Introduction to acceleration processes

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1. Introduction

- Observations of the photon radiation at TeV energies from cosmic particle accelerators by the H.E.S.S. and MAGIC air Cherenkov telescopes have detected more than 70 sources:

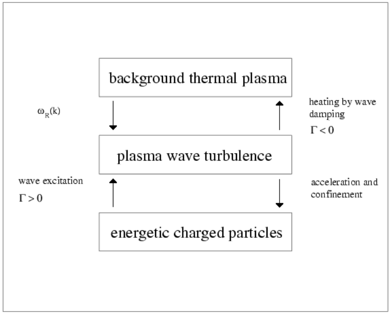
  7 supernova remnants, 18 pulsar wind nebulae, 2 extended sources, 4 binary systems, 24 extragalactic active galactic nuclei (AGN), 1 starburst galaxy, 3 radio galaxies, 21 unidentified sources

- These objects therefore are cosmic charged particle accelerators ("usual suspects"): in order to produce photons with energies of 1 TeV$= 10^{12}$ eV, the radiating charged particles must have even higher energies (non-thermal radiation processes).

- **Striking**: "Extreme" (compact, high photon luminosities, high magnetic field strength) objects (Pulsars=neutron stars, pulsar wind nebulae, supernova shock waves, microquasare, AGNs) with established high (often relativistic) velocity outflows (particle beams, jets, shock waves)

- AUGER experiment finds close correlation of arrival directions of UHE cosmic rays with location of known AGNs

- **Fundamental physics issue**: Conversion of directed kinetic outflow energy into high energy cosmic charged particles (=cosmic rays) in interactions with ambient target matter and photon radiation fields



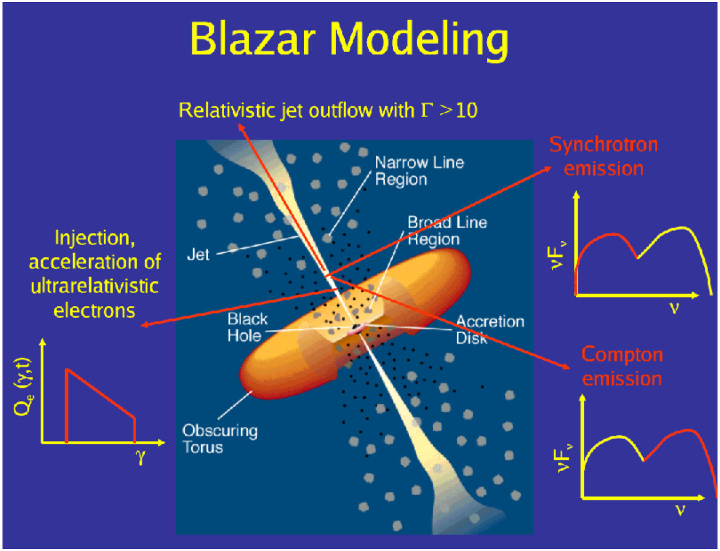
- However: all nonstellar cosmic plasmas are collision-free: plasma parameter $g = \nu_{ee}/\omega_{p,e} \ll 1$, i.e. electromagnetic interactions dominate elastic collisions.

  Consequences: (a) particle distribution functions are not Maxwellians , (b) ideal MHD is not applicable, (c) anomalous MHD requires determination of nonideal viscosities, heat conduction coefficient etc., (d) if shock waves form their properties are different from classical hydrodynamical shocks, (e) full kinetic theory is required

- Have to understand plasma physics of cosmic explosions in collision-free environment. How is explosion energy dissipated ?

2. Nonthermal radiation processes

Active Galactic Nuclei: Doppler boosted γ-ray emission from the jet.



Are radiating electrons primary accelerated particles or secondaries from hadron interactions?

2.1. Electron and positron radiation processes

– Synchrotron radiation
– Inverse Compton scattering of transverse target photons
– Electrostatic bremsstrahlung=inverse Compton scattering of longitudinal electrostatic plasma waves into transverse photons
– Nonthermal bremsstrahlung
– Pair annihilation

2.2. Hadronic radiation processes

– Pion production in inelastic hadron-hadron collisions
– Pion production in inelastic hadron-photon collisions
– Suprathermal proton bremsstrahlung (difference from ordinary bremsstrahlung: here electrons at rest and heavy proton is moving)

Photon production spectra from all production processes strongly depend on equilibrium energy spectrum $N(\vec{r}, \gamma, t)$ of radiating particles!

Equilibrium spectrum results from competition af all acceleration and energy loss processes and particle transport processes. For more information: e. g. Schlickeiser 2002, Cosmic Ray Astrophysics, Springer

2.3. Hadronic processes contain leptonic processes

Pion production in inelastic hadron-hadron- and hadron-photon-collisions:

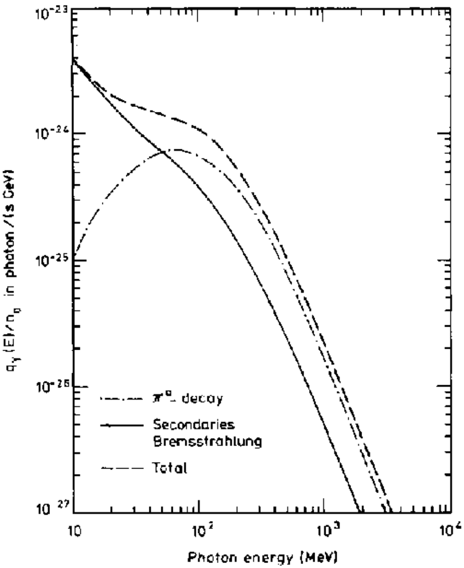
neutral pions $\pi^0 \to 2\gamma$ directly decay into two photons. Detection of characteristic (symmetry at 70 MeV$\simeq 0.5 m_\pi c^2$) photon energy spectrum discriminates between hadron-produced and lepton-produced photons (Morrison 1958, Ginzburg 1964).

