Fermi Acceleration at Relativistic Shocks, Generation of Electromagnetic Turbulence and Performances

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- inhibition of Fermi cycles by the mean field (superluminal regime generic for UR-shocks)
- the challenge of the generation of e.m. turbulence upstream
- a critical transition towards the onset of Fermi cycles
- performances of acceleration

what is a relativistic collisionless shock?

- transition layer of width $\ll$ mean free path from a cold relativistic flow upstream to an isotropized distribution downstream /frame in subsonic (velocity $< c/\sqrt{3}$) motion.

- anisotropy upstream $\Rightarrow$ micro-instabilities $\Rightarrow$ micro-turbulence $\Rightarrow$ isotropization and heating

- hydrodynamic jump relations fulfilled with some amount of energy density and pressure in turbulent waves

- isotropized distribution downstream either thermal or thermal with some power law tail in $\epsilon^{-s}$ with $s = 2.2-2.3$ when Fermi process works
Relativistic Fermi process with no mean field
(Achterberg & Galand, Kirk et al., Ostrowski & Bednarz, Ellison & Double, Lemoine & Pelletier)

- shock forms with microinstabilities (OTSI, Weibel); front motion characterized by $\Gamma_s \gg 1$. Width of a few tens of inertial length $c/\omega_p$ (Sagdeev, Medvedev & Loeb 99, Spitkovsky 08...)

- growth of instabilities, turbulent scattering and Fermi cycles granted

- after the first Fermi cycle (gain of $\Gamma_s^2$), gain by a factor 2, sizable proba for return

- power law spectrum with universal index $s=2.2$

- short acceleration time scale. But intrinsic limitation of energy...
**inhibition of F-cycles by the mean field**
(Niemiec, Pohl, Ostrowski 06, Lemoine, Pelletier, Revenu 06)

- most relativistic shocks are “superluminal”: particles don’t move along the field lines \( \sin \theta_B > 1/\Gamma_s \)
- particles undergo at most one and half cycles \( \Rightarrow \) energy gain \( \Gamma_s^2 \)
- the same with a turbulent field with large coherence length (Kolmogorov)

- penetration time upstream: \( t_L/\Gamma_s \Rightarrow \) maximum penetration length/shock \( r_L/\Gamma_s^3 \) (measured upstream)
- only intense turbulence at scales shorter than \( r_L/\Gamma_s^3 \) can produce scattering of suprathermal particles for further Fermi cycles
critical transition via whistler waves generation when $\Gamma_s < 800$ for $\sigma < \sigma_{\text{crit}}$

magnetization:
$\sigma = B^2/4\pi \rho c^2$

CR-conversion factor:
$\xi_{\text{cr}} = P_{\text{cr}}/\rho \Gamma_s^2 c^2$

$X = \Gamma_s m_e/m_p$

$Y = \Gamma_s^2 \sigma / \xi_{\text{cr}}$

(M. Lemoine & G.P. 09) (for OTSI, see A. Bret et al.)
**e\textsuperscript{+}-e\textsuperscript{-} plasma**

A. Spitkovsky 2008 (unmagnetized)

- Fermi process ab initio together with generation of micro-turbulence

- \( \Gamma_s \approx 20 \), \( \xi_{cr} \approx 10^{-1} \), \( \xi_{e.m.} \approx 10^{-2} \)

- spectrum index \( s \approx 2.4 \)

- (M. Lemoine & G.P. 09) **critical transition** with a mean field through the excitation of oblique two stream instability: \( \sigma<\sigma_{crit} = \frac{\xi_{cr}^{2/3}}{\Gamma_s^2} \)

- Weibel instability excited for \( \sigma<\frac{\xi_{cr}}{\Gamma_s^2} \)

- typical scale \( \delta = c/\omega_p \)
scattering and Fermi cycles

- once e.m. turbulence excited upstream for \( \sigma < \sigma_{\text{crit}} \), waves are transmitted downstream where scattering can take place. However, turbulent scattering still difficult upstream; scattering off mean or large scale field.

- condition for breaking mean field inhibition downstream:
  \[
  (\tau_s < \tau_L) \quad \sigma < \sigma^* = \chi \xi_{\text{e.m.}}^2
  \]

- where the e.m. conversion factor \( \xi_{\text{e.m.}} = U_{\text{e.m.}} / p \Gamma_s c^2 \)

- and the coherence length \( l_c = \chi c / \omega_p \)

- maximum energy achieved: \( \varepsilon_{\text{max}} = \Gamma_s m_p c^2 (\sigma^* / \sigma)^{1/2} \)

- sufficient condition for working: \( \sigma < \sigma_{\text{crit}} < \sigma^* \) so that \( \xi_{\text{e.m.}} > (2 \sigma_{\text{crit}} / \chi)^{1/2} \)
for which cosmic events?

- Blazar jets? magnetization too strong (alternatives: 2nd order Fermi acceleration, shear Fermi acceleration, reconnections)
- Hot spot of FR2 jets? magnetization too strong. But relativistic shocks?
- Pulsar wind terminal shock? magnetization too strong (alternative: pair wind carrying baryons, leads to power law spectrum not through Fermi process (Arons, Hoshino, Gallant 92))
- Terminal shock of Gamma Ray Bursts? Yes! $\sigma_{\text{ism}} \sim 10^{-9}$, $\sigma_{\text{crit}} \sim 10^{-6}$
- Maximum energy measured in obs frame: $\varepsilon_{\text{max}} = 1.6 \times 10^{52} (\sigma_{\text{crit}}/\sigma)^{1/2}$
  OK for the electrons and radiation. But UHECRs? Still opened
criterium for accelerator candidate completely reconsidered

- Hillas criterium ($\epsilon_{\text{max}} = \Gamma \text{ZeBR}$) based on the relation $r_L(\epsilon) \sim \lambda \leq l_c \sim R$ ruled out for relativistic shocks

- with relativistic shocks $\epsilon_{\text{max}} \propto B^{-1} \Gamma_s^{-1/2}$
main issues for PIC simulations  
(Spitkovsky & Sironi, Nishikawa, Hededal, Dieckmann, Katz, Keshet, Waxmann, Lembège, etc.)

• identification of the instabilities and their role in the shock structure

• importance of the magnetic barrier in a proton-electron plasma

• effective coherence length as a function of particle energy (Keshet et al. 09, Medvedev & Zakutnyaya 09): \( l_c = \chi(\varepsilon)c/\omega_p \)

• turbulence level, spectrum, relevant NL effects

• checking the law of critical magnetization and relevant instabilities at the transition