Plasma instabilities in fast pair beams in cosmic voids

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COST Workshop - The biggest accelerators in space and on earth

March 19, 2013

RUHR UNIVERSITÄT BOCHUM
TP4 RUB

Outline

1. From TeV radiation from blazars to fast electron-positron pair beams interacting with the IGM
2. Kinetic theory of plasma instabilities
3. Instabilities in cold pair beams
4. Effects of the instabilities
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Interaction of TeV emission from blazars with extragalactic background light

- Blazars more distant than $z \approx 0.16$ create electron positron pair beams in intergalactic space
- TeV γ-rays interact with extragalactic background light (EGBL) and produce relativistic electron-positron pairs
- Model: interaction of power law spectrum of TeV photons with a maximum energy M with Wien-type distribution of EGBL
- Pair beam spectrum is strongly peaked in energy as well as angular distribution
- Pairs are beamed into the direction of the initial gamma-ray photons

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- System contains beam electrons, beam positrons, IGM protons and IGM electrons.
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- Particles and fields of a plasma can be described by the coupled Vlasov-Maxwell system of equations

  $\Rightarrow$ In general: Difficult!
- Describe plasma instabilities by the linearised Vlasov equation for particle distribution function (PDFs) in one-particle phase space $f_a(\vec{x}, \vec{p}, t)$ for species a
- Fourier-Laplace transform to frequency space (k real $\Rightarrow \omega$ generally complex) to yield late term behaviour of small amplitude fluctuations
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- Maxwell operator $\Lambda_{ij} = \frac{c^2 k^2}{\omega^2}\left(\frac{k_i k_j}{k^2} - \delta_{ij}\right) + \psi_{ij}$
- Dielectric tensor $\psi_{ij} = \delta_{ij} + \frac{4\pi\imath}{\omega}\sigma_{ij}$
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Distribution function for the beam in the rest frame of the IGM

$$f\left(p_{\parallel}, p_{\perp}\right) = \frac{1}{2\pi p_{\perp}} \frac{1}{\left(m_e c\right)^3} \delta\left(p_{\perp} - Q\right) \delta\left(p_{\parallel} - P\right)$$

where $P = \Gamma_1 m_e \beta_1 c$ and $Q = P \tan\theta$

Electrostatic instability in cold pair beams

Substitute the PDF into the general electrostatic dispersion relation:

Dispersion relation for electrostatic waves

$$\Lambda_e = 1 - \frac{\omega_{p,e}^2}{\omega^2} - \underbrace{\frac{2\omega_{p,e}^2}{\Gamma} \frac{n_b}{N_e} \frac{1-\beta^2\cos^2\theta}{(\omega-\beta\cos\theta)^2}}_{beam}$$

We have introduced $\Gamma := \sqrt{1+P^2+Q^2}$ and neglected a term $\sim n_b/N_e \propto 10^{-15}$.

Solution

- This dispersion relation has been analysed before by Davidson
- Instability implies a positive imaginary frequency $\gamma > 0$
- Show that the dispersion relation has a minimum ω_0 and that $\Lambda_e(\omega_0) > 0$.
- This implies the existence of an imaginary solution to the dispersion relation, viz. an instability
- To determine the maximum growth rate of the instability, we investigate $\frac{\partial \omega}{\partial k} = \frac{\partial \Lambda_e}{\partial k}\left(\frac{\partial \Lambda_e}{\partial \omega}\right)^{-1}$
- We find the frequency to have the form $\omega = \frac{k v_\parallel \cos\theta}{1+\frac{\alpha}{2}\left(1-\imath\sqrt{3}\right)}$ for some real α and integer $n = 1$
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Frequency and growth rate for the electrostatic instability at maximum growth

$$(\Re\,\omega)_{max} = \omega_{p,e}\left[1 - \left(\frac{n_b}{N_e\Gamma_6}\right)^{1/3}\frac{\left(1-\beta^2\cos^2\theta\right)^{1/3}}{\Gamma^{1/3}}\right]\ \mathrm{Hz}$$

$$(\Im\,\omega)_{max} = \frac{\sqrt{3}}{2}\,\omega_{p,e}\left(\frac{n_b}{N_e\Gamma_6}\right)^{1/3}\frac{\left(1-\beta^2\cos^2\theta\right)^{1/3}}{\Gamma^{1/3}}$$

$$\approx 8\cdot 10^{-7}\,\omega_{p,e}\left(\frac{n_{22}}{N_7\Gamma_6}\right)^{1/3}\left(1-\beta^2\cos^2\theta\right)^{1/3}\ \mathrm{Hz}$$

Maximum growth occurs at an angle of 39.2° between the beam direction and the wave vector orientation:

