Turbulence in Collisionless Shocks & Fermi Acceleration Efficiency

focus: relativistic shock case

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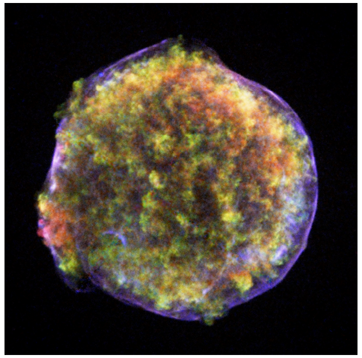
Outlines

- Conditions on turbulence properties for Fermi cycle in *relativistic shocks*
- Streaming instabilities in the magneto-hydrodynamic (MHD) limit
- Instabilities beyond MHD
- Conclusions.

Magnetic field amplification

Observations: $\varepsilon_B = B^2/4\pi\rho v_{sh}^2$



Hwang et al'02

Supernova Remnants

- X-ray filaments: $\varepsilon_B = 10^{-2/-1}$

- Gamma-Ray radiation: $E_{max} \sim 100$ TeV

Aharonian et al'08

GRB	ϵ_e	ϵ_B (%)
970508	$0.342^{+0.008}_{-0.01}$	$25.0^{+0.6}_{-2}$
980329	$0.12^{+0.02}_{-0.02}$	17^{+3}_{-3}
980703	$0.27^{+0.03}_{-0.03}$	$0.18^{+0.04}_{-0.03}$
000926	$0.15^{+0.01}_{-0.01}$	$2.2^{+0.5}_{-0.6}$

Yost et al'03

Gamma-Ray bursts

- NT radiation: energy indices s ~ 2.2

Theory:

- Streaming instabilities:

$\varepsilon_B = (V_{sh}/c)\varepsilon_{CR} = 10^{-2/-1}$

Bell & Lucek'01, Bell'04, Pelletier et al'06 …

$\Rightarrow$ Relativistic GRB shocks

Milosavljevic & Nakar'06, Reville et al'06

- Strong impact of the upstream magnetisation

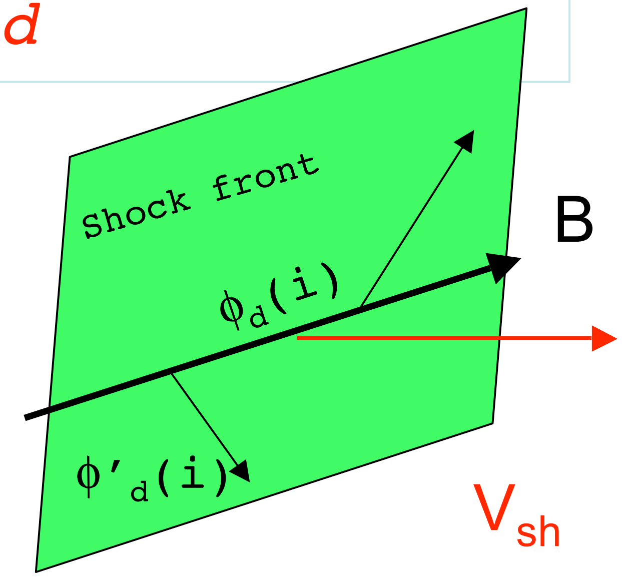
$\sigma = B^2/4\pi\rho c^2 = 10^{-6/-12}$ in the ISM

