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The forming of a relativistic partially electromagnetic planar plasma shock

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The forming of a relativistic partially electromagnetic planar plasma shock

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Contents

Introduction

- Gamma-ray bursts are energetic eruptions at cosmological distances
- Source process of long gamma-ray bursts: Massive supernovae
- Origin of gamma ray flash: Ultra-relativistic jet
- Process yielding gamma rays: Synchrotron radiation
- What do we not know:

  (1) Which process accelerates electrons to ultra-relativistic speeds ?

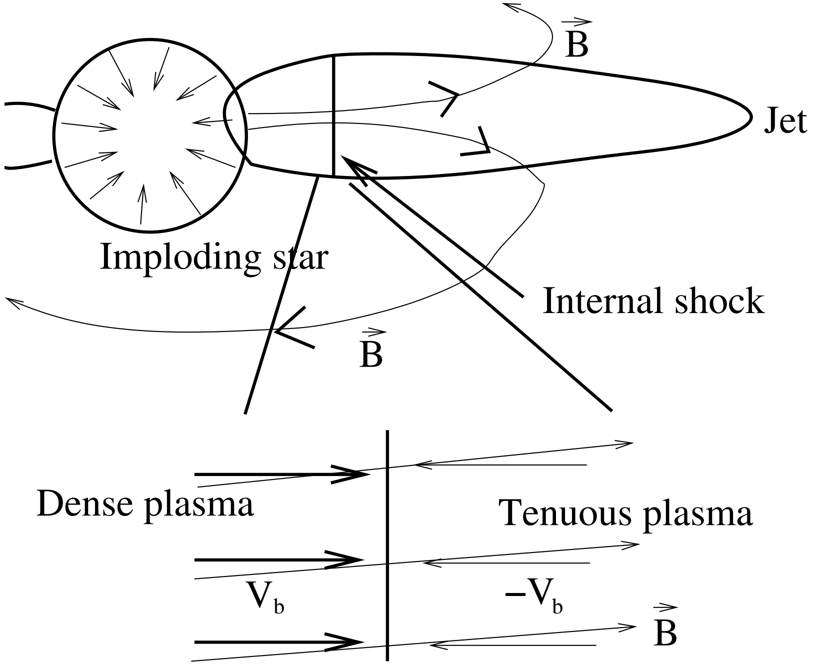
  (2) How are the strong magnetic fields generated ?

  Possible mechanism: Filamentation instability at internal shocks.

  Problem: Weak electron acceleration and 'weak' small-scale $\mathbf{B}$
- Here: We consider shocks due to a more powerful wave

Internal shock model

- Imploding strongly magnetized star results in compact object
- Magnetic field and angular momentum conservation constrain plasma flow: Jets may escape along magnetic poles.
- The jets may reach Lorentz factors of hundreds
- Time dependent jet source: Jet density and speed varies ⇒ Internal shocks



Assumptions:
Two plasma clouds collide,
Relative speed: $v = 0.9c$,
Density ratio: 10,
Quasi–parallel magnetic field,
Each slab consists of equal numbers
of ions and electrons: Mass ratio 400

Magnetic energy = 0.008 Kinetic energy

Particle-in-cell simulation: Maxwell-Lorentz equations

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \ , \ \ \nabla \times \mathbf{B} = \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \mu_0 \mathbf{J} \tag{1}$$

$$\nabla \cdot \mathbf{B} = 0 \ , \ \ \nabla \cdot \mathbf{E} = \rho / \epsilon_0 \ , \ \ \frac{d\mathbf{p}}{dt} = e \left(\mathbf{E} + \mathbf{v} \times \mathbf{B} \right) \tag{2}$$

Simulation strategy: $\mathbf{v}_b$ is plasma flow velocity and $\mathbf{B}_0$ initial magnetic field

- Use $\mathbf{B}_0 \cdot \mathbf{v}_b \neq 0$ to suppress waves with $\mathbf{k}$ oblique / perpendicular to $\mathbf{v}_b$
  $\Rightarrow$ We can use 1D PIC simulations
  Test the suppression with 2D simulations
- Use $|\mathbf{B}_0 \times \mathbf{v}_b| \neq 0$ to trigger new waves