Charged pions decay via myons into secondary electrons and neutrinos $\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$, $\mu^\pm \to e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$. Relation to high energy neutrino astronomy (ICECUBE, KM3NET).

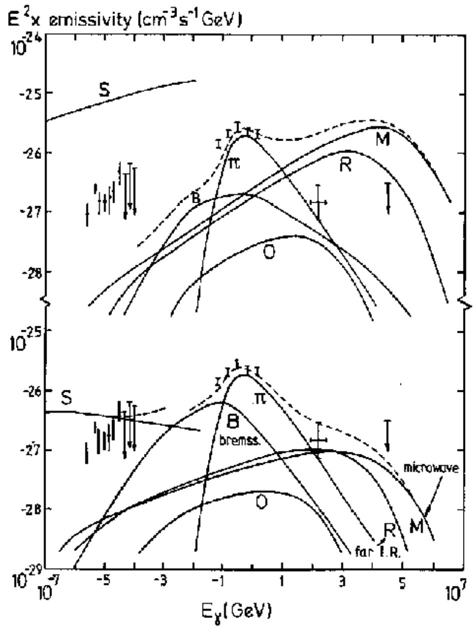
Good templates by Kelner et al. (2007) and Kelner and Aharonian (2008) for implementing hadron-hadron and hadron-photon collisions.

Secondary electrons undergo all leptonic radiation processes (2.1). Contamination of oure π^0-decay spectrum by secondary electron radiation contribution.

Problem: bremsstrahlung-contamination by secondary $e^{\pm}$ from $\pi^{\pm} \rightarrow e^{\pm} + ..$
in same inelastic hadron-collisions (e.g. RS 1982)



Electron-contamination minimal at photon energies of 1-100 GeV (Protheroe und Wolfendale 1980)



3. Acceleration of cosmic ray particles

3.1. Role of electric fields

Acceleration of charged particles requires **electric fields**:
from equations of motion

$$\dot{\vec{p}} = \vec{F} = q\left[\vec{E}_T(\vec{x},t) + \frac{\vec{v}\times\vec{B}_T(\vec{x},t)}{c}\right], \quad \dot{\vec{x}} = \vec{v} = \frac{\vec{p}}{\gamma m_a}$$

$\rightarrow$ particle spectra are controlled by particle rigidity $R = p/q$

$\rightarrow$ $\vec{p}\cdot\frac{d\vec{p}}{dt} = \frac{1}{2}\frac{dp^2}{dt} = q\,\vec{p}\cdot\vec{E}$ or

$$\frac{dp^2}{dt} = 2q\,\vec{p}\cdot\vec{E}$$

$\rightarrow$ change of energy $W = mc^2\sqrt{1+\frac{p^2}{m^2c^2}}$

$$\frac{dW}{dt} = \frac{1}{2W}\frac{dp^2}{dt} = \frac{q}{W}\vec{p}\cdot\vec{E}$$

but cosmic plasmas have very large conductivities
$\rightarrow$ difficult to sustain steady, constant electric fields
Electric fields appear as
(a) transient phenomena (magnetic reconnection, aperiodic ($\omega_R = 0$) fluctuations in Weibel-type filamentation instabilities)
(b) fluctuating wave fields (plasma turbulence) in magnetized plasmas

$$\vec{E} = \vec{0} + \delta\vec{E},\ \vec{B} = \vec{B}_0 + \delta\vec{B}$$

with averages $< \delta\vec{E} >= 0, \ < \delta\vec{B} >= 0$

3.2. 4 fundamental types of acceleration processes:

(1) Magnetic reconnection (generation of particle beams by reconnecting ordered magnetic fields, then (4))
(2) (Diffusive) shock acceleration (but kinetic description of shock structure required)
(3) Stochastic acceleration ($\delta\vec{E}$)
(4) Conversion of bulk motion (=particle beams) to energetic particles by $\delta\vec{B}$ alone (relativistic pick-up process)

Understanding acceleration/conversion processes (1)-(4) $\leftrightarrow$ understanding electric and magnetic fluctuations

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3.3. Equations used

Competition between injection, escape, energy gain (acceleration) and energy loss (catastrophic and continous) processes

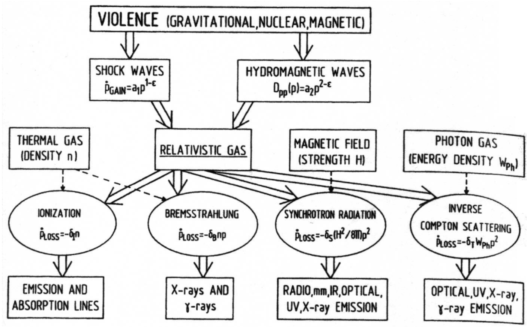


Diagram showing schematically the basic physical model for the formation of cosmic ray momentum spectra. The **arrows** represent the direction of energy flow

Balance equation in 5-dim. phase space $(\vec{r}, p, t)$:

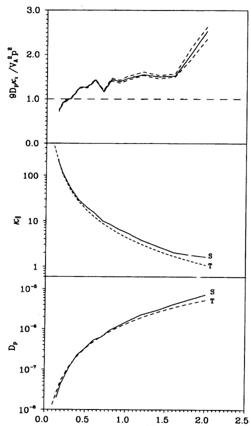
$$\frac{dN}{dt} = \text{sources(injection, acceleration)} - \text{losses}$$

$$\frac{dN}{dt} = \frac{\partial N}{\partial t} + \frac{\partial N}{\partial t}_{B_0+\delta B, \delta E} + \frac{\partial}{\partial p}(\dot{p}N) + \frac{N}{T_c} = q(p, \vec{r}, t)$$

3.4. Theoretical description of particle acceleration

Two methods:
– numerical simulations
– quasilinear theory (QLT) with nonlinear improvements e.g. SOQLT (Shalchi 2009, Nonlinear Cosmic Ray Diffusion Theories, Astrophysics and Space Science Library, Vol. 362, Springer, Berlin)

QLT approach is perturbation calculation of charged particle orbits in partially random field $(\vec{B} = \vec{B}_0 + \delta\vec{B}, \vec{0} + \delta\vec{E})$ to first order in ratio $q_L = (\delta B/B_0)^2 < 1$.



