Thermalization of pair plasma with proton loading

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Pair plasma in GRBs

Why e^+e^- pairs?

- Energy range: $10^{48} < E_0 < 10^{54}$ erg

(isotropic energy release, fraction of stellar mass)

- Size range: $10^6 < R_0 < 10^8$ cm

(time variability, NS-BH size)
Optical depth for pair production: $\tau = \sigma_T n_\gamma R \approx \sigma_T E_0 / R_0^2 \gg 1$.
Why baryons?

- Time duration of the whole burst, spectrum
- Progenitors of GRBs: massive stars, NS

Issues:

1. Microphysics: processes, baryonic loading, ...
2. Macrophysics: global dynamics, geometry, ...
3. Radiation: mechanisms, transparency, ...

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- **The classicality parameter $\varkappa = e^2/(\hbar v_r) = \alpha/\beta_r$, $v_r = \beta_r c$ is mean relative velocity of particles. $\varkappa \gg 1$ ($\varkappa \ll 1$): classical (quantum) description of scattering.**

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- Intensity of interactions between photons and other particles $\tau = n\sigma R$.
- **Plasma degeneracy** $\theta_F = \left[\left(\frac{\hbar}{mc}\right)^2 \left(3\pi^2 n_-\right)^{\frac{2}{3}} + 1\right]^{1/2} - 1.$

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- In our energy range $\epsilon \lesssim 10$ MeV the plasma is non-degenerate $\theta_F > \theta_{th}$.
- **Natural parameters for perturbative expansion are α and m/M.**

Proton loading

When admixture of **protons** and electrons is allowed it is characterized by a new parameter, the baryonic loading

$$\mathbf{B} = \frac{NMc^2}{\mathcal{E}_\gamma} = \frac{n_p Mc^2}{\rho_\gamma}. \tag{1}$$

In equilibrium, while e^+e^- are relativistic, $\epsilon_\pm \sim mc^2 \sim k_B T$, protons are not $Mv_p^2 \sim k_B T$, and thus

$$\frac{v_p}{c} \sim \sqrt{\frac{m}{M}}.$$

Also in equilibrium with $\epsilon_\pm \geq mc^2$ we have $\rho_\pm \approx n_\pm mc^2$ and thus

$$\frac{n_p}{n_\pm} \sim \frac{m}{M} B.$$

If in addition **neutrons** are present, they are coupled to protons by elastic nuclear scattering.

Pair plasma is transparent to **neutrinos**.

Interactions with pairs

Binary interactions	Radiative and pair producing variants
Møller and Bhabha scattering $e_1^\pm e_2^\pm \longrightarrow e_1^{\pm\prime} e_2^{\pm\prime}$ $e^\pm e^\mp \longrightarrow e^{\pm\prime} e^{\mp\prime}$	Bremsstrahlung $e_1^\pm e_2^\pm \longleftrightarrow e_1^{\pm\prime} e_2^{\pm\prime} \gamma$ $e^\pm e^\mp \longleftrightarrow e^{\pm\prime} e^{\mp\prime} \gamma$
Single Compton scattering $e^\pm \gamma \longrightarrow e^\pm \gamma'$	Double Compton scattering $e^\pm \gamma \longleftrightarrow e^{\pm\prime} \gamma' \gamma''$
Pair production and annihilation $\gamma\gamma' \longleftrightarrow e^\pm e^\mp$	Radiative pair production and three photon annihilation $\gamma\gamma' \longleftrightarrow e^\pm e^\mp \gamma''$ $e^\pm e^\mp \longleftrightarrow \gamma\gamma'\gamma''$
	$e^\pm \gamma \longleftrightarrow e^{\pm\prime} e^\mp e^{\pm\prime\prime}$

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Coulomb scattering	Bremsstrahlung
$p_1 p_2 \longrightarrow p_1' p_2'$	$p_1 p_2 \longleftrightarrow p_1' p_2' \gamma$
$pe^{\pm} \longrightarrow p' e^{\pm\prime}$	$pe^{\pm} \longleftrightarrow p' e^{\pm\prime} \gamma$
	$pe_1^{\pm} \longleftrightarrow p' e_1^{\pm\prime} e^{\pm} e^{\mp}$
Single Compton scattering	Double Compton scattering and radiative pair production
$p\gamma \longrightarrow p' \gamma'$	$p\gamma \longleftrightarrow p' \gamma' \gamma''$
	$p\gamma \longleftrightarrow p' e^{\pm} e^{\mp}$

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- **Proton Compton scattering:** $(n_p t_{\gamma p})^{-1} \approx \left(\frac{\epsilon}{Mc^2}\right)^2 (n_- t_{\gamma e})^{-1}$, $\epsilon \geq mc^2$.

Boltzmann equation

Relativistic Boltzmann equations in spherically symmetric case

$$\frac{1}{c}\frac{\partial f_i}{\partial t} + \beta_i \left(\mu \frac{\partial f_i}{\partial r} + \frac{1-\mu^2}{r}\frac{\partial f_i}{\partial \mu} \right) - \nabla U \frac{\partial f_i}{\partial \mathbf{p}} = \sum_q \left(\eta_i^q - \chi_i^q f_i \right), \qquad (2)$$

where $\mu = \cos\vartheta = \mathbf{r}\cdot\mathbf{p}$, U is a potential due to some external force, $\beta_i = v_i/c$, $f_i(\epsilon, t)$ are distribution functions, and η_i^q and χ_i^q are the emission and the absorption coefficients. This is a coupled system of partial-integro-differential equations.
For homogeneous and isotropic distribution functions of electrons, positrons and photons (2) reduces to

$$\frac{1}{c}\frac{\partial f_i}{\partial t} = \sum_q \left(\eta_i^q - \chi_i^q f_i \right). \qquad (3)$$

In (3) we also explicitly neglect the Vlasov term.

Collisional integrals 1: probability

Differential probability for all processes per unit time and unit volume ($\hbar = c = 1$)

$$dw = (2\pi)^4 \delta^{(4)}(P_f - P_i) \frac{|M_{fi}|^2}{\prod_b 2\epsilon_b} \prod_a \frac{d\mathbf{p}'_a}{(2\pi\hbar)^3},$$

where $\mathbf{p}'_a$ are momenta of outgoing particles, ϵ_b are energies of particles before and after interaction, M_{fi} are corresponding matrix elements, $\delta^{(4)}$ stands for energy-momentum conservation.
As example consider absorption coefficient for Compton scattering

$$\chi^{\gamma e^{\pm} \to \gamma' e^{\pm\prime}} f_\gamma = \int d\mathbf{k}' d\mathbf{p} d\mathbf{p}' w_{\mathbf{k}',\mathbf{p}';\mathbf{k},\mathbf{p}} f_\gamma(\mathbf{k}, t) f_\pm(\mathbf{p}, t),$$

where $\mathbf{p}$ and $\mathbf{k}$ are momenta of electron (positron) and photon respectively, $d\mathbf{p} = d\epsilon_\pm do \epsilon_\pm^2 \beta_\pm / c^3$, $d