Proceedings of ICRC 2001: 2713 © Copernicus Gesellschaft 2001

ICRC 2001

Longitudinal, electrostatic instabilities in the channeled blast wave model

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Abstract. To address the important issue of how kinetic energy of collimated blast waves is converted into radiation, Pohl and Schlickeiser (2000) have recently investigated the relativistic two-stream instability of electromagnetic turbulence. They have shown that swept-up matter is quickly isotropized in the blast wave, which provides relativistic particles and, as a result, radiation.
Here we present new calculations for the electrostatic instability in such systems. It is shown that the electrostatic instability is faster than the electromagnetic instability for highly relativistic beams. However, even after relaxation of the beam via the faster electrostatic turbulence, the beam is still unstable with respect to the electromagnetic waves, thus providing the isotropization required for efficient production of radiation. While the emission spectra in the model of Pohl and Schlickeiser have to be modified, the basic characteristics persist.

1 Introduction

Published models for the γ-ray emission of blazars are usually based on interactions of highly relativistic electrons of unspecified origin propagating in the relativistic jet of active galactic nuclei. The usual shock or stochastic electron acceleration processes would have to be very fast to compete efficiently with the strong radiative losses at high electron energies. Energetic electrons may also result as secondaries from photomeson production of highly relativistic hadrons, but the observed short variability timescale places extreme conditions on the magnetic field strength, for the hadron gyroradius has to be much smaller than the system size, and on the Doppler factor, for the intrinsic timescale for switching off the cascade is linked to the observed soft photon flux.

Here we consider the energisation of relativistic particles in jets by interactions with the surrounding medium. We

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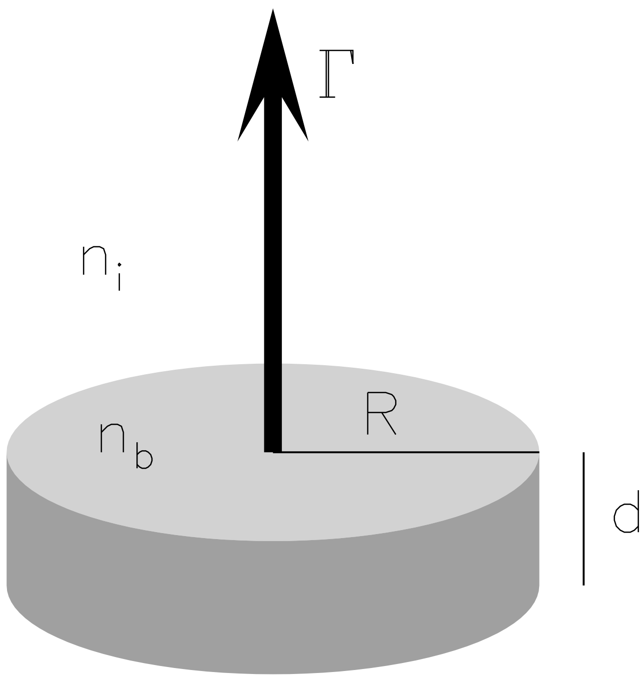

Fig. 1. Sketch of the basic geometry. The blast waves, containing an electron-proton plasma of density n_b, moves with Lorentz factor Γ through ambient, interstellar matter of density n_i.

model the relativistic jet as a channeled outflow with relativistic bulk velocity V, consisting of cold electrons and protons of density n_b^* (see Fig.1). For convenience we assume that the outflow is directed parallel to the uniform background magnetic field. This beam of protons and electrons propagates into the surrounding interstellar medium that consists of cold protons and electrons of density n_i^*. Viewed from the coordinate system comoving with the outflow, the interstellar protons and electrons represent a proton-electron beam propagating with relativistic speed $-V$ antiparallel to the uniform magnetic field direction. This situation is un-