Fermi cycles in relativistic shocks *with a mean magnetic field*

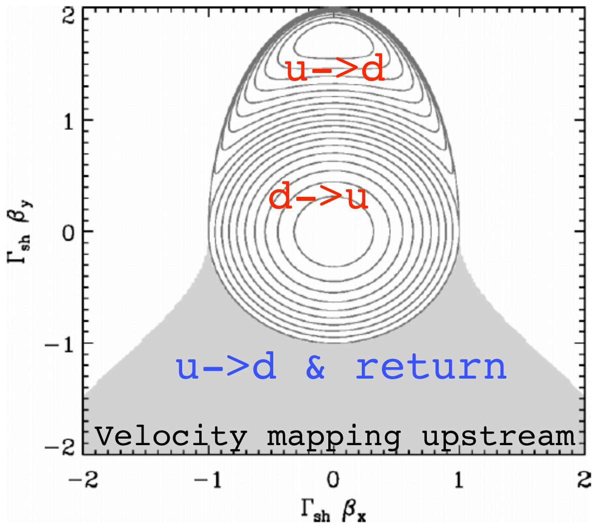
* Only a mean regular field

- In the front rest-frame the magnetic field is perpendicular.
- Kinematic conditions for Fermi cycles (d=>u=>d):
  - Return d -> u possible if and only if $-\pi < \phi_d(i) < 0$ but for all $\phi_u(i)$, $0 < \phi'_d(i) < \pi$ => return impossible: correlated trajectories !
- Limitation to 1-1/2 Fermi cycle in a regular field.

⇒ Turbulence is mandatory to mix the phase angles and allow further cycles.
⇒ Coherence length sh-frame $l_{coh-sh} < r_{L-sh}$
Coherence length up-frame $l_{coh-u}\,\Gamma_{sh} < r_{L-u}$



Niemiec & Ostrowski'06
Lemoine et al'06



General turbulence properties

- Turbulence level $A=\delta B/B_{reg}$; $B_{tot} = (B_{reg}^2+\delta B^2)^{1/2}$
- Condition on A (up- & downstream): Pelletier, Lemoine & A.M. al'09

$$A > \frac{r_L}{\Gamma_{sh}\ell_{coh}} > 1$$

N.B. $r_L = E/ZeB_{tot}$

- Strong turbulence is required. A denotes the dynamical range of particle energies.
- Conditions on l_{coh} (MHD instabilities):

$$\ell_{MHD} < \ell_{coh} < \ell_{prec-u}$$

Pelletier, Lemoine & A.M. al'09

$l_{MHD} = (V_{a\text{-}reg}/c)\ r_{0\text{-}reg}$

$l_{prec\text{-}u}$ = precursor size upstream

Streaming instability: MHD regime

- Linear analysis in the MHD limit.

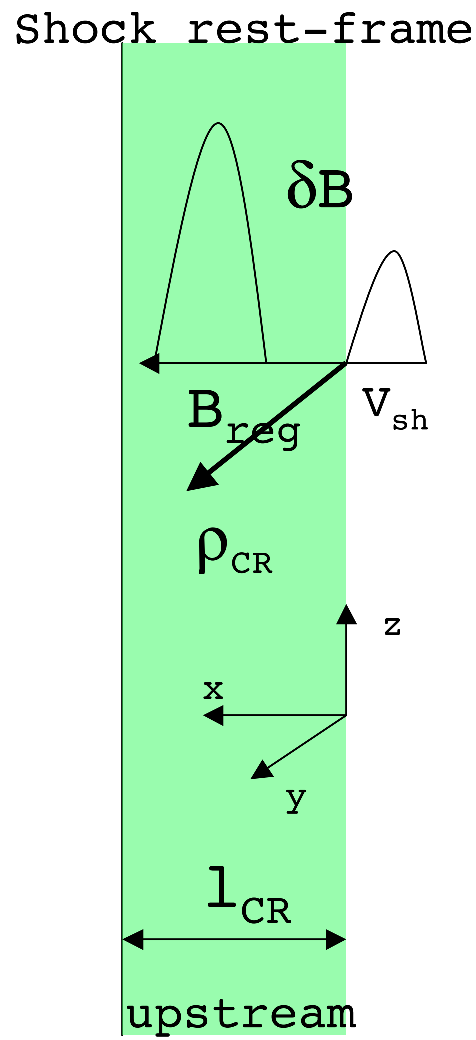
Pelletier, Lemoine & A.M. al'09

- Top-hat CR charge distribution over l_{CR} => counter charge in the background plasma.

- Destabilisation of: Alfvèn waves: $\delta B \perp B_{reg}$ and Magneto-sonic waves δB // B_{reg}

- Driving term: $w=\rho_u c^2$

$$u_z^{'} = \frac{du_z}{dx} = \frac{1}{1+\beta_A^2}\left(\frac{\rho_{CR} B_{reg}}{\Gamma_{sh} w}\right)$$



In the limit Γ_{sh} >>1:

Alfvén waves are found to be stable

Ms waves are destabilised ≠ modes Bell analysis

Magnetosonic mode properties

- Spatial growth rates: G_x increase with k_*

$$G_x = \frac{\sqrt{3}}{2}\left(k_*^2 k_x\right)^{1/3}; k_x >> k_*, k_y \approx 0$$

$$G_x = (k_* k_y)^{1/2}; k_y >> k_*^{1/3} k_x^{2/3}$$

- Typical wave number: $k_* \sim u_z'/c\Gamma_{sh}$ verifies:
  $k_* l_{MHD} << 1$ and $k_* l_{CR} >> 1$: small scale turbulence

- In the linear limit: $\delta B/B_{reg} \sim 1$ do not allow more than 1 1/2 Fermi cycle.

- If higher CR energies are present:
  - $G_x l_{CR,*}$ scales as $p^{b+a(1-s)}$, Usually $b+a(1-s) > 0$;hence increases with p
    s index of the particle distribution, a=1/3 or 2/3 and b=2 for small scale turbulence.
  - $k_* l_{MHD}$ scales as $p^{(1-s)}$;hence decreases with p as $s > 1$.

Perspectives

- These MS waves are important in many aspects !
  - $G_x l_{CR}$ increases with p: efficient contribution of HE CRs to the MHD instabilities.
  - In the non-linear regime:
    - They can couple with Alfvèn waves if large scale turbulence is present (Pelletier, Lemoine & A.M.'06)
    - They can produce secondary MS shocks $\delta\rho/\rho_0 > 1$.
      Further heating and magnetic compression in the precursor.
      Contribute to a shock front corrugation instability (Casse & A.M. in prep).

- Non-linear simulations undertaken with an R-MHD code AMR-VAC [van der Holst et al'08], Casse & A.M. in prep.

- But concerning the init of the Fermi cycles instabilities beyond MHD are required => mediation of the shock structure, particle scattering and allow Fermi cycles.

Microscopic instabilities

- PIC simulations: Shock is formed once two counter flows interact (Nishikawa et al'07, Spitkovsky'05)

- Shock: electrostatic or magnetic barrier that reflect incoming cold ions => relativistic cold beam in the upstream frame => micro-instabilities.

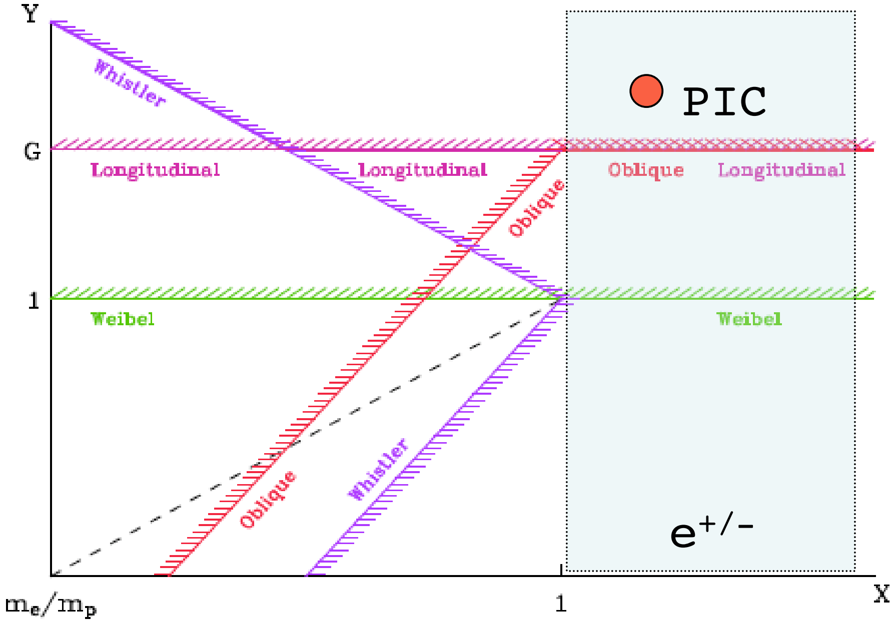
  * With a mean magnetic field (Lemoine & Pelletier'09)
  - Superluminal case
    - Longitudinal modes (k//B)
    - Whistler modes (k has a component // v_{beam}) ($\omega_{ci} << \omega << \omega_{ce}$)
    - Extraordinary modes ($k \perp B$) and Magnetosonic modes in the MHD limit.
    - Alfvén modes (k // B)
    - Weibel filamentation modes ($k \perp v_{beam}$, $k \perp B$) ($\omega_{ci} << \omega << \omega_{ce}$) => non resonant.
  - Subluminal case:
    - + Streaming instability (Bell type modes) in the quasi-parallel configuration.

Instability diagrams

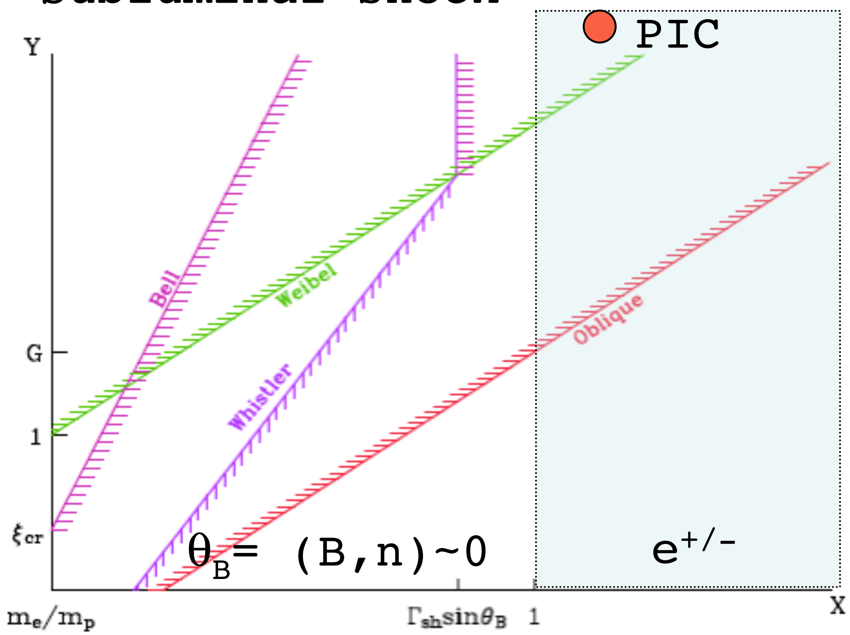
Sironi & Spitkovsky'09

No restriction for longitudinal modes

Superluminal shock



Subluminal shock



$X = \Gamma_{sh}\ m_e/m_p$ <=> shock velocity

$Y = \Gamma_{sh}^2\ \sigma/\xi_{CR}$ <=> magnetisation

$G = (\xi_{CR}\ m_e/m_p)^{-1/3}$

$\xi_{CR} = P_{CR}/\Gamma_{sh}^2 \rho_u c^2$

⇒ Longitudinal & oblique modes have the fastest growth rates

⇒ Main limiting factor $G_x l_{cr} >> 1$: instability quenched by advection in the superluminal case.

⇒ Resonant modes: normal modes. If advected downstream => B_{down}.

Conclusions

- Necessary conditions for *Fermi cycles* in relativistic flows:
  - High level of turbulence
  - Small scale fluctuations ($l_c << r_L$)
- MHD instabilities:
  - Only magnetosonic waves are destabilised by the CR streaming.
  - Saturation at $\delta B/B \sim 1$ (not enough to permit Fermi cycles).
  - Non-linear investigation is mandatory.
- Beyond MHD:
  - Magnetisation select the dominant instability.
  - Usually longitudinal & oblique modes grow the faster.
  - Resonant modes are important to be transmitted downstream.
- Important point: the structure of a relativistic shock is not understood:
  - Importance of compressive modes (MHD, extraordinary ionic) as heating agent of the precursor => if both p^+ / e^- are heated => e^+/e^- plasma (Weibel is the dominant mode: