Electron Acceleration in γ-ray Binaries

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Variable Galactic Gamma-ray Sources

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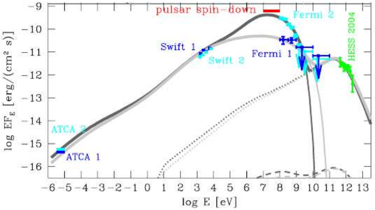
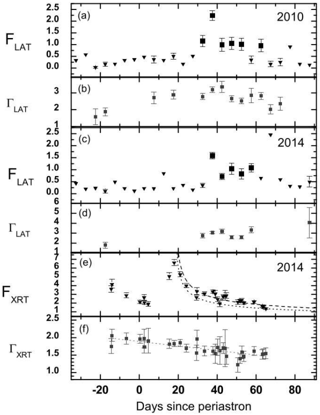
Motivation

PSR B1259-63



Fermi/LAT collaboration et al. 2011



Tam et al. 2015

Motivation

Features

- shape of power-law $\frac{dN}{d\gamma} \propto \gamma^{-p}$
- efficient acceleration
- sizeable fraction of the pulsar spin-down power (e.g. PSR B1259-63)

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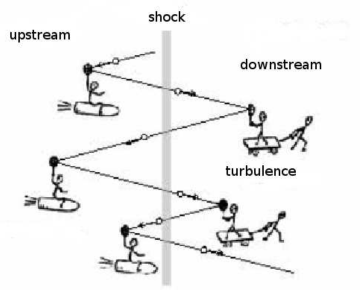
Fermi acceleration

- ultra-relativistic shock
- perpendicular shock
- particle injection in the process



Outline

1. Simulation of the Pulsar Wind

2. Numerical integration of test particle trajectories

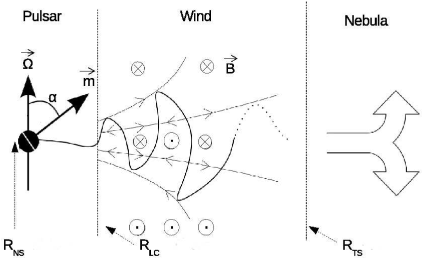
Simulation of the pulsar wind

Set-up

- two relativistic fluids (e^-, e^+)
- 1D simulation
- ultra-relativistic shock $\Gamma_{sh} = 40$
- magnetised flow
  $\sigma = \frac{\textit{Poynting flux}}{\textit{particle kinetic energy density}} = 10$

The wind

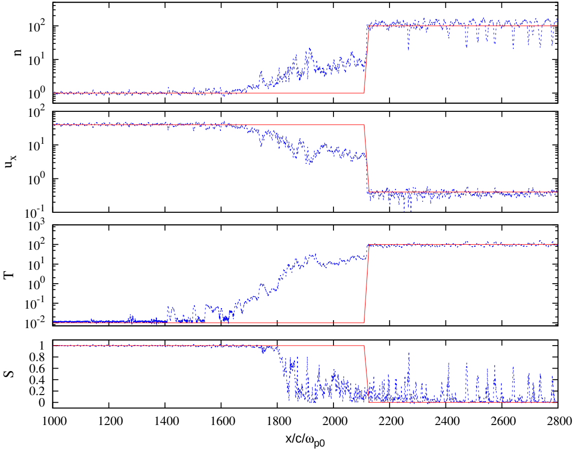
- fully transverse, circularly polarised magnetic shear wave
- null phase-averaged magnetic field
- $\omega \propto \omega_{p0}$ with $\omega_{p0} = \sqrt{\frac{8\pi ne^2}{m}}$
  upstream proper plasma frequency



Simulation of the pulsar wind

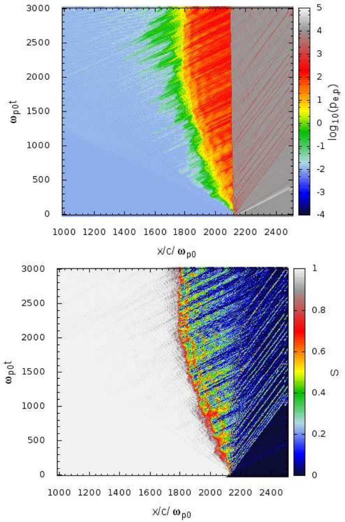
snapshot at $\omega_{p0} t = 2500$, the shock front is at $x_{sh} \frac{\omega_{p0}}{c} = 2120$