The simulated values of the spatial diffusion coefficient ($\kappa_\parallel$), the momentum diffusion coefficient (D_p) and their product in comparison with the quasi-linear values versus the wave amplitude δB (in units of B_0) for linearly polarized plane Alfvén waves. From Michalek and Ostrowski (1996 [351])

3.4.1. Fokker-Planck equation in non-uniform magnetic field

QLT: reduction of collisionless Boltzmann equation for phase space density $f(\vec{x}, p, \mu, \phi, t)$ to Fokker-Planck-equation for gyrotropic part $f_0(\vec{x}, p, \mu, t)$ (Schlickeiser and Jenko 2010, JPP, in press)

$$\frac{\partial f}{\partial t} + v\mu \frac{\partial f}{\partial z} + \frac{v}{2L_3} \frac{\partial}{\partial \mu} \left[\left(1-\mu^2\right) f \right] + \frac{\epsilon_a v r_L (1-\mu^2)}{2L_2} \frac{\partial f}{\partial X} - \frac{\epsilon_a v r_L (1-\mu^2)}{2L_1} \frac{\partial f}{\partial Y}$$

$$-p^{-2} \partial_p \left[p^2 \dot{p}_{\rm loss} f \right] - S(z, X, Y, p, t) = p^{-2} \partial_\nu \left[p^2 D_{\nu\sigma} \partial_\sigma f \right]$$

$$= \partial_\mu D_{\mu\mu} \partial_\mu f + p^{-2} \partial_\mu \left(p^2 D_{\mu j} \partial_j f \right) + p^{-2} \partial_k \left(p^2 D_{k\mu} \partial_\mu f \right) + p^{-2} \partial_k \left(p^2 D_{kj} \partial_j f \right) \tag{1}$$

Non-uniformity of magnetic field $\vec{B} = (0, B_y, B)$, with $B_y \ll B$, provides via mirror force $-(p_\perp^2/2m\gamma B)\nabla B$ additional adiabatic focusing of particles along the guide field (Roelof 1969, Earl 1974) and the gradient and curvature drifts of the cosmic ray guiding center perpendicular to the guide field characterized by focusing length L_3 and perpendicular field gradients

$$L_3^{-1} = -\frac{\partial \ln B}{\partial z}, \; L_1^{-1} = -\frac{\partial \ln B}{\partial x}, \; L_2^{-1} = -\frac{\partial \ln B}{\partial y} \tag{2}$$

The term $p^{-2} \partial_p \left[p^2 \dot{p}_{\rm loss} f \right]$ with the positively counted loss rate $\dot{p}_{\rm loss}(p)$ accounts for additional continuous momentum loss processes resulting from the interactions of cosmic rays with ambient target photon and matter fields such as

Coulomb interactions, ionization, pion production, bremsstrahlung, synchrotron radiation and inverse Compton interactions.
The 16 Fokker-Planck-coefficients account for the random electromagnetic forces resulting from weak plasma turbulence and depend on the respective correlation tensors of electric and magnetic field fluctuations. They are calculated using QLT or from nonlinear improvements of quasilinear theory such as nonlinear guiding center theory and extended second-order QLT, including also effects from magnetic field line wandering (Hauff, Jenko, Shalchi, RS, 2010, ApJ, in press). Depending on the specific type of turbulence considered, not all of them are non-zero, and some of them are much larger than others.

3.4.2. Modified diffusion-convection transport equation

For magnetohydrodynamic turbulence the fluctuating electric fields are much smaller than the fluctuating magnetic fields ($\delta E \ll \delta B$). In this case the gyrotropic particle phase space distribution function $f(X, Y, z, p, \mu, t)$ due to dominating pitch-angle diffusion adjusts very quickly to a quasi-equilibrium through pitch-angle diffusion which is close to the isotropic equilibrium distribution $F(X, Y, z, p, t)$. The diffusion approximation (Jokipii 1966, Hasselmann and Wibberenz 1968, Skilling 1975, Schlickeiser 1999) yields

