq \beta_{\text{sh}} \]
  - cycle time:
    \[ t_{\text{cycle}} \simeq \frac{t_{\text{scatt}}}{\beta_{\text{sh}}} \]

  acceleration timescale:
  \[ t_{\text{acc}} = t_{\text{cycle}}/g \sim \frac{t_{\text{scatt}}}{\beta_{\text{sh}}^2} \]

  \( E_{\text{max}} \) = \( \frac{1}{g} \frac{1}{1 + \log(1/P_{\text{ret}})} \) \( \simeq 2.0 \)
Fermi acceleration at ultra-relativistic shock waves

- **Energy gain:** \( g \equiv \Gamma_{\text{rel}}^2 (1 + \beta_{\text{rel}} \cos \theta_{\text{down} \rightarrow \text{up}}) (1 - \beta_{\text{rel}} \cos \theta_{\text{up} \rightarrow \text{down}}) - 1 \sim \Gamma_{\text{rel}}^2 \) ?

- **a crucial difference:** ultra-relativistic shock wave propagates about as fast as the ultra-relativistic particle… for example: \( \Gamma_{\text{sh}} = 100 \leftrightarrow \beta_{\text{sh}} = 0.99995! \)

- **upstream:** particle cannot turn around, it is overtaken by the shock front

  \[ \cos \theta_{\text{up} \rightarrow \text{down}} \sim 1 \Rightarrow g \sim 1 \quad \text{except at 1st cycle} \] Gallant & Achterberg 99

- **downstream:** advected away from the shock at speed \( c/3 \) \( \Rightarrow \) large escape probability
Fermi acceleration at ultra-relativistic shock waves

- **No Fermi acceleration**: if the Larmor radius of accelerated particles $\ll$ coherence length of $B$, the particle is captured on a field line and advected away downstream since the magnetic field is shock compressed to a perpendicular configuration (M.L., Pelletier & Revenu 2006)

\[
B_{\perp,\text{down}} \approx \Gamma_{\text{sh}} \sqrt{8} B_{\perp,\text{up}} \\
B_{\parallel,\text{down}} = B_{\parallel,\text{up}}
\]

$⇒$ the Fermi process stops after 1 cycle… unless the magnetic field is strongly amplified on small spatial scales $\ll r_L$

- **GRB afterglows**: synchrotron from $e^-$ accelerated at external shock with $\Gamma_{\text{sh}} \sim 300 \rightarrow 1$
  - requires downstream amplification of ISM magnetic field by 4 orders of magnitude
  - X-ray afterglow also requires amplification of upstream magnetic field by $\geq 2$ orders of magnitude (Li & Waxman 2006)

$⇒$ a connection between theory and observations … ?
Fermi acceleration at ultra-relativistic shock waves

**Monte Carlo simulations:**

- follow particle trajectories in pre-determined magnetic turbulence
- $\Rightarrow$ test particle approximation

\[ \delta B \ll B \]

Niemiec et al: inefficient Fermi process unless $\delta B \gg B$

**Conditions for successful Fermi acceleration at ultra-relativistic shock waves:**

- noise associated with motion in the small scale turbulent magnetic field overcomes the unperturbed trajectory in the large scale coherent magnetic field:

\[
\Gamma_{sh} \lambda_B \ll r_L \ll \frac{\delta B}{B} \Gamma_{sh} \lambda_B \quad \text{upstream}
\]

or

\[
\lambda_B \ll r_L \ll \frac{\delta B}{B} \lambda_B \quad \text{downstream}
\]

Niemiec, Ostrowski & Pohl 06:

Pelletier, M.L. & Marcowith 08
Micro-instabilities at relativistic shock waves

**Current situation:** relativistic Fermi acceleration requires strong amplification of upstream or downstream magnetic field… which instability?

- **downstream:** Weibel two stream (Gruzinov & Waxman 99, Medvedev & Loeb 99)
  
  → amplifies the magnetic field on small scales downstream $\sim c/\omega_{p,\text{down}} \sim 10^5$ cm
  → **BUT:** does not explain amplification of upstream field
  → open question: evolution of short scale field on long timescales?