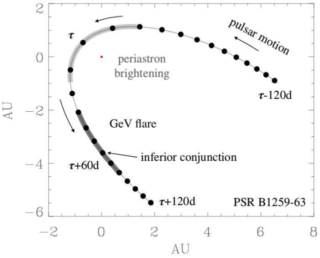
$\omega = 0.4\omega_{p0}$, $\omega = 1.2\omega_{p0}$



Simulation of the pulsar wind

$\omega = 1.2\omega_{p0}$, $x_{sh} = 2120$





Dubus & Cerutti 2013

$$\omega_{p0} = \sqrt{\frac{8\pi n e^2}{m}}$$

Numerical integration of particle trajectories

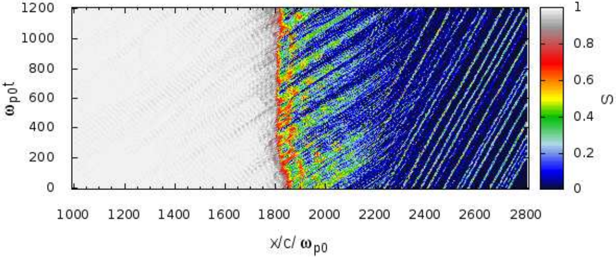
$$\frac{d\vec{x}}{dt} = \vec{\beta}$$

$$\frac{d\vec{\mu}}{dt} = \frac{q}{m\gamma\beta}[\vec{E}_\perp + \vec{\beta} \times \vec{B}]$$

$$\frac{d\gamma}{dt} = \frac{q}{mc}\beta\vec{\mu} \cdot \vec{E}$$

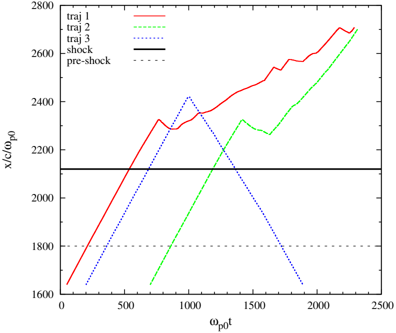
using 4th order Runge-Kutta method in the test particle limit

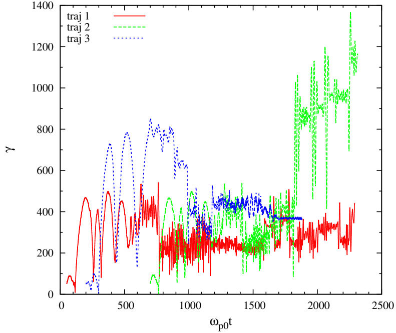
Periodic boundaries and initial conditions



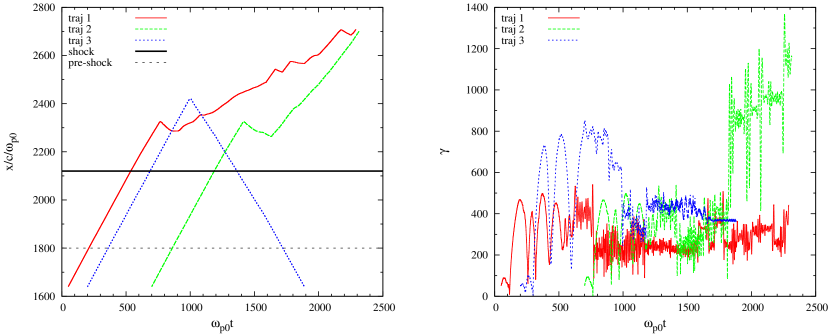
Trajectories started off far upstream of the shock ($x_{sh} = 2120$) with isotropic distribution in the upstream fluid frame

