Strong quasistatic magnetic fields in astrophysical scenarios

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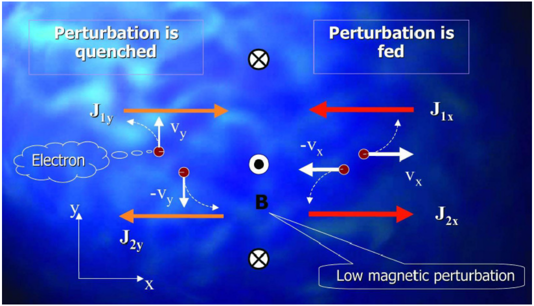
Abstract

Magnetic fields play a crucial role for the onset of most nonthermal phenomena in cosmological plasma sources. Nonthermal radiation usually having a power-law emission spectrum is observed from numerous relativistic outflow sources in jets and shocks of Active Galactic Nuclei (AGN), Gamma Ray Bursts (GRBs), galactic microquasars or Crab-like supernova remnants. In these plasma systems the emission is thought to be generated by the accelerated charges moving arround sufficiently **strong quasistatic magnetic fields**, via the synchrotron mechanism.

Our intention is to show that the Weibel-type instabilities can be made responsible for the generation of such intense magnetic fields in regions with anisotropic thermal distributions, or in counterstreaming plasmas.

Origin of Weibel-type instabilities → velocity anisotropy



$$v_x \neq v_y \rightarrow -\mathbf{J}_{1\text{total}} = \mathbf{J}_1\mathbf{y} - \mathbf{J}_1\mathbf{x} = \mathbf{J}_2\mathbf{x} - \mathbf{J}_2\mathbf{y} = \mathbf{J}_{2\text{total}}$$

Weibel-type instabilities are driven by a velocity anisotropy:
* **Filamentation instability** (Fried 1959) originates in a macroscopic velocity anisotropy as in counterstreaming plasmas, or beam-plasma systems;
* **Weibel instability** (Weibel 1959) originates in a microscopic velocity anisotropy, e.g., bi-Maxwellian distribution functions.

Features of magnetic instabilities

- Both instabilities (Weibel and filamentation) are aperiodic, i.e., $\omega_{\rm real} = 0$ (nonresonant) $\longrightarrow$ can be saturated only by nonlinear effects and not by kinetic effects, such as collisionless damping or resonance broadening. The magnetic field can be thus amplified to very high values.
- Instabilities are self-saturating, continuing until all the free energy due to the particle distribution function (PDF) anisotropy is transferred to the magnetic field energy.
- The produced magnetic field is randomly oriented in the directions perpendicular to the microscopic or macroscopic flows $\longrightarrow$ the Lorentz force randomize particle motion over the pitch angle, and hence introduce an effective scattering into the otherwise collisionless system.

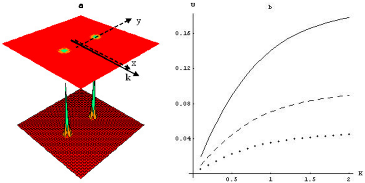
Kinetic theory: Vlasov-Maxwell equations

Filamentation instability - two cold counterstreaming plasmas → distribution function (fluid theory can be also used in this case)

$$f_0(v_x, v_y, v_z) = (1/2)\delta(v_x)\left[\delta(v_y - v_0) + \delta(v_y + v_0)\right]\delta(v_z)$$

Dispersion relation (only electron contribution):

$$\omega^2 = k^2c^2 + \omega_{pe}^2\left(1 + \frac{k^2 v_0^2}{\omega^2}\right)$$



Left: Distribution function. **Right**: Filamentation growth rates for $v_{\mathrm{th}}/c = 0.1$, $v_0/c = 0.05, 0.1, 0.2$.

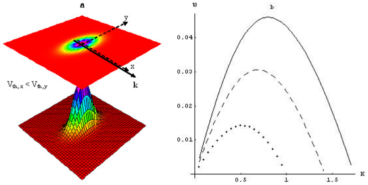
Kinetic theory: Vlasov-Maxwell equations

Weibel instability - anisotropic plasma $\longrightarrow$ bi-Maxwellian distribution

$$f_0(v_x, v_y, v_z) = \frac{1}{\pi^{3/2} v_{\mathrm{th},x}^2 v_{\mathrm{th},y}} \exp\left[-\left(\frac{v_x^2 + v_z^2}{v_{\mathrm{th},x}^2} + \frac{v_y^2}{v_{\mathrm{th},y}^2}\right)\right], \quad A = \left(\frac{v_{\mathrm{th},y}}{v_{\mathrm{th},x}}\right)^2 - 1$$

Dispersion relation (only electron contribution):

$$\omega^2 = k^2 c^2 + \omega_{pe}^2 \left[1 + \frac{1}{2}(A+1) Z'\left(\frac{\omega}{k v_{\mathrm{th},x}}\right)\right]$$



Left: Distribution function. **Right**: Weibel growth rates for $A = 1, 2, 3$, $v_{\mathrm{th}}/c = 0.1$.