- **upstream:** feedback of accelerated particle population?
  
  e.g.: streaming instability  
  Milosavljevic & Nakar 06, Reville et al. 07
  → **BUT:** streaming instability limited to parallel shock waves $\Theta_B < 1/\Gamma_{sh}$, and for generic (oblique) shock waves, MHD instability saturates at $\delta B/ B \sim 1$
  Pelletier, M.L. & Marcowith 08
  → Weibel like instability between accelerated particles and upstream plasma  
  (Medvedev & Zakutnyaya 08) or resonant Cerenkov with plasma modes  
  (Pelletier, M.L. & Marcowith 09)

**Implications:**

- micro-instabilities act on small scales $\Rightarrow$ large $t_{\text{scatt}} \Rightarrow$ large $t_{\text{acc}}$ … unlikely to reach UHE
- spectral index of relativistic Fermi acceleration still unknown (no canonical value!)
- much ongoing work on: efficiency vs upstream magnetization, wave particle interactions,… both analytical and numerical
Particle in cell simulations of relativistic Fermi acceleration

- **PIC simulations of e-p plasma:** e.g. Nishikawa et al., Hededal et al., Dieckmann et al., Spitkovsky et al.

  → solve self-consistently for particle – field interactions: ⇒ **beyond test particle**

  … sees evidence for Fermi acceleration and particle – wave interactions

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**Graphical Representation:**

- **downstream**
- **upstream**
- **shock**
- **accelerated particle population**
- **Fermi cycles**

**Spitkovsky 2008**

**Evidence for Fermi acceleration**

**Position** → **Energy** → **Time**

**Momentum along x**
Acceleration to UHE in gamma-ray burst fireballs

Fermi at mildly relativistic internal shocks (Waxman 95, 01)

decoupling because \( p+\gamma \rightarrow n+\pi \)

\( n \) + PeV \( \nu \)

\( p \)

shock

internal shocks

at external shock (Vietri 95)

Gallant & Achterberg 99, Vietri et al. 03: Fermi 1 in pulsar wind

Dermer & Humi 01: Fermi 2 in downstream turbulence

overall: models allow acceleration to \( \sim 10^{20} \) eV provided some assumptions about the source parameters are verified (e.g. B, turbulence, …)

to fit the CR flux: \( E_{\text{UHECR, iso}} > 10^{53} \) ergs

with a rate (z=0): \( \frac{dn}{dt} \sim 0.3 \) /Gpc\(^3\)/yr

Budnik et al. 08, Guetta & Piran 07, Zitouni et al. 07

Fermi 2 through multiple interactions with mildly relativistic internal shocks (Gialis & Pelletier 03)

decoupling because \( E_{\text{max}} > E_{\text{conf}} \)

\( p \)

at reverse shock, if mildly relativistic (Waxman 01)

\( p \)

p scatters across a velocity gradient

shear acceleration in the core of the jet (Rieger & Duffy 06)
Acceleration – a luminosity bound

- **A generic case**: acceleration in an outflow

  - acceleration timescale (comoving frame): \( t_{\text{acc}} = \mathcal{A} t_L \)

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<th>( \mathcal{A} &gt; 1 ) is expected:</th>
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| non-relativistic Fermi I: \( \mathcal{A} \sim \frac{g}{\beta_{sh}^2} \)
  - with \( \kappa \gtrsim 1 \), \( g \sim 1 \) at most (Bohm diffusion): \( g = \frac{D}{r_L c} \)
| non-relativistic Fermi II: \( \mathcal{A} \sim \frac{g}{\beta_{\Lambda}^2} \)
| mildly relativistic Fermi I (\( \Gamma_{sh} \beta_{sh} \sim 1 \)): \( \mathcal{A} \sim g \)
| ultra-relativistic Fermi I:
  - expect \( \mathcal{A} \sim \frac{1}{\Gamma_{sh}} \frac{r_L}{\Gamma_{sh} \lambda_B} \gg \frac{1}{\Gamma_{sh}} \)
  - \( \mathcal{A} \propto r_L \Rightarrow \) inefficient acceleration at high energies
| shear acceleration: \( \mathcal{A} \sim \frac{\Delta r^2}{\Delta \beta^2 r_L^2 g} \)
  - (if \( \Delta r \sim r \), \( \mathcal{A} > 1 \) and \( \mathcal{A} \) becomes \( g/\Delta \beta^2 \) at the deconfinement limit)

