PIC Simulations of relativistic transverse magnetosonic shocks

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Outline

- Astrophysical relevance of the subject

- PIC simulations of relativistic transverse magnetosonic shocks in e−–e+–p plasmas
  - Resonant cyclotron absorption
  - Questions left open by previous work on the subject
  - What can still be learned from 1D PIC

- Simulations with increased mass-ratio between ions and pairs (up to 100): now outdated
  - Acceleration mechanism still effective
  - Electron acceleration seen for the first time
  - Effects of finite temperature of the plasma

- Summary and Conclusions
Relativistic shocks in astrophysics

MQSs $\Gamma \sim \text{a few}$

AGNs $\Gamma \sim \text{a few tens}$

GRBs $\Gamma \sim 10^2$

PWNe $\Gamma \sim 10^4 - 10^6$
Properties of the flow and particle acceleration

- These shocks are collisionless: transition between non-radiative (upstream) and radiative (downstream) takes place on scales too small for collisions to play a role
- They are generally associated with non-thermal particle acceleration but with a variety of spectra and acceleration efficiencies

Self-generated electromagnetic turbulence mediates the shock transition: it must provide both the dissipation and particle acceleration mechanism

The detailed physics and the outcome of the process strongly depend on composition ($e^-e^+p$?) magnetization ($\sigma=B^2/4\pi n\Gamma mc^2$) and geometry ($\Gamma \times \Theta(B \cdot n)$) of the flow, which are usually unknown....
Magnetized relativistic shocks in PWNe accelerate particles very efficiently!!!

Look at the Crab Nebula:
✓ Efficiency >20% of total $L_{sd}$
✓ Maximum energy: for Crab ~few x $10^{15}$ eV (close to total available $\Delta V$ at the PSR)

- unmagnetized shock: efficient Fermi I (Spitkovsky 08)
- acceleration associated to reconnection (Lyubarsky & Petri 07)

3D PIC of magnetized pair shocks hint at low efficiency (Spitkovsky 08)

Magnetic reconnection? Or maybe ions?

Resonant cyclotron absorption
Synchrotron Emission maps from 2D MHD simulations of PWNe

$\sigma=0.025$, $b=10$

(Hester et al. 95)

(Del Zanna et al. 06)
Particle In Cell Simulations

The method:
✓ Collect the current at the cell edges
✓ Solve Maxwell's eqs. for fields on the mesh
✓ Compute fields at particle positions
✓ Advance particles under e.m. force

Approximations
In principle only cloud in cell algorithm

But Computational limitations force:
Reduced spatial and time extent
Mistaken transients
Far-from-realistic values of the parameters
An example of the effects of reduced $m_i/m_e$ in the following

Powerful investigation tool for collisionless plasma physics:
allowing to resolve the kinetic structure of the flow on all scales

Reduced dimensionality of the problem

$e^-e^+$ plasma flow:
- in 1D:
  - No shock if $\sigma=0$
  - No accel. for any $\sigma$
- in 3D
  - Shock for any $\sigma$
  - Fermi accel. for $\sigma=0$

For some aspects of problems involving species with different masses 1D WAS still the only way to go
Leading edge of the shock

Configuration at the leading edge
~ cold ring in momentum space

Drifting e⁺-e⁻-p plasma
B increases

Magnetic reflection mediates the transition

Coherent gyration leads to collective emission of cyclotron waves

Pairs thermalize to $kT \sim m_e \Gamma c^2$ over $10-100 \times (1/\Omega_{ce})$

Plasma starts gyrating

Ions take their time: $m_i/m_e$ times longer

Pairs can absorb ion radiation resonantly
1D PIC Simulations of shocks in $e^-e^+-p$ plasmas

From 1D PIC with $m_i/m_e=100$
(Amato & Arons 06)
Using XOOPIC (Verboncouer et al. 95)

1D PIC sim. with $m_i/m_e$ up to 20
(Hoshino & Arons 91, Hoshino et al. 92)
$e^+$ effectively accelerated if $U_i/U_{tot}>0.5$

- Drifting species
- Thermal pairs
- Cold gyrating ions

- Particles enter simulation box from left
- Impact on a wall on the right
- Wait until shock far from right boundary

e.m. fields
Resonant cyclotron absorption in ion-doped plasma

\[ \Omega_{ci} = \frac{m_i}{m_e} \Omega_{ce} \]