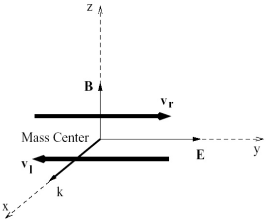
Counterstreaming plasmas with thermal anisotropies

$$f_0(v_x, v_y, v_z) = \frac{1}{2\pi^{3/2} v_{\mathrm{th},x}^2 v_{\mathrm{th},y}} e^{-\frac{v_x^2+v_z^2}{v_{\mathrm{th},x}^2}} \left[e^{-\frac{(v_y+v_0)^2}{v_{\mathrm{th},1,y}^2}} + e^{-\frac{(v_y-v_0)^2}{v_{\mathrm{th},2,y}}} \right]$$

$$A_j = \left(\frac{v_{\mathrm{th,j},y}}{v_{\mathrm{th,j},x}}\right)^2 - 1, \quad \mathrm{j} = 1,2 \quad v_r = v_l = v_0$$

Dispersion relation:

$$\omega^2 = k^2c^2 + \omega_{pe}^2 \left\{ 1 + \frac{1}{2} \left[1 + \frac{1}{2}(A_1 + A_2) + 2\left(\frac{v_0}{v_{\mathrm{th},x}}\right)^2 \right] Z'\left(\frac{\omega}{k v_{\mathrm{th},x}}\right) \right\}$$

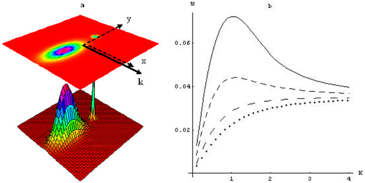


Linear coupling of filamentation and Weibel instabilities in counterstreaming plasmas with thermal anisotropies (Lazar et al. - 2006)

Positive anisotropies → Enhancing effect

$$f_0(v_x, v_y, v_z) = \frac{1}{2\pi^{3/2} v_{\mathrm{th},x}^2 v_{\mathrm{th},y}} e^{-\frac{v_x^2+v_z^2}{v_{\mathrm{th},x}^2}} e^{-\frac{(v_y+v_0)^2}{v_{\mathrm{th},y}^2}} + \frac{1}{2}\delta(v_x)\delta(v_y - v_0)\delta(v_z)$$

$$A_j = \left(\frac{v_{\mathrm{th,j},y}}{v_{\mathrm{th,j},x}}\right)^2 - 1 > 0 \quad \mathrm{j} = 1, 2$$



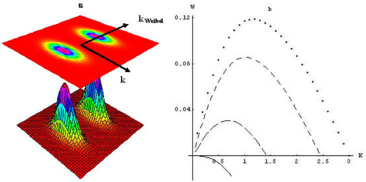
Left: Distribution function. **Right**:Enhancing effect for $v_{\mathrm{th}}/c = 0.1$, $v_0/c = 0.05$ and $A = -3, 0, 4, 9$.

Linear coupling of filamentation and Weibel instabilities in counterstreaming plasmas with thermal anisotropies (Lazar et al. - 2006)

Negative anisotropies → Stabilization effect: suppression of instability

$$\text{Right}: \; f_0(v_x, v_y, v_z) = \frac{1}{2\pi^{3/2} v_{\mathrm{th},x}^2 v_{\mathrm{th},y}} e^{-\frac{v_x^2+v_z^2}{v_{\mathrm{th},x}^2}} \left[e^{-\frac{(v_y+v_0)^2}{v_{\mathrm{th},1,y}^2}} + e^{-\frac{(v_y-v_0)^2}{v_{\mathrm{th},2,y}^2}} \right]$$

$$A_j = \left(\frac{v_{\mathrm{th,j},y}}{v_{\mathrm{th,j},x}} \right)^2 - 1 < 0 \;\; \mathrm{j} = 1, 2$$



Left: Distribution function. **Right**: Suppression of filamentation mode for $v_{\mathrm{th}}/c = 0.1$, $v_0/c = 0.2$ and $A_1 = A_2 = 1$ (dotted line),-2, -6 (dashed lines), -8 (solid line).