$$
\begin{aligned}
&\frac{\partial F}{\partial t} - S - p^{-2}\partial_p\left[p^2 \dot{p}_{\rm loss}F\right] + \frac{\epsilon_a v r_L}{3L_2}\partial_X F - \frac{\epsilon_a v r_L}{3L_1}\partial_Y F - \frac{\partial}{\partial z}\left[\frac{v a_j}{4}\partial_j F\right] \\
&-\frac{\partial}{\partial z}\left[\frac{v^2 K_0}{8}\right]\left[\frac{\partial F}{\partial z} - \frac{F}{L_3}\right] + \frac{\partial}{\partial z}\left[\frac{\epsilon_a v^2 r_L K_1}{24 L_2}\partial_X F\right] - \frac{\partial}{\partial z}\left[\frac{\epsilon_a v^2 r_L K_1}{24 L_1}\partial_Y F\right] \\
&+\partial_X\left[\frac{\epsilon_a v^2 r_L K_1}{24 L_2}\left(\frac{\partial F}{\partial z} - \frac{F}{L_3}\right)\right] - \partial_Y\left[\frac{\epsilon_a v^2 r_L K_1}{24 L_1}\left(\frac{\partial F}{\partial z} - \frac{F}{L_3}\right)\right] \\
&+\partial_X\left[\frac{\epsilon_a v r_L h_j}{12 L_2}\partial_j F\right] - \partial_Y\left[\frac{\epsilon_a v r_L h_j}{12 L_1}\partial_j F\right] - \partial_X\left[\frac{v^2 r_L^2 K_2}{72 L_2^2}\partial_X F\right] \\
&-\partial_Y\left[\frac{v^2 r_L^2 K_2}{72 L_1^2}\partial_Y F\right] + \partial_X\left[\frac{v^2 r_L^2 K_2}{72 L_1 L_2}\partial_Y F\right] + \partial_Y\left[\frac{v^2 r_L^2 K_2}{72 L_1 L_2}\partial_X F\right] \\
&= p^{-2}\partial_k p^2\Bigg[\frac{1}{2}\left(\left[\int_{-1}^{1} d\mu D_{kj}\right] - c_{kj}\right)\partial_j F - \frac{v a_k}{4}\left[\frac{\partial F}{\partial z} - \frac{F}{L_3}\right] \\
&\qquad + \frac{\epsilon_a v r_L h_k}{12 L_2}\partial_X F - \frac{\epsilon_a v r_L h_k}{12 L_1}\partial_Y F\Bigg] \qquad (3)
\end{aligned}
$$

with $k, j \in [p, X, Y]$. In this most general form the modified diffusion-convection transport equation is rather involved. It simplifies enormously for axisymmetric isospectral undamped slab Alfvenic turbulence to

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$$\frac{\partial F}{\partial t} - S + \frac{\partial}{\partial X}\left(\left[1 - \frac{vK_1}{8L_3}\right]\frac{\epsilon_a v r_L F}{3L_2}\right) - \frac{\partial}{\partial Y}\left(\left[1 - \frac{vK_1}{8L_3}\right]\frac{\epsilon_a v r_L F}{3L_1}\right) + \frac{\partial}{\partial z}\left(\frac{\kappa_{zz}}{L_3}F\right)$$

$$-\frac{1}{p^2}\frac{\partial}{\partial p}\left(\left[p^2\dot{p}_{\mathrm{loss}} + \frac{a_{zp}p^2}{L_3}\right]F\right)$$

$$= \begin{pmatrix} \partial_X \\ \partial_Y \\ \partial_z \\ p^{-2}\partial_p p^2 \end{pmatrix} \cdot \begin{pmatrix} \kappa_{XX} & \kappa_{YX} & \kappa_{zX} & a_{Xp} \\ \kappa_{YX} & \kappa_{YY} & \kappa_{zY} & a_{Yp} \\ \kappa_{zX} & \kappa_{zY} & \kappa_{zz} & a_{zp} \\ -a_{Xp} & -a_{Yp} & -a_{zp} & A \end{pmatrix} \begin{pmatrix} \partial_X F \\ \partial_Y F \\ \partial_z F \\ \partial_p F \end{pmatrix} \quad (4)$$

with the pitch-angle averaged transport parameters

$$A = \frac{1}{2}\int_{-1}^{1} d\mu \left[D_{pp}(\mu) - \frac{D^2_{\mu p}(\mu)}{D_{\mu\mu}(\mu)}\right], \quad (5)$$

$$\kappa_{zz} = \frac{v^2 K_0}{8} = \frac{v^2}{8}\int_{-1}^{1} d\mu \frac{(1-\mu^2)^2}{D_{\mu\mu}(\mu)}, \quad (6)$$

$$\kappa_{XX} = \frac{v^2 r_L^2 K_2}{72L_2^2} = \frac{v^2 r_L^2}{72L_2^2}\int_{-1}^{1} d\mu \frac{\mu^2(1-\mu^2)^2}{D_{\mu\mu}(\mu)}, \quad (7)$$

$$\kappa_{YY} = \frac{v^2 r_L^2 K_2}{72L_1^2} = \frac{v^2 r_L^2}{72L_1^2}\int_{-1}^{1} d\mu \frac{\mu^2(1-\mu^2)^2}{D_{\mu\mu}(\mu)}, \quad (8)$$

$$\kappa_{YX} = -\frac{v^2 r_L^2 K_2}{72 L_1 L_2} = -\frac{v^2 r_L^2}{72 L_1 L_2} \int_{-1}^{1} d\mu \frac{\mu^2 (1-\mu^2)^2}{D_{\mu\mu}(\mu)}, \tag{9}$$

$$\kappa_{zX} = -\frac{\epsilon_a v^2 r_L K_1}{24 L_2} = -\frac{\epsilon_a v^2 r_L}{24 L_2} \int_{-1}^{1} d\mu \frac{\mu (1-\mu^2)^2}{D_{\mu\mu}(\mu)}, \tag{10}$$

$$\kappa_{zY} = \frac{\epsilon_a v^2 r_L K_1}{24 L_1} = \frac{\epsilon_a v^2 r_L}{24 L_1} \int_{-1}^{1} d\mu \frac{\mu (1-\mu^2)^2}{D_{\mu\mu}(\mu)}, \tag{11}$$

$$a_{Xp} = -\frac{\epsilon_a v r_L h_p}{12 L_2} = -\frac{\epsilon_a v r_L}{12 L_2} \int_{-1}^{1} d\mu \frac{\mu (1-\mu^2) D_{\mu p}(\mu)}{D_{\mu\mu}(\mu)}, \tag{12}$$

$$a_{Yp} = \frac{\epsilon_a v r_L h_p}{12 L_1} = \frac{\epsilon_a v r_L}{12 L_1} \int_{-1}^{1} d\mu \frac{\mu (1-\mu^2) D_{\mu p}(\mu)}{D_{\mu\mu}(\mu)}, \tag{13}$$

and

$$a_{zp} = \frac{v a_p}{4} = \frac{v}{4} \int_{-1}^{1} d\mu \frac{(1-\mu^2) D_{\mu p}(\mu)}{D_{\mu\mu}(\mu)}, \tag{14}$$

respectively.