**Frequency**

Pairs initially need \( n \sim \frac{m_i}{m_e} \) for resonant absorption!!! Then lower \( n \)

**Growth-rate**

Growth-rate independent of \( n \) (Hoshino & Arons 91)

\( m_i/m_e \) much lower than reality implies \( n_i/n_e \) correspondingly larger to guarantee sufficiently large \( U_i/U_{tot} \)

Elliptical polarization of ion waves

**Spectrum is cut off at \( n \sim u/\delta u \)**

growth-rate ~ independent of \( n \) if plasma cold (Amato & Arons 06)

**Preferential absorption by \( e^+ \)**
Polarization of the waves

\[ \frac{m_i}{m_e} = 20, \ \frac{n_i}{n_-} = 0.4 \]

\[ \frac{m_i}{m_e} = 40, \ \frac{n_i}{n_-} = 0.2 \]

\[ \frac{U_i}{U_{\text{tot}}} = 0.7 \] same in both simulations

Upstream flow:
Lorentz factor: \( \Gamma = 40 \)
Magnetization: \( \sigma_{\pm} = 2 \)

Simulation box:
\( \Delta x = r_{Le}/10 \)
\( L_x = r_L i \times 10 \)

Positron tail extends to \( \gamma_{\text{max}} = \frac{m_i}{m_e} \Gamma \)

First evidence of electron acceleration
Particle spectra and acceleration efficiency for $m_i/m_e=100$

Acceleration efficiency:
- $\sim$ few% for $U_i/U_{tot} \sim 60$
- $\sim$ 30% for $U_i/U_{tot} \sim 80$

Spectral slope:
- $>3$ for $U_i/U_{tot} \sim 60$
- $<2$ for $U_i/U_{tot} \sim 80$

Maximum energy:
- $\sim 20\% m_i c^2 \Gamma$ for $U_i/U_{tot} \sim 60$
- $\sim 80\% m_i c^2 \Gamma$ for $U_i/U_{tot} \sim 80$

Mechanism still works at large $m_i/m_e$ for both $e^+$ and $e^-$

Upstream flow:
- Lorentz factor: $\Gamma = 40$
- Magnetization: $\sigma_z = 2$

Simulation box:
- $\Delta x = r_{Le}/10$
- $L_x = r_{Li} \times 10$

$n_i/n_-=0.2$
$U_i/U_{tot}=0.8$
Effects of thermal spread

\[ \frac{\delta u}{u} = 0 \]
\[ \eta = 5\% \quad \alpha = 2.7 \]

\[ \frac{\delta u}{u} = 0.1 \]
\[ \eta = 3\% \quad \alpha = 4 \]

\[ \frac{\delta u}{u} = 0.2 \]
\[ \eta = 27\% \quad \alpha = 1.6 \]

\[ \frac{\delta u}{u} = 0.4 \]
\[ \eta = 4\% \quad \alpha = 3.3 \]

Initial particle distribution function is a gaussian of width \( \delta u \)

Accelerating effectively suppressed!!!
Summary and Conclusions

We have explored the physics of relativistic transverse magnetosonic shocks in ion-doped plasmas through 1D PIC simulations: still about the only possibility to explore the behaviour of the system for large $m_i/m_e$

**Aims:**

- Checking whether RCA would still provide any particle acceleration
- Checking whether any electron acceleration for larger mass-ratios (upstream plasma closer to quasi-neutrality)

**Results:**

- Pairs are efficiently accelerated even for $m_i/m_e=100$ if $U_i/U_{tot}>0.5$
- Electron acceleration finally seen!!!
- Less efficient than for positrons due to elliptical polarization of the waves (forced by low $m_i/m_e$ which implies large $n_i/n_e$ to ensure $U_i/U_{tot}>0.5$)
- Extrapolation to realistic $m_i/m_e$ predicts same efficiency for accelerating $e^+$ and $e^-$
- Efficiencies and spectra as observed in PWNe can be obtained depending on ion fraction
- The acceleration is effectively suppressed if initial thermal spread larger than $m_e/m_i$