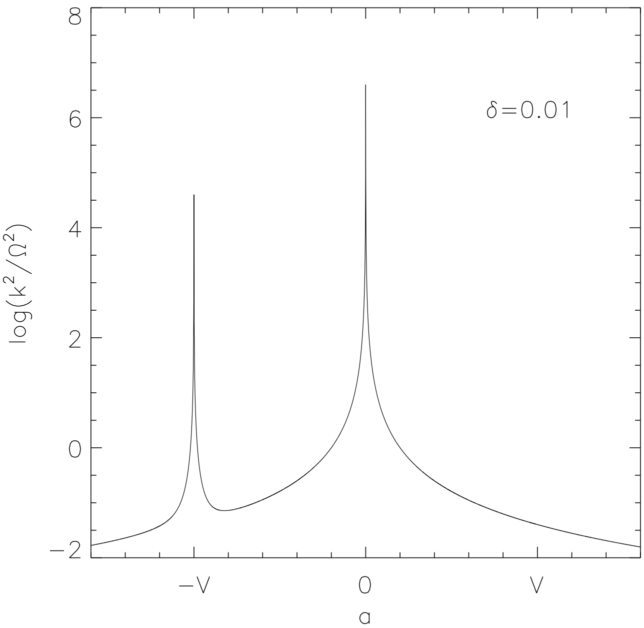

Fig. 2. The dispersion relation for longitudinal, electrostatic waves. There is always a real solution in the range $a \leq -V$, and another real solution in $a \geq 0$. In the remaining range $-V \leq a \leq 0$ the dispersion relation returns two real values of a only if k^2 exceeds $k^2_{\rm min}$.

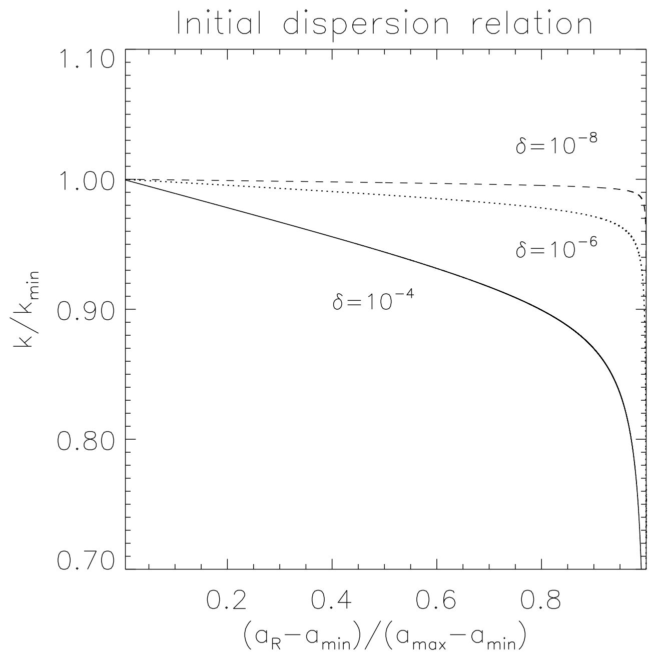

Fig. 3. The dispersion relation for longitudinal waves in the unstable phase velocity range. For small perturbation parameters, δ, $k/k_{\rm min}$ is essentially flat, unless $a_{\rm R}$ is very close to $a_{\rm max}$.

stable and waves will be excited which backreact on the incoming beam. In the earlier analysis (Pohl and Schlickeiser, 2000) the stability of this beam was examined under the assumption that the background magnetic field is uniform and directed parallel to the direction of motion. It was shown that the beam very quickly excites low-frequency electromagnetic waves, which quasi-linearly isotropize the incoming interstellar electrons and protons in the blast wave plasma, thus providing relativistic particles. The high energy emission produced by these particles has characteristics typical of BL Lacertae objects. The secular variability of the γ-ray emission of AGN would be related to the existence or nonexistence of a relativistic blast wave in the sources, and thus to the availability of free energy in the system. The observed fast variability on the other hand would be caused by density inhomogeneities in the interstellar medium of the sources.

In parallel to the γ-rays neutrinos are emitted, whose spectrum and flux would be closely correlated with those of the γ-rays, which permits to use the γ-ray light curves of blazars to very efficiently search for neutrino emission as a diagnostic for an hadronic origin of the high energy radiation (Schuster, Pohl and Schlickeiser, 2001).

We now expand on the previous treatment by calculating the two-stream instability for longitudinal, electrostatic waves. In contrast to electromagnetic waves, which scatter the particles in pitch angle but preserve their kinetic energy until the distribution is isotropized, the electrostatic waves change the particle's energy until a plateau distribution is established.