2D PIC simulation in x-y plane: Impact of flow-aligned magnetic field B_x

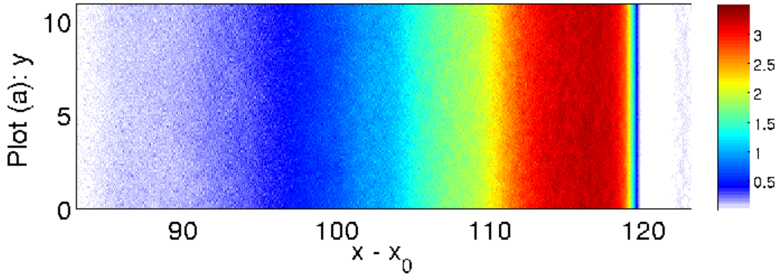
Initial contact boundary at $t = 0$: $x - x_0 = 0$. Dense slab moves to the right. Position in units of $\lambda_e = c/\omega_p$

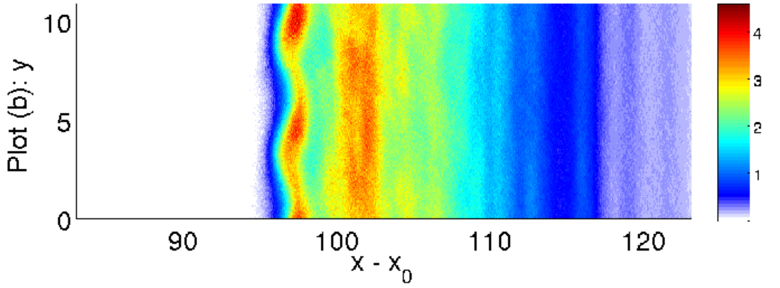
Filamentation instability modulates B_z: Both figures show $log_{10}|B_z|$:

Upper plot: Strong flow-aligned magnetic field

Lower plot: No flow-aligned magnetic field

Flow-aligned magnetic field enforces planarity ⇒ 1D geometry



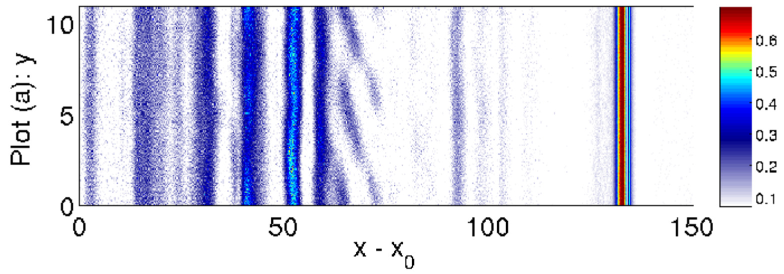


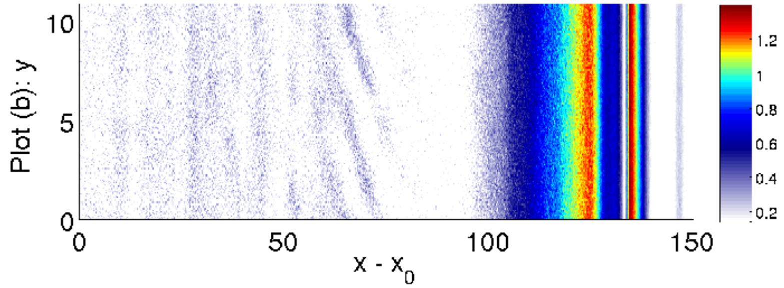
2D PIC simulation in x-y plane: Electric fields

Position in units of $\lambda_e = c/\omega_p$. Flow-aligned $\mathbf{B}_0$ present

