Structure of a collisionless pair jet in a magnetized electron–proton plasma: flow-aligned magnetic field

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Motivation

- Accreting black holes can emit jets which are composed of electrons, positrons and some ions.
- Hydrodynamic models suggest that the jet material flows through a channel that is enclosed by a contact discontinuity.
- Shock 1 separates jet material from the inner cocoon (IC).
- Shock 2 separates ambient material from the outer cocoon (OC).
- Can we find a similar jet structure in collision-less plasma?
- Collisionless shocks have been widely examined.

- Is there an electromagnetic “contact discontinuity” that separates a pair plasma from an electron-proton plasma?
Simulation setup

- Our simulation box is filled uniformly with ambient electrons and protons with the density $n_0$ and temperature $T_0 = 2 \text{ keV}$.

- A uniform magnetic field $B_0 = (B_0, 0, 0)$ fills the simulation box at the time $t=0$.

- We set $P_B = B_0^2/2\mu_0 = n_0 k_B T_0 = P_T$.

- A pair cloud is injected at the left boundary with the mean velocity $v_c = (0.9c, 0, 0)$ and temperature $200 T_0$.

- Its density has a maximum $5n_0$ and decreases quadratically to both vertical sides.
Global jet structure

- Upper left to lower right: densities of the cloud electrons, cloud positrons, ambient electrons, protons and moduli of the electric and magnetic fields.

- Time unit: inverse proton plasma frequency \( \omega_{pp} = (n_0 e^2 / m_p \epsilon_0)^{0.5} \)

- We resolve \( 0 \leq t \leq 34 \).

- Space unit: proton skin depth \( \lambda_s = c/\omega_{pp} \).

- Time scale (\( n_0 \) in particles per \( \text{cm}^3 \)): 0.7 ms/\( \sqrt{n_0} \) and spatial: \( 2.3 \cdot 10^5 \text{ m/} \sqrt{n_0} \)
Electromagnetic discontinuity

- Protons represent the ambient plasma.
- Positrons represent the jet material.
- The contour lines show where the magnetic pressure exceeds the thermal pressure of the ambient electrons by the factor 100.
- Time covered: $13.5 \leq t \leq 34$.
- The discontinuity is a stable and coherent magnetic field structure.
- It is practically impenetrable for the ambient protons and confines well the positrons.
Proton acceleration

- Animation of the proton phase space density distribution $f(x, y, |v|)$ for the interval $y < 0$ (half the jet).
- Long axis: $x$ in $\lambda_s$
- Axis to the right: $y$ in $\lambda_s$
- Vertical axis: $|v|$ in proton thermal speeds ($4.4 \cdot 10^5 \text{ m/s}$)
- Maximum speed $0.132c$
- Protons reach 4 MeV.
Summary

- An initially charge- and current-neutral pair cloud expanded into an electron-proton plasma.
- A stable discontinuity formed after about $10/\omega_{pp}$. It separated the positrons from the protons.
- Strong coherent magnetic fields are immersed by positrons with a relativistic temperature ⇒ radio synchrotron emissions.
- Positrons are accelerated at the jet’s head while jet electrons are slowed down. ⇒ positrons outrun the jet with multi-MeV energies.
- Proton energies grow from 2 keV to 4 MeV ⇒ fast magneto-sonic shocks form with a Mach number 11.

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