Typical trajectories





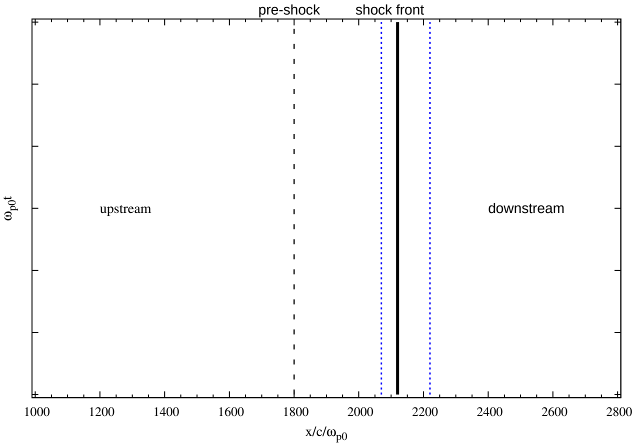
Typical trajectories



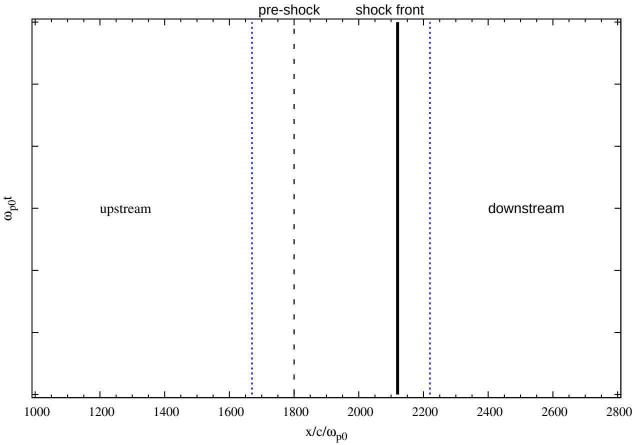
Questions

- spectrum of reflected and transmitted particles?
- angular distribution of reflected and transmitted particles?
- reflection probability $\Longleftrightarrow$ injection probability?