We notice immediately that all perpendicular spatial diffusion coefficients are caused by the non-vanishing gradient and curvature drift terms. For infinitely large perpendicular scale length ($L_1 = L_2 = \infty$), Eq. (4) reduces to Eq. (17) of Schlickeiser and Shalchi (2008, ApJ 686, 292) which refers to the linear phase space density $FB(z)$.

3.4.3. Nonparallel spatial diffusion coefficients

For a specific (symmetric in μ) choice of the pitch-angle Fokker-Planck coefficient $D_{\mu\mu} = \frac{v^2}{2(2-s)(4-s)\kappa_{zz}}|\mu|^{s-1}(1-\mu^2)$ we obtain $\kappa_{zX} = \kappa_{zY} = 0$, and for the ratios of the remaining perpendicular to parallel spatial diffusion coefficients and mean free paths

$$\frac{\kappa_{XX}}{\kappa_{zz}} = \frac{\lambda_{XX}}{\lambda_{zz}} = \frac{2-s}{6-s}\left(\frac{r_L}{6L_2}\right)^2 = \frac{2-s}{36(6-s)}\left(\frac{\partial r_L}{\partial Y}\right)^2, \qquad (15)$$

$$\frac{\kappa_{YY}}{\kappa_{zz}} = \frac{\lambda_{YY}}{\lambda_{zz}} = \frac{2-s}{6-s}\left(\frac{r_L}{6L_1}\right)^2 = \frac{2-s}{36(6-s)}\left(\frac{\partial r_L}{\partial X}\right)^2, \qquad (16)$$

and

$$\frac{\kappa_{YX}}{\kappa_{zz}} = \frac{\lambda_{YX}}{\lambda_{zz}} = -\frac{2-s}{6-s}\left(\frac{r_L}{6L_1}\right)\left(\frac{r_L}{6L_2}\right) = -\frac{2-s}{36(6-s)}\frac{\partial r_L}{\partial X}\frac{\partial r_L}{\partial Y}, \qquad (17)$$

involving the spatial first derivatives of the non-constant Larmor radius in the non-uniform magnetic field. Due to the Larmor radius dependence, the ratios of perpendicular to parallel spatial diffusion coefficients increase proportional ($\propto (p/\mathtt{q\_a})^2$) to the square of the particle rigidity. Moreover, cosmic rays with the same rigidity value have the same ratios of perpendicular to parallel spatial diffusion coefficients.

3.4.4. Uniform magnetic field

For uniform magnetic fields ($L_1 = L_2 = L_3 = \infty$) the *diffusion-convection-equation* for the isotropic, gyrotropic part of phase space density $F(\vec{x}, p, t) = N(\vec{x}, p, t)/4\pi p^2$ ($z \parallel B_0$) reads

$$\frac{\partial N}{\partial t}_{B_0+\delta B,\delta E} = -\mathrm{div}\left[\kappa \mathrm{grad N} - \tilde{\mathrm{V}}\mathrm{N}\right] - \frac{\partial}{\partial \mathrm{p}}\left[\mathrm{p}^2 \mathrm{A}\frac{\partial(\mathrm{Np}^{-2})}{\partial \mathrm{p}} + \frac{\mathrm{p}}{3}(\mathrm{div}\tilde{\mathrm{V}})\mathrm{N}\right]$$

with spatial diffusion tensor, spatial convection, momentum diffusion (Fermi II), momentum convection (Fermi I) terms calculated as pitch-angle ($\mu = \cos\theta$) averages of 5 Fokker-Planck coefficients:

3.5. Volume-integrated transport equations

For **spatially unresolved** sources →, theory for volume-integrated particle spectrum

$$\eta(p,t) = \int_{\text{source}} d^3r N(p,\vec{r},t)$$

provides simpler balance equation in 2-dim. phase space (p,t)

$$\frac{\partial\eta}{\partial t} - \frac{\partial}{\partial p}\left[p^2 A \frac{\partial(\frac{\eta}{p^2})}{\partial p} + (a_1 p + \dot{p})\eta)\right] + \frac{\eta}{T} = Q(p,t)$$

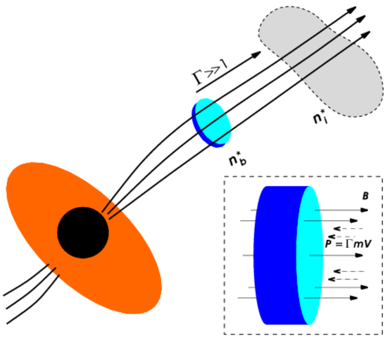
where $T^{-1} = T_c^{-1} + T_{\text{esc}}^{-1}$

1) determine "equilibrium" energy spectrum $\eta(p,t)$ of radiating particles

2) then calculate resulting radiation products (photons, neutrinos)

4. Dissipation of cosmic outflows in unmagnetized environment

Interaction of outflow jet plasma with ambient interstellar medium: Free energy = kinetic relativistic outflow energy



What are the relevant dissipation processes? Upshot (Michno and RS; 2010, ApJ, submitted):
Nonrelativistic outflows: predominant generation of electric fluctuations (→ stochastic acceleration)
Relativistic outflows: predominant generation of electric fluctuations (→ relativistic pick-up)