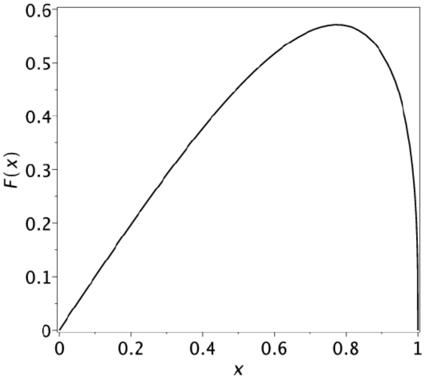

Figure: Angular distribution of the growth rate for the electrostatic mode in cold pair beams (*From: Schlickeiser, Ibscher, Supsar, 2012 ApJ 708, 102*)

Transverse mode: the Weibel instability

Dispersion relation for the Weibel mode in Lerche variables $E := \sqrt{1 + \frac{p_\perp^2 + p_\parallel^2}{m_e^2 c^2}}$ and $y := \frac{p_\parallel}{m_e c}$:

$$\Lambda_t = 1 - \frac{1}{z^2} - \frac{\omega_{p,e}^2}{k^2 c^2 z^2} - \frac{2\pi\omega_{p,e}^2}{k^2 c^2 z^2} \frac{n_b}{N_e} (m_e c)^3 \times \int_1^\infty \mathrm{d}\, E \int_{-\sqrt{E^2-1}}^{\sqrt{E^2-1}} \mathrm{d}\, y \, \frac{E^2 - 1 - y^2}{y - Ez} \left[\frac{\partial f}{\partial y} + z \frac{\partial f}{\partial E}\right]$$

with the complex phase speed $z = \frac{\omega}{kc} = R + \imath S$.

Inserting the PDF and performing the integrations yields for ultrarelativistic $P \gg 1$:

$$1 - \frac{1}{z^2}\left[1 + \frac{\omega_{p,e}^2}{k^2c^2}\left(1 + \frac{2n_b}{PN_e}\right)\right] - \frac{2\omega_{p,e}^2}{k^2c^2}\frac{n_b}{N_eP}\frac{1}{z^4} = 0$$

- Solving this biquadratic equation provides two oscillating undamped wave modes, one damped and one growing solution
- The instability has the growth rate

$$\gamma_W = \frac{\omega_{p,e}}{\sqrt{2}} \left[\sqrt{(1+\Psi+\kappa^2)^2 + 4\Psi\kappa^2} - 1 - \Psi - \kappa^2 \right]^{1/2}$$

  with the parameter $\Psi := \frac{2n_b}{PN_e} \approx 2 \cdot 10^{-21} \frac{n_{22}}{N_7 \Gamma_6}$ and $\kappa := \frac{kc}{\omega_{p,e}}$.
- The maximum growth rate is $\gamma_{W,max} \simeq \omega_{p,e} \, \Psi^{1/2} = 8 \cdot 10^{-10} \left(\frac{n_{22}}{\Gamma_6} \right)^{1/2}$ Hz.
- Smaller than the maximum growth rate for the electrostatic instability by a factor $1375 \left(\frac{\Gamma_6 N_7}{n_{22}} \right)^{1/6}$

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Intense blazars

- Blazars that produce a beam density higher than $n_c = 4.8 \cdot 10^{-25} \frac{N_7}{\gamma_6} T_4^2$
- Electrostatic instability causes the onset of the modulation instability in the beam
- Energy dissipation by modulation instability is an order of magnitude faster than the electromagnetic cascade
- Modulation instability exhausts all free energy
- Heating of the IGM with heating rates $Q > 9.8 \cdot 10^{-33} \frac{N_7^{3/2} T_4^{8/3}}{\Gamma_6^{2/3}} \frac{\mathrm{erg}}{\mathrm{cm^3 s}}$

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Weak blazars

- Weak blazars: Nonlinear Landau damping instead of modulation instability
- Most of the free energy is transferred to superluminal phase speeds
- Remaining energy in electrostatic instability relaxes the beam to a plateau distribution
- Inverse Compton scattering of superluminal electrostatic instabilities into light at optical frequencies
- This leads to the prediction of optical bremsstrahlung halos from weak blazars with small spectral flux densities $F_B < 4.8 \cdot 10^{-7} \frac{T_4^2}{\Gamma_6^2}$ Jy

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Summary

- Reaction of TeV blazar photons in cosmic voids with the EGBL creates strongly beamed electron-positron pair beams
- These pairs are subject to electrostatic and electromagnetic instabilities
- Electrostatic instability in cold beams grows fastest, with $\gamma_{max} \approx$ at an angle of 39.9°.
- The effects of the instabilities causes the IGM to be heated for intense blazars
- Pair halos for weak blazars
- In progress: Calculations for more realistic distribution functions

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