Saturated magnetic field value

The unstable magnetic field perturbations grow up to a sufficiently large amplitude so that the fields saturate due to magnetic trapping of plasma particles.
In the simulations it is found that saturation occurs when the magnetic bounce frequency increases to a value comparable to the linear growth rate prior to saturation:

$$\omega_{i,\max} \simeq \omega_B = \left| \frac{e k_{\max} v_{\mathrm{th},y} B}{m_e c} \right|^{1/2}$$

Weibel regime: $v_{\mathrm{th},y} \simeq \rho_B \, \omega_{i,\max}$ and $k_{\max} \simeq \rho_B^{-1} = m_e c/(eB) \rightarrow$

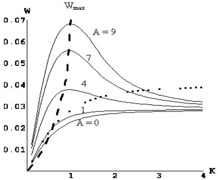
$$B = \frac{m_e c \, \omega_{i,\max}}{e}$$

Filamentation regime: $\omega_{i,\max} = (\omega_{p,e} v_0)/c$ and $k_{\max} \simeq \rho_B^{-1} = m_e c/(eB) \rightarrow$

$$B = \sqrt{4\pi n_e m_e} \, \frac{v_0}{v_{\mathrm{th},y}}$$

Weibel regime: $\omega_{i,\max} = ?$

$$f_0(v_x, v_y, v_z) = \frac{1}{2\pi^{3/2} v_{\mathrm{th},x}^2 v_{\mathrm{th},y}} e^{-\frac{v_x^2+v_z^2}{v_{\mathrm{th},x}^2}} e^{-\frac{(v_y+v_0)^2}{v_{\mathrm{th},y}^2}} + \frac{1}{2}\delta(v_x)\delta(v_y - v_0)\delta(v_z)$$



Dispersion relation:

$$\omega^2 = k^2c^2 + \frac{\omega_{pe}^2}{2}\left[2 + \frac{k^2v_0^2}{\omega^2} + \frac{1}{2}\left(1 + \frac{2v_0^2}{v_{\mathrm{th},x}^2}\right) Z'\left(\frac{\omega}{kv_{\mathrm{th},x}}\right)\right]$$

Exact evaluation of $(\omega_{i,\max};\, k_{\max}) \to$ only numerically

$$\frac{d\omega_i}{dk} = 0 \;\; \to \;\; \omega_{i,\max} = \omega_i(k_{\max})$$

Approximative: the asymptotic approximations of plasma dispersion function.

Astrophysical scenarios

* **Pulsar magnetosphere**

- Coherent curvature radiation (Ruderman and Sutherland - 1975): filamentation instability induced by the outflowing positrons through pair plasmas → bunching of relativistic particles
- Synchrotron-emitting particles (Langdom et al. - 1988): filamentation and cycltron maser instabilities → strong EM fields in the downstream region of magnetosonic shocks
- Wisps generation in Crab Nebula (Yang et al. - 1992)): instability occurs in the relativistic magnetosonic shock wave of a pair-proton plasma → pitch-angle scattering of the charged particles

* **Gamma Ray Burst sources** (Medvedev & Loeb - 1999): intensity of synchrotron (nonthermal) radiationn of prompt or afterglow emission observed in GRBs requires for

- Strong quasistatic magnetic fields
- (Relativistic) accelerated particles

* **Magnetization of the intergalactic medium** (Schlickeiser & Shukla - 2003): filamentation and Weibel instabilities generated by the relative motion of the filaments and sheets of galaxies.

Conclusions

* Filamentation and Weibel instabilities are the most plausible mechanisms for the generation of strong magnetic fields in many astrophysical applications (e.g., creation of magnetic fields in the GRBs sources, or in the early universe).
* From observational data the magnetic energy is expected to saturate at higher values than those calculated before considering only the simple filamentation instability of two counterstreaming cold plasmas, or with isotropic Maxwellian distributions.
* For a more realistic scenario of counterstreaming plasmas with thermal anisotropies, the effects of filamentation and Weibel modes can couple leading to growth rates by orders of magnitude larger than that of a simple filamentation mode. Of particular interest is in this case, the re-evaluation of the magnetic field strength reached at saturation.
* New models are also prepared for the conditions under which, involving protons and relativistic streaming velocities for electrons might enhance the magnetic energy to even higher values.