(Norman et al. 95, Waxman 05, Lyutikov & Ouyed 05, M.L. & Waxman 09)

(Achterberg et al. 01, M.L., Pelletier & Revenu 06)

(Rieger, Bosch-Ramon & Duffy 07)
Acceleration – a luminosity bound

- **A generic case**: acceleration in an outflow
  - acceleration timescale (comoving frame): \( t_{\text{acc}} = A t_L \)
  - \( A \gtrsim 1, \ A \sim 1 \) at most:
    - for non-relativistic Fermi I, \( A \sim g/\beta_{\text{sh}}^2 \) with \( g \gtrsim 1 \)
  - time available for acceleration (comoving frame): \( t_{\text{dyn}} \approx \frac{R}{\beta \Gamma c} \)
  - maximal energy: \( t_{\text{acc}} \leq t_{\text{dyn}} \Rightarrow E_{\text{obs}} \leq A^{-1} Z e B R / \beta \)
  - ‘magnetic luminosity’ of the source: \( L_B = 2\pi R^2 \Theta^2 \frac{B^2}{8\pi} \Gamma^2 \beta c \)
  - lower bound on total luminosity: \( L_{\text{tot}} \geq 0.65 \times 10^{45} \Theta^2 \Gamma^2 A^2 \beta^3 Z^{-2} E_{20}^2 \) erg/s

1045 ergs/s is robust:
- for \( \beta \to 0 \), \( A^2 \beta^3 \geq 1 / \beta \geq 1 \)
- for \( \Theta \Gamma \to 0 \), \( L_{\text{tot}} \geq 1.2 \times 10^{45} A \beta \frac{\kappa}{r_{\text{LC}}} Z^{-2} E_{20}^2 \) erg/s

- **Lower limit on luminosity of the source**:
  - low luminosity AGN: \( L_{\text{bol}} < 10^{45} \) ergs/s
  - **Seyfert galaxies**: \( L_{\text{bol}} \sim 10^{43}-10^{45} \) ergs/s
  - high luminosity AGN: \( L_{\text{bol}} \sim 10^{45}-10^{47} \) ergs/s
  - gamma-ray bursts: \( L_{\text{bol}} \sim 10^{51} \) ergs/s

\( \Rightarrow \) only most powerful AGN jets, GRBs or magnetars
NGC5506 (21x11 kpc)

IC 5169 (50x50 kpc)

NGC 7315 (40x40 kpc)

NGC 424 (40x40 kpc)

ESO 139-G12 (40x40 kpc)

NGC 1204 (40x40 kpc)

NGC 1358 (40x40 kpc)

NGC 4945 (70x70 kpc)

Centaurus A (300x600 kpc)

Centaurus A (15x15 kpc)

$L_{\text{jet}} \approx 10^{43}$ ergs/s

IC 5169 (50x50 kpc)
Fermi type processes:

- Fermi acceleration at ultra-relativistic shock waves does not operate unless instabilities remodel the magnetic field on short spatial scales:

  \[ \lambda_B \ll r_L \ll \frac{\delta B}{B} \lambda_B \]

- much ongoing work (analytical + PIC simulations) to understand under which conditions relativistic Fermi acceleration can proceed

  however, acceleration timescale in short scale turbulence \( \propto r_L^2 \) \( \Rightarrow \) unlikely to reach UHE

  … no canonical value for the spectral index…

- most efficient Fermi accelerators: mildly relativistic shocks \( \Gamma_{sh} \beta_{sh} \sim 1 \)

  e.g. moderately relativistic internal (or reverse) shocks in a ultra-relativistic wind (benefit from Doppler boost of the wind)

- luminosity bound on the source: \( L_{tot} \geq 0.65 \times 10^{45} \Theta^2 \Gamma^2 A^2 \beta^3 Z^{-2} E_{20}^2 \text{ erg/s} \)

  \( \Rightarrow \) PAO correlation with nearby weak AGN does not support the AGN model of UHECR origin

Note - there exist other acceleration mechanisms, e.g. in strongly magnetized outflows

  ex.: tapping the potential difference in a magnetar \( \text{(Arons 03)} \)

  \( \rightarrow \) the luminosity bound can be generalized to these processes