2 The dispersion relation

The initial particle distribution function for protons and electrons is

$$f(\boldsymbol{p},t=0) = \frac{n_{\rm i}\delta(p_\perp)\delta(p_\parallel + P)}{2\pi p_\perp} + \frac{n_{\rm b}\delta(p_\perp)\delta(p_\parallel)}{2\pi p_\perp} \quad (1)$$

with $P = mV\Gamma$. Then, for charge e, mass m particles under the action of an electric field $\boldsymbol{E} = \boldsymbol{e}_\parallel E_\parallel \, \exp(\imath k(x-at))$, in the direction parallel to an ambient magnetic field the perturbations, $\delta f \, \exp(\imath k(x-at))$, to the original distribution function satisfy

$$\frac{\partial \delta f}{\partial t} + \boldsymbol{v}\frac{\partial \delta f}{\partial \boldsymbol{x}} + e\boldsymbol{E}\frac{\partial f}{\partial \boldsymbol{p}} = 0 \quad (2)$$

which, to first order in $\delta f/f$, yields the dispersion relation

$$k^2 = 4\pi \sum e^2 \int \frac{\frac{\partial f}{\partial p_\parallel}}{v_\parallel - a}\, d^3p = \Omega^2 \left[\frac{1}{a^2} + \frac{\delta}{(a+V)^2}\right] \quad (3)$$

where $\Omega^2 = \omega^2_{p,p} + \omega^2_{p,e}$ and $\delta = n_i/\left(n_b\,\Gamma^3\right)$. A plot of k^2 versus a is given in Fig.2. The waves are unstable for negative k with

$$k^2 \leq k^2_{\rm min} = \frac{\Omega^2}{V^2}(1+\delta^{1/3})^3 \quad (4)$$

and

$$a_{\rm min}\,(k_{\rm min}) = -V(1+\delta^{1/3})^{-1} \ > -V \ , \quad (5)$$

in which range the dispersion relation has the solution

$$a\,V^{-1} = -\sin^2\phi + \imath y_I \quad (6)$$

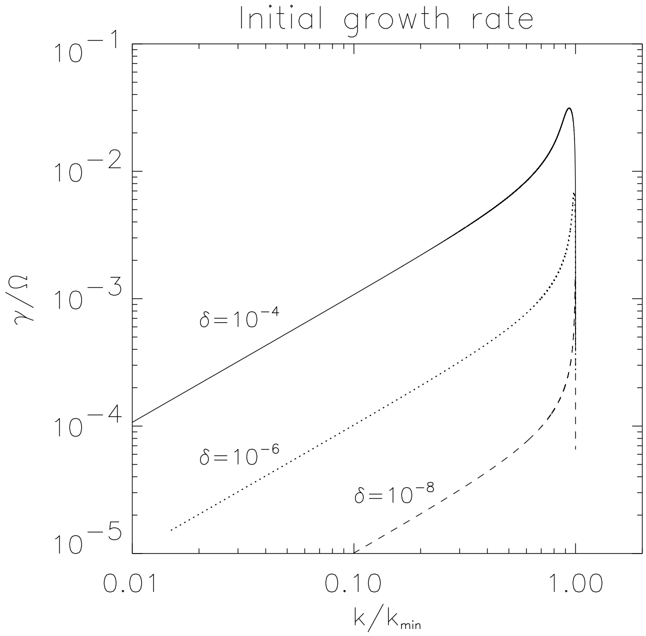

Fig. 4. The growth rate γ as a function of the wave number k for three values of the perturbation parameter $\delta = n_i/\left(n_b\,\Gamma^3\right)$. Most of the instability occurs in a small wavenumber range close to $k_{\min}$.

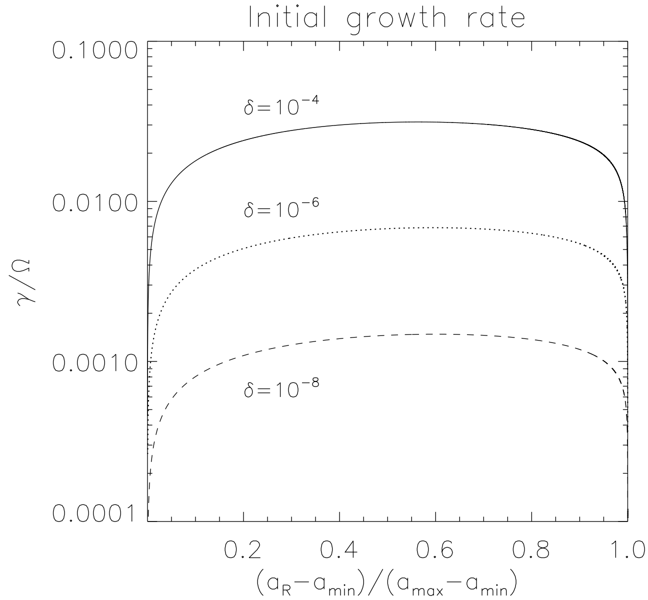

Fig. 5. The growth rate γ as a function of the phase velocity $a_{\rm R}$ for three values of the perturbation parameter δ. The perturbation parameter controls only the speed of the instability, but not its spectral form.