4.1. Any cosmic outflow is counterstream plasma

Outflow distribution function in laboratory system: 4 cold sreams

$$f^*(p_\perp^*, p_\parallel^*) = \frac{\delta(p_\perp^*)}{2\pi p_\perp^*}\Big[n_1\delta(p_\parallel^* - \gamma_1 m_+ v_1) + n_1\delta(p_\parallel^* - \gamma_1 m_- v_1)$$
$$+ n_2\delta(p_\parallel^* - \gamma_2 m_+ v_2) + n_2\delta(p_\parallel^* - \gamma_2 m_- v_2)\Big]$$

Two $(i = 1, 2)$ overall-neutral mono-energetic plasma beams of densities n_i propagating with different positive velocities $\vec{v}_i = v_i \vec{e}_z$, $v_i = \beta_i c$ along the z-axis. Each individual particle beam consists of the same number of positively $(+)$ and negatively $(-)$ charged particles, so one has charge neutrality in each stream. $m_\pm$ denote the masses of the charged particles, Lorentz factors $\Gamma_i = [1 - (v_i/c)^2]^{-1/2}$.

Because of the assumption of an equal number of positively and negatively charged particles, no restrictions apply to the values of n_1, n_2, v_1 and v_2 in order to avoid large-scale charge and current densities. Difference to 3-stream (plasma electrons, plasma ions, beam electrons) analysis of Bret (2009).

Transform the lab-distribution function to a different inertial system $(p_\perp, p_\parallel, E)$ propagating with velocity $\vec{V} = V\vec{e}_z$, $V = Bc$, $\Gamma = (1-B^2)^{-1/2}$ along the z-axis. Using the invariance of the phase space function $f = f^*$ we obtain for the particle distribution function in the new coordinate system

$$f(p_\perp, p_\parallel) = \frac{\delta(p_\perp)}{2\pi p_\perp}\Big[N_1\delta(p_\parallel - \Gamma_1 m_+ u_1) + N_1\delta(p_\parallel - \Gamma_1 m_- u_1)$$
$$+N_2\delta(p_\parallel - \Gamma_2 m_+ u_2) + n_2\delta(p_\parallel - \Gamma_2 m_- u_2)\Big]$$

with

$$N_1 = n_1\Gamma(1-\beta_1 B), \quad N_2 = n_2\Gamma(1-\beta_2 B),$$
$$u_1 = \frac{\beta_1 - B}{1-\beta_1 B}c, \ \ u_2 = \frac{\beta_2 - B}{1-\beta_2 B}c,$$
$$\Gamma_1 = \Gamma\gamma_1(1-\beta_1 B), \ \ \Gamma_2 = \Gamma\gamma_2(1-\beta_2 B)$$

Counterstream frame of reference defined by $u_1 = -u_2 = u$ yielding for the transformation velocity B

$$B = \frac{1}{\beta_1+\beta_2}\left[1+\beta_1\beta_2 - \sqrt{(1-\beta_1^2)(1-\beta_2^2)}\right] = \frac{1}{\beta_1+\beta_2}\left[1+\beta_1\beta_2 - \gamma_1^{-1}\gamma_2^{-1}\right]$$

4.2. Compact form of plasma dispersion relation

Calculate the Maxwell operator of linear fluctuations in counterstream coordinate system adopting fluctuations of the form $\exp[\imath\vec{k}\cdot\vec{x}-\imath\omega t]$ with wave vector $\vec{k}=k_{\parallel}\vec{e}_z+k_{\perp}\vec{e}_x$. Solution of dispersion relation besides electromagnetic waves

$$\left[\frac{c^2k^2}{\omega^2}-1+\frac{\Omega^2(1+r)}{\omega^2}\right]\left[1-\frac{g\Omega^2}{\Gamma_0^2}\right]=\frac{4r\Omega^4u^2k_{\perp}^2}{\omega^2(\omega^2-k_{\parallel}^2u^2)^2} \tag{11}$$

with abbreviation

$$g(k_{\parallel})\equiv\frac{1}{(\omega-k_{\parallel}u)^2}+\frac{r}{(\omega+k_{\parallel}u)^2},$$

the plasma frequency of the first component

$$\Omega^2\equiv\frac{4\pi e^2(1+\chi)n_1}{m_-\gamma_1}$$

and density ratio

$$r=\frac{A_2}{A_1}=\frac{N_2}{N_1}=\frac{n_2(1-\beta_2B)}{n_1(1-\beta_1B)}=\frac{n_2\gamma_1}{n_1\gamma_2}\in[0,\infty]$$

4.3. Electrostatic instability (EI) for parallel propagation

For fluctuations parallel to the flow speed the dispersion relation (11) yields electrostatic waves

$$1 = \frac{g\Omega^2}{\Gamma_0^2} = \frac{\Omega^2}{\Gamma_0^2}\left[\frac{1}{(\omega - ku)^2} + \frac{r}{(\omega + ku)^2}\right]$$

with the maximum growth rate shown

$$(\Im\omega)_{\max}(r) = \frac{3^{1/2}ku\alpha}{1+\alpha+\alpha^2} = \frac{3^{1/2}\omega_2\alpha}{2(1+\alpha+\alpha^2)}\left[1 + \frac{1+2\alpha+3\alpha^2}{\alpha^3(2+\alpha)}\right]^{1/2}$$

$$= \frac{3^{1/2}\Omega\alpha}{2\Gamma_0(1+\alpha+\alpha^2)}\left[1 + \frac{1+2\alpha+3\alpha^2}{\alpha^3(2+\alpha)}\right]^{1/2}$$

where

$$\frac{1+2\alpha}{\alpha^3(2+\alpha)} = r$$

Interpolation formula

$$(\Im\omega)_{\max}(r) \simeq \frac{3^{1/2}}{2^{4/3}}\omega_2\frac{r^{1/3}}{(1+r)^{1/6}} = \frac{3^{1/2}}{2^{4/3}}\frac{\Omega}{\Gamma_0}\frac{r^{1/3}}{(1+r)^{1/6}}$$

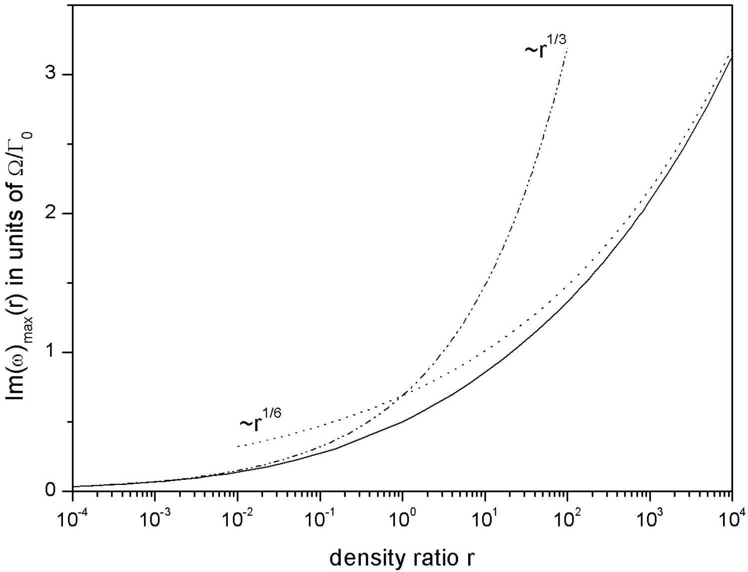


Figure 1: Maximum growth rate of the electrostatic instability in units of Ω/Γ_0 as a function of the density ratio r.

4.4. Filamentation instability (FI) for perpendicular propagation

For fluctuations perpendicular to the flow speed the dispersion relation (11) becomes with $x \equiv \frac{\omega^2}{\Omega^2(1+r)}$

$$\frac{c^2k^2}{\Omega^2(1+r)} = F(x),\ F(x) = \frac{x(x-1)(x-\Gamma_0^{-2})}{(x-x_1)(x+x_2)}$$

where

$$x_{1,2} = \frac{1}{2\Gamma_0^2}\left[\sqrt{1+\frac{16r}{(1+r)^2}\Gamma_0^2(\Gamma_0^2-1)} \pm 1\right] > 0$$

Aperiodic fluctuation solutions occur for negative $x = -y$, $y \geq 0$, corresponding to purely imaginary frequencies $\omega = \pm\imath\Omega(1+r)^{1/2}y^{1/2}$ so that one root is purely growing in time.

$$\frac{c^2k^2}{\Omega^2(1+r)} = F(y),\ F(y) = \frac{y(y+1)(y+\Gamma_0^{-2})}{(x_2-y)(y+x_1)}$$

The function $F(y)$ is shown for $\Gamma_0 = 2$ and $r = 0.5$.
Solutions with real y require positive values of the function $F(y) \geq 0$ which is only possible for values $y \leq x_2$.

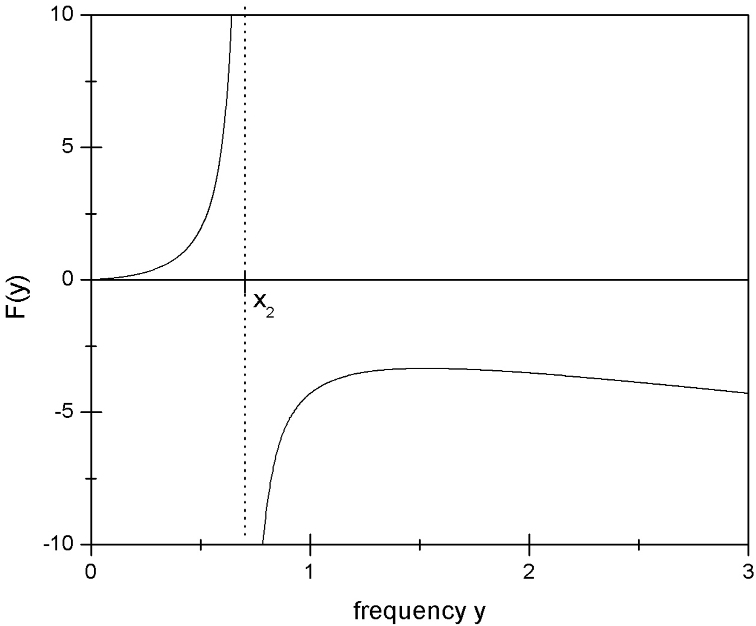


Figure 2: Sketch of the function $F(y)$ for $\Gamma_0 = 2$ and $r = 0.5$.

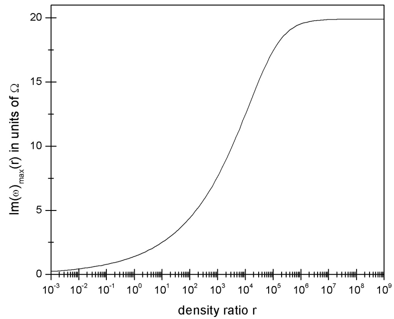


Figure 3: Maximum growth rate of the filamentation instability as a function of density ratio r calculated for $\Gamma_0 = 10$.

The maximum growth rate of the filamentation instability occurs at large wavenumbers and as a function of the density ratio r is given by

$$(\Im\omega)_{\max}(r) = \Omega(1+r)^{1/2}x_2^{1/2} = \frac{\Omega(1+r)^{1/2}}{2^{1/2}\Gamma_0}\left[\sqrt{1+\frac{16r}{(1+r)^2}\Gamma_0^2(\Gamma_0^2-1)}-1\right]^{1/2}$$

4.5. Comparison of maximum growth rates for EI and FI

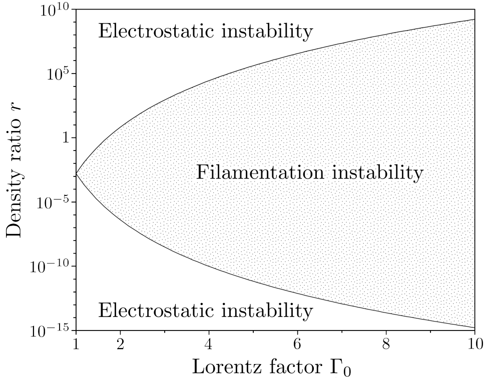


Figure 4: Sketch of the domains of validity for a dominating EI or FI in the r-Γ_0 parameter space.

4.5.1. Nonrelativistic flows

For nonrelativistic flows $\mathtt{u} \ll c$ the EI has the maximum growth rate

$$(\Im\omega)_{\max}(r) \simeq \frac{3^{1/2}}{2^{4/3}} \Omega \frac{r^{1/3}}{(1+r)^{1/6}}$$

at parallel wavenumbers

$$k_{\|,\max} \simeq \frac{\Omega(1+r)^{1/2}}{2\mathtt{u}}$$

The FI attains its maximum growth rate

$$(\Im\omega)_{\max}(r) \simeq 2\Omega\frac{\mathtt{u}}{c}\left(\frac{r}{r+1}\right)^{1/2}$$

at perpendicular wavenumbers much larger than

$$k_{\perp} \gg \frac{\Omega(1+r)^{1/2}}{c}$$

For nonrelativistic flows the EI has a much larger (factor $c/\mathtt{u} \gg 1$)) maximum growth rate than the FI. We conclude that for nonrelativistic flows the EI is the fastest instability. Hence nonrelativistic outflows preferentially generate **electric** fluctuations → stochastic acceleration.

4.5.2. Relativistic flows

At relativistic flows ($\Gamma_0 \gg 1$) FI growth rate factor Γ_0^2 larger than EI growth rate for density ratios $r \leq \Gamma_0^{12}$. For relativistic flows the FI is the fastest instability, generating **magnetic** fluctuations → conversion but not stochastic acceleration.

4.6. Open questions

– Role of oblique fluctuations ?
– Effect of finite plasma temperatures, guide magnetic field
– Nonlinear evolution of fluctuations ?

4.7. Relativistic pick-up

In relativistic outflows filamentation instabilities are the most important dissipation processes generating aperiodic magnetic fluctuations $\delta B \propto \exp(\imath \vec{k} \cdot \vec{x} + \Gamma t), \quad \omega_R = 0$. Because $\omega_R = 0$ these fluctuations are not group-propagating (zero phase and group speed), so they stand with the exciter.

These instabilities are best known in unmagnetized ($B_0 = 0$) plasmas but also occur in weakly magnetized ($B_0 < B_c$) plasmas. The instabilities are suppressed in strongly magnetized plasmas ($B_0 > B_c$).

Interstellar ions, electrons and neutrals enter the outflow plasma as weak beam, beam excites aperiodic magnetic fluctuations (δB) propagating perpendicular to counterstream direction that then isotropise incoming p^+, e^- after time t_s, i.e. **pick-up of interstellar ions and electrons in outflow**

consequence 1: outflow picks up interstellar p^+ and e^- with

$$E_{p,\max} = \Gamma m_p c^2 = 100\Gamma_{100} \text{ GeV}$$

$$E_{e,\max} = \Gamma m_e c^2 = 0.05\Gamma_{100} \text{ GeV}$$

primary energy output at TeV energies in lab frame:

in $p^+ - e^-$ outflows $E^*_{\gamma,\max} = 20\Gamma^2_{100}$ TeV

in pair outflows $E^*_{\gamma,\max} = 0.01\Gamma^2_{100}$ TeV

5. Summary and conclusions

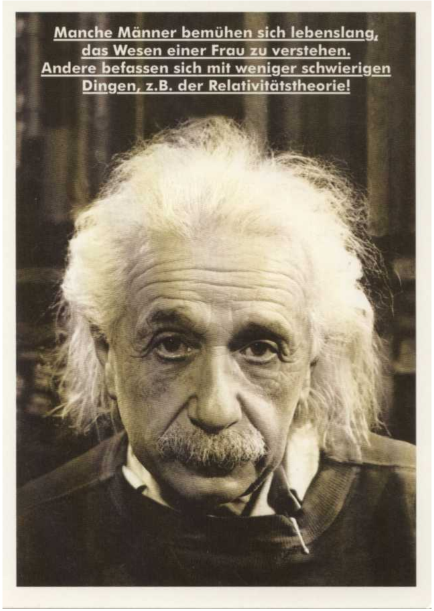
- We have identified the fundamental dissipation processes of cosmic explosions in collisionless plasma environments.

- Important difference for relativistic and nonrelativistic outflows: in relativistic outflows central role played by filamentation instabilities that generate **magnetic** fluctuations. In nonrelativistic outflows electrostatic instabilities are quicker generating **electric** fluctuations.

- For **magnetic** fluctuations energization by conversion processes (relativistic pick-up) most relevant. For **electric** fluctuations stochastic acceleration processes most important.

- We begin to understand the formation of particle momentum spectra from competition of acceleration/energization, loss and escape processes.

- Ongoing efforts to improve theory in all details.



"Some men try all their life to understand the character of a woman. Others are concerned with less difficult things, e.g the theory of relativity" or particle acceleration processes.