Upper plot: $|E_x|$ parallel to $\mathbf{v}_b$: Electrostatic field

Lower plot: $|E_y + \imath E_z|$: Electromagnetic field



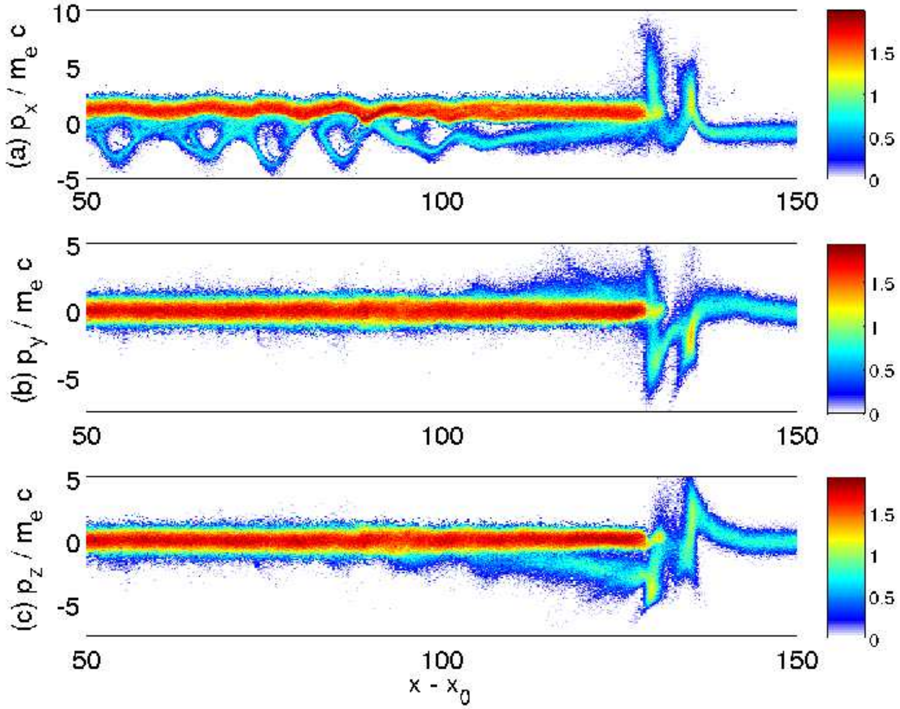


Mode at leading edge of plasma slab: Mixed polarity

Modes further downstream: Quasi-electrostatic polarity

Projected electron phase space distributions: Early time

Plasma flow along x-direction. Position is in units of $\lambda_e = c/\omega_p$

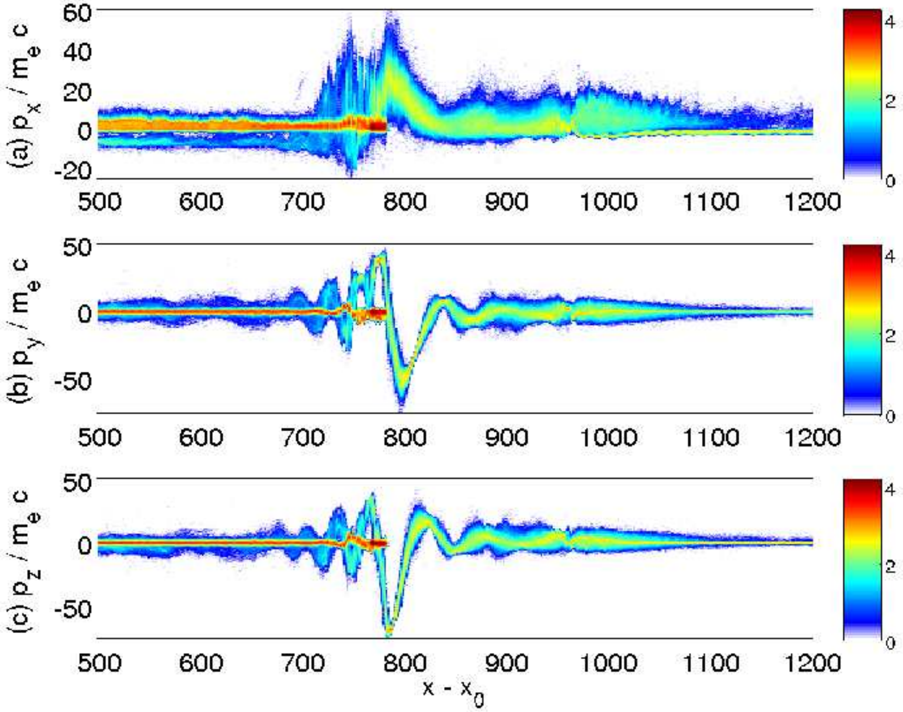