with

$$\frac{k^2}{k^2_{\min}} = \left(\frac{\tan^2\phi+1}{\tan^2\phi-1}\right)^2 \frac{(\tan\phi-\sqrt{\delta})(1-\tan\phi\sqrt{\delta})}{\tan\phi\,(1+\delta^{1/3})^3} \qquad (7)$$

and

$$y_I^2 = \frac{\tan\phi(\sqrt{\delta}\tan^3\phi-1)}{(1+\tan^2\phi)^2(\tan\phi-\sqrt{\delta})} \qquad (8)$$

The range of ϕ is restricted to $\delta^{-1/6} \le \tan\phi \le \delta^{-1/2}$. On $\tan\phi = \delta^{-1/6}$ note that $k^2 = k^2_{\min}$ and $a_{\rm R} = a_{\min}$, and on $\tan\phi = \delta^{-1/2}$, $k = 0$ and $a_{\rm R} = -V(1{+}\delta)^{-1} = a_{\max}$. Thus $\tan\phi$ covers the complete wavenumber spectrum where instability can occur.

In Fig.3 we show the unstable region of the dispersion relation in phase velocity; k^2 is basically independent of the phase velocity $a_{\rm R}$.In Figs.4 and 5 we show the growth rate as a function of the wavenumber, k, and phase velocity, $a_{\rm R}$, respectively. The growth rate is sharply peaked at wavenumbers close to $k_{\min}$, but is essentially independent of the phase velocity, $a_{\rm R}$.

3 The backreaction on the proton-electron beam

The time-dependent behavior of the intensities $I(k,t)$ of the excited waves is given by $\frac{\partial}{\partial t} I(k,t) = 2\,\gamma\, I(k,t)$ (Lerche, 1967; Lee and Ip, 1987). To describe the long-term influence of the excited waves on the beam particles, one uses the quasi-linear Fokker-Planck equation. Because the longitudinal waves act with an electric vector only, and because that vector parallels the magnetic field, the phase space density for the resonant particles then has only its momentum parallel to the ambient field influenced by the longitudinal turbulence. Hence, the corresponding Fokker-Planck equation reads

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial p_\parallel}\left(D\frac{\partial f}{\partial p_\parallel}\right) \qquad (9)$$

where the diffusion coefficient, D, is given by

$$D = \frac{\langle \Delta p_\parallel^2\rangle}{\Delta t} = 16\pi^2 e^2 \int_{k_{\min}}^0 dk\; I(k)\,\delta\left[k(v_\parallel - a_R)\right]$$

$$= 16\pi^2 e^2 \int_{k_{\min}}^0 dk\; \frac{I(k)}{|k|}\,\delta(v_\parallel - a_R) \qquad (10)$$

Because of the unknown nature of the initial wave spectrum, and because other processes ignored in the development will also influence the generation of waves, one of the standard devices is to ignore the wave intensity spectrum generation and to use *models* of how one believes the wave spectrum has evolved to its current state.

For the growth rate as a function of phase velocity, Fig.5 shows that the growth rate is essentially independent of $a_{\rm R}$. Neglecting the possible effects of damping and cascading, the intensity spectrum in phase velocity, $I(a_{\rm R}) = I(k)\frac{dk}{da_{\rm R}}$ is then flat between $a_{\min}$ and $a_{\max}$, and zero outside this range. Upon interaction with this wave spectrum the beam will relax to a plateau distribution between the velocities $-V$ and $v_\parallel = a_{min}$. The energy available for the build-up of the waves comes from the beam. Because the wave growth is much faster than the relaxation of the beam we may estimate the final wave intensity spectrum as the ratio of the energy

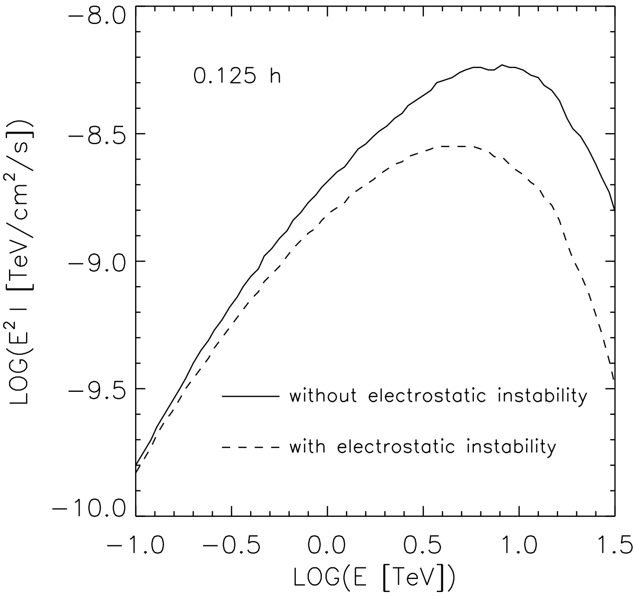

Fig. 6. π^0-decay spectra calculated with and without the electrostatic instability. The spectra refer to an observed time of 0.125 hours after the blast wave over-runs an isolated cloud. At this time the spectrum of swept-up particles has evolved very little. At the peak, about 50% of the beam particle energy is lost due to the effect of the electrostatic instability. There is little effect at smaller photon energies.

density lost by the beam during relaxation to a plateau between the velocities $-V$ and $v_\parallel = a_{min}$ and the phase velocity range in which effective growth occurs, namely $\delta^{1/3}V$. Therefore

$$I(a_\mathrm{R}) \simeq \frac{\Delta E}{\Delta a_\mathrm{R}} \simeq \frac{n_i\, m_p c^2\, \Gamma^3}{2\,V} = I_0 \tag{11}$$

The diffusion coefficient is then

$$D(p_\parallel) = 16\pi^2 e^2\, I_0 \int_{a_\mathrm{max}}^{a_\mathrm{min}} da_\mathrm{R}\, \frac{1}{|k|}\, \delta\left(v_\parallel - a_\mathrm{R}\right)$$

$$\simeq 2\pi\, m_e\, m_p\, c^2 \Gamma^3\, \Omega\, \frac{n_i}{n_b} \tag{12}$$

where we have again used that $k \simeq k_\mathrm{min} \simeq -V/\Omega$ in the resonant range. The time scale for the relaxation of the beam by the electrostatic instability can then be estimated as

$$\tau \simeq \frac{P^2}{D} \simeq \frac{m_p\, n_b}{2\pi\, m_e\, n_i\, \Omega\, \Gamma} \simeq 5 \cdot 10^{-3}\, \frac{\sqrt{n_8}}{\Gamma_2^2\, n_i^*} \quad \mathrm{sec} \tag{13}$$

where n_i^* is the interstellar matter density in the laboratory frame, $n_8 = 10^{-8} n_b$, and $\Gamma_2 = 10^{-2}\Gamma$. The relaxation time scale is two orders of magnitude shorter than the time scale for the electromagnetic instability derived in Pohl and Schlickeiser (2000).

4 Consequences

The electrostatic instability provides a plateau-distribution in $p_\parallel$, which is still unstable with respect to electromagnetic waves, implying that isotropization in the blast wave still occurs on roughly the same time scale as calculated in Pohl and Schlickeiser (2000).Therefore, the effect of the electrostatic instability is to provide a change in the spectrum of swept-up particles. Instead of the old result for the differential sweep-up rate in the absence of the electrostatic instability

$$\dot{N}(\gamma)\Big|_{\text{no e.s.i.}} = N_0\, \delta(\gamma - \Gamma) \tag{14}$$

we now obtain, if the electrostatic instability is much faster than the electromagnetic one,

$$\dot{N}(\gamma)\Big|_{\text{e.s.i.}} = \frac{N_0}{\Gamma - 1}\, \Theta(\Gamma - \gamma) \tag{15}$$

In the radiation spectra this change corresponds to a reduction of efficiency by roughly 50% at the highest energies and little change at smaller energies, because in the inelastic pp collisions the pion source power scales roughly with the kinetic energy of the incident proton, hence the pion spectra are dominated by the pions produced by the protons of high energy for flat proton spectra. In Fig.6 we show the spectra of π^0-decay γ-rays for the case of a fast electrostatic instability (Eq.15) in comparison with the case of the electromagnetic instability only (Eq.14). At photon energies well below the peak energy of the νF_ν-spectra the difference in spectral index is only $\Delta s \simeq 0.1$. Similarly small changes can be expected for the injection spectra of secondary electrons and hence for the synchrotron spectra at optical to X-ray frequencies. Therefore the isotropization and radiation conclusions drawn by Pohl and Schlickeiser (2000) remain valid.

Acknowledgements. Partial support by the Bundesministerium für Bildung und Forschung through DESY, grant 05AG9PCA, is acknowledged.

References

Lerche I., ApJ, 147, 689–696, 1967.
Lee M.A., Ip W.-H., JGR, 92, 11041–11052, 1987.
Pohl, M., Schlickeiser, R., A&A, 354, 395–410, 2000.
Schuster, C., Pohl, M., Schlickeiser, R., A&A, submitted, 2001.