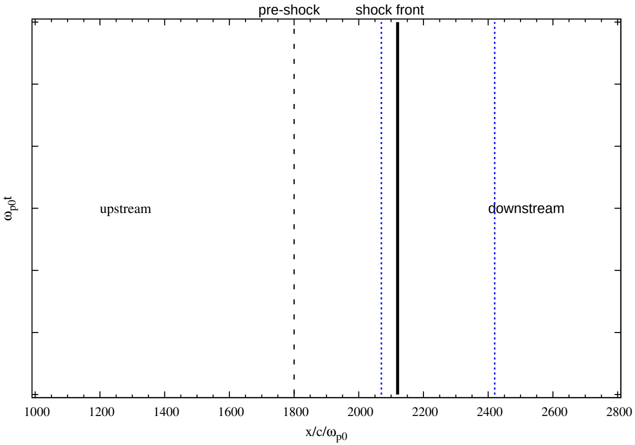
Reflection probability



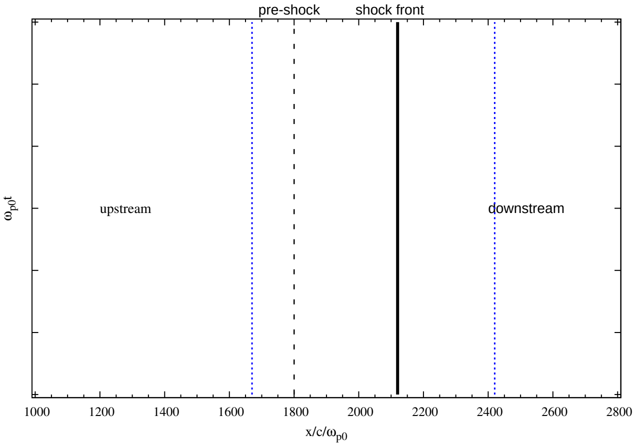
Reflection probability



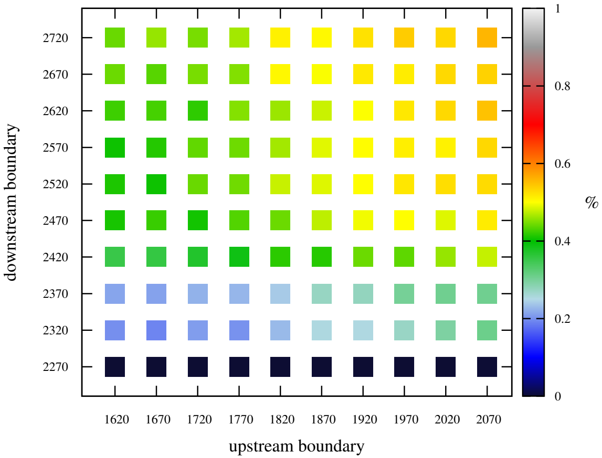
Reflection probability



Reflection probability

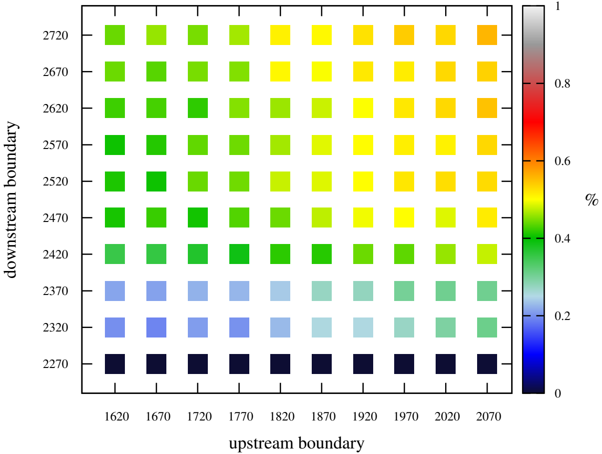


Reflection probability



$$x_{sh} = 2120,\ x_{pre-sh} \approx 1800$$

Reflection probability

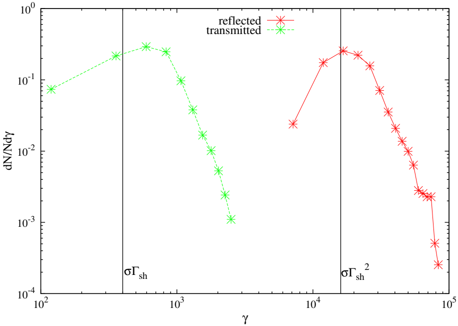


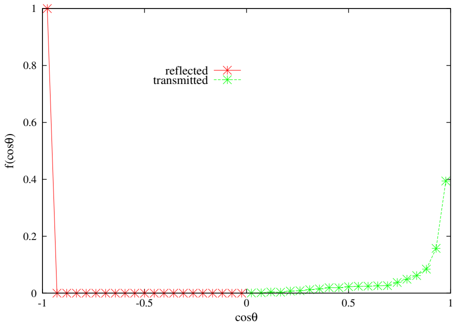
$$x_{sh} = 2120,\ x_{pre-sh} \approx 1800$$

$P_{refl} \sim 44\,\%$ to be compared with $P_{refl} \sim 12\,\%$ Achterberg et al. 2001

Spectrum and angular distribution

reflected particles are measured at $x_{up} = 1670$ (quantities expressed in the upstream rest frame)
transmitted particles are measured at $x_{down} = 2720$ (quantities expressed in the downstream rest frame)





Summary

- scenario for particle acceleration
- application to γ-ray binaries
- onset of shock precursor for $\omega > \omega_{p0}$
- $P_{refl} = P_{inj} \sim 44\% \gg$ other shocks (Non-Rel., Rel. cases)

Outlook

- investigation of true Fermi-type acceleration
- magnetic fluctuations supplemented both upstream and downstream
- integration of stochastic differential equations via Euler scheme

BACK UP SLIDES

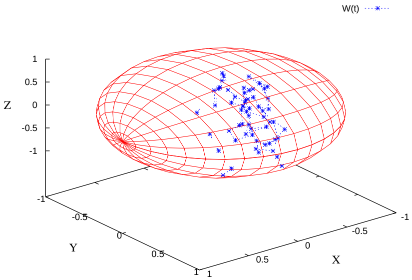
Pitch-angle diffusion

scattering off magnetic turbulences

elastic scattering in the fluid rest frame

simulated using Itō stochastic differential equation

$$d\vec{\mu} = \vec{a}(x,t) * dt + \vec{b}(x,t) * dW(t)$$



Definition of the magnetic shear wave

Lab. frame (Shock frame)

$$B_x = 0$$
$$B_y = B_0 \cos(kx - \omega t)$$
$$B_z = -B_0 \sin(kx - \omega t)$$
$$E_x = 0$$
$$E_y = \beta B_z$$
$$E_z = -\beta B_y$$
$$k = \omega/\beta$$
$$\omega = 1.2\omega_{p0}$$

Upstream fluid frame

$$B_x{}' = 0$$
$$B_y{}' = B_y/\Gamma_s$$
$$B_z{}' = B_z/\Gamma_s$$
$$E_x{}' = 0$$
$$E_y{}' = 0$$
$$E_z{}' = 0$$
$$k' = k/\Gamma_s$$
$$\omega' = 0$$

$$\beta = \sqrt{1 - 1/\Gamma_s^2}, \qquad \omega_{p0} = \sqrt{\frac{8\pi n e^2}{m}}, \qquad \bar{k} = (k, 0, 0)$$

Spectrum and angular distribution with periodic boundaries

overall integration time $\sim$ 2400, (a) dt=1200 foldings=2, (b) dt=600 foldings=4, (c) dt=480 foldings=5