Electromagnetic structure at slab front: 3D momentum oscillation

Electrostatic structures downstream: Electron phase space holes

Projected electron phase space distributions: Later time

Plasma flow along x-direction. Position is in units of $\lambda_e = c/\omega_p$

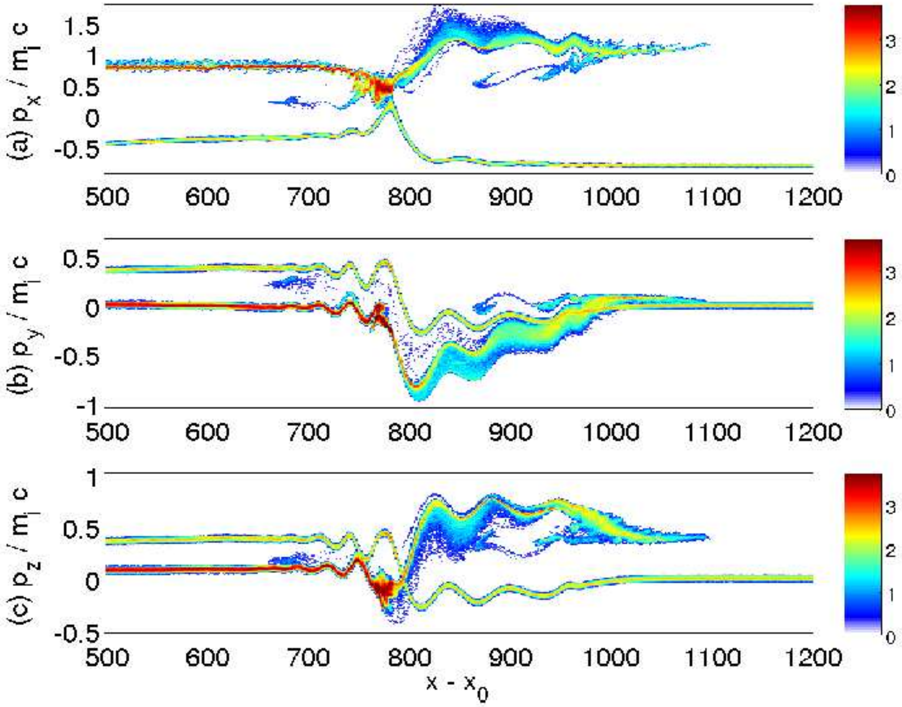


Momentum oscillations at slab front increase.

Relativistic electron mass is not small compared to the ion mass!

Projected ion phase space distributions: Later time

Plasma flow along x-direction. Position is in units of $\lambda_e = c/\omega_p$

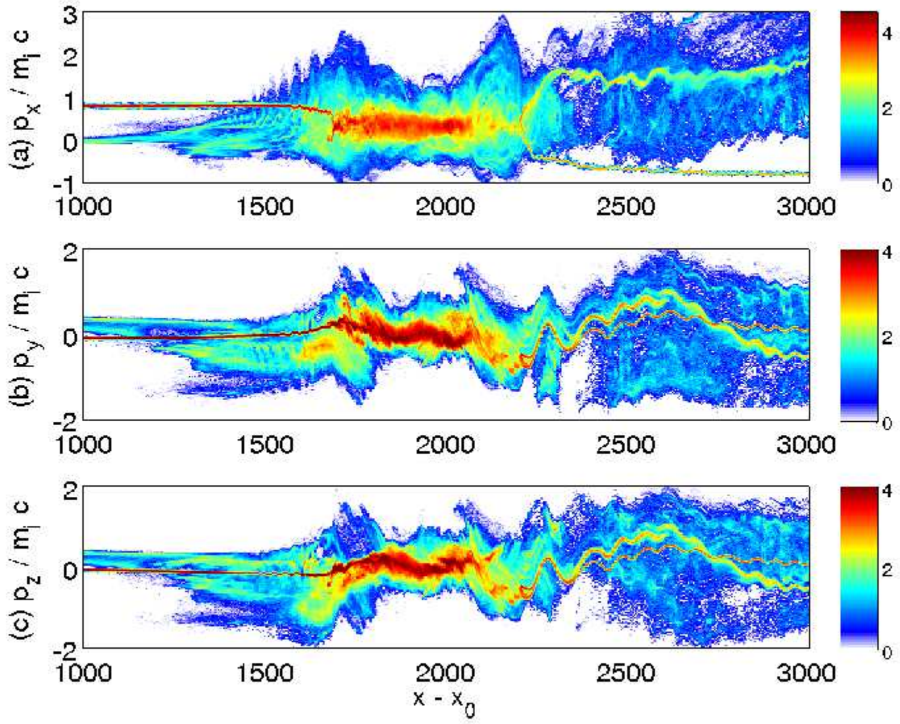


The ions of both slabs react: Strong momemtum modulation at $x - x_0 = 780$

Note: Ions of dense slab with $x - x_0 > 780$ are <u>not</u> shock-reflected

Projected ion phase space distributions: Final time

Plasma flow along x-direction. Position is in units of $\lambda_e = c/\omega_p$



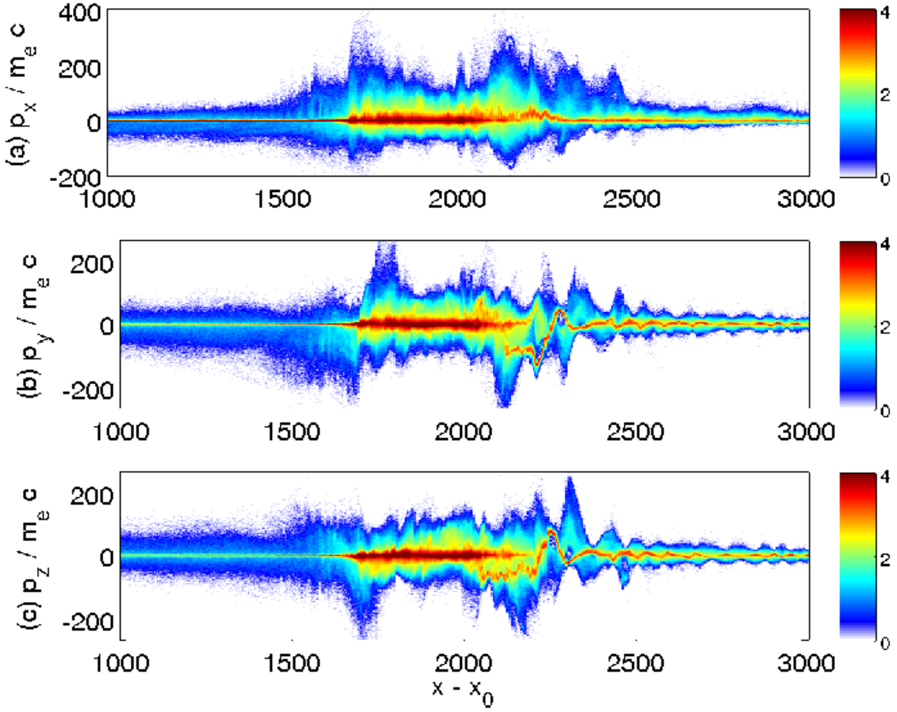
Between $1600 < x - x_0 < 2100$: forming downstream

Net flow of downstream: asymmetric forward / reverse shocks

Shock-reflected ion beam at $2300 < x - x_0$.

Projected electron phase space distributions: Final time

Plasma flow along x-direction. Position is in units of $\lambda_e = c/\omega_p$



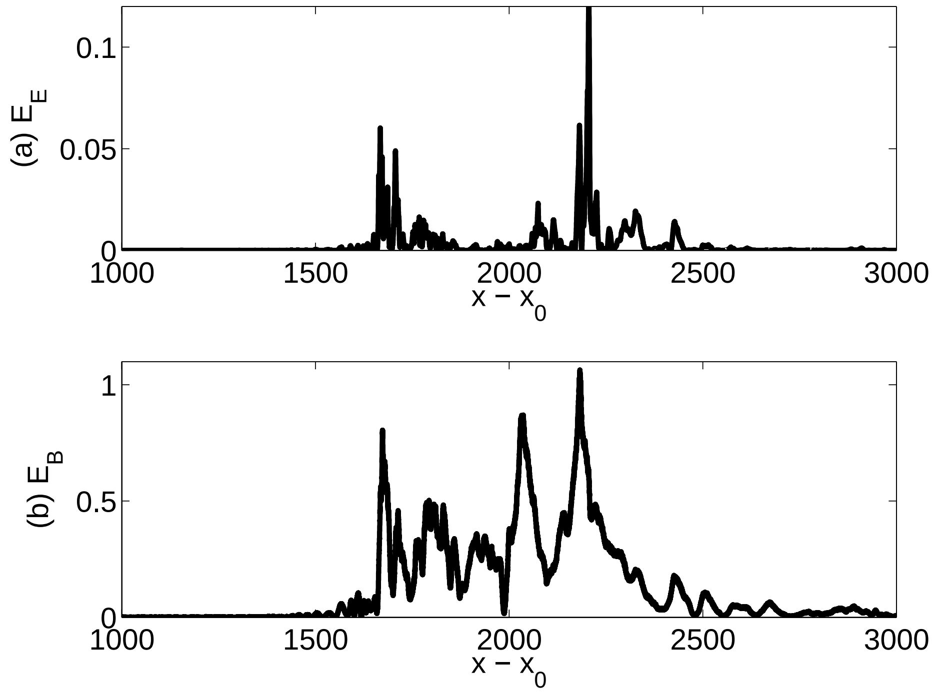
Peak electron Lorentz factor: 400 $\sim m_i/m_e$

Relativistically hot electrons in 'downstream': Probably energy equi-partition between electrons and ions

Electric E_E and magnetic E_B energy densities: Final time

Position is in units of $\lambda_e = c/\omega_p$

$E_E = \epsilon_0 E^2$ and $E_B = B^2/2\mu_0$. Units: initial average plasma energy density



Energy equi-partition in downstream plasma also between plasma and $\mathbf{B}$!

Time / energy scales in physical units:

- Simulation runtime: $\omega_p t \approx 5400$, where ω_p is plasma frequency for box-averaged electron number density $n_e \approx 130/cm^3$.

  Time in physical units: 8 milliseconds
- Jet density n_e not known: However, time scales with $\sqrt{n_e}$ (robust)
- Internal shock moves in jet frame. Jet Lorentz factor $\approx 400 \Rightarrow$ Shock development in 3-4 seconds in Earth frame
- Electrons reach $\gamma \approx const\, m_i \,/\, m_e$ (?) $\Rightarrow$ GeV in jet frame. $const$ depends on shock collision speed.

  $\Rightarrow$ Lorentz-boosted $\gamma \approx 1.5 \times 10^6$ or TeV energy in Earth frame.
- Size of structure in jet frame $10^3 c/\omega_p \approx 500$ km. In Earth frame 1 km.

Discussion

- A flow-aligned magnetic field can stabilize the plasma against waves with $\mathbf{k}$ oblique or perpendicular to flow velocity vector.

  Required $|\mathbf{B}|$ rises fast with $\gamma(\mathbf{v}_b)$: Only practical for internal shocks
- A weak perpendicular magnetic field triggers a powerful structure of mixed polarity, probably an oblique whistler
- The perpendicular magnetic field is amplified and it reaches an energy comparable to the mean plasma kinetic energy.
- A shock forms: Electrons and ions get accelerated / heated
- Note: During its nonlinear evolution, the shock structure may filament, which is not represented by our simulation. The plasma temperature may suppress this?!
- Assuming a Lorentz factor of 400 of a gamma-ray burst jet: Variability of electron energies on TeV and second scales in Earth frame
- Good news: Plasma instabilities can, in principle, provide the particle acceleration and magnetic field amplification required to explain the prompt gamma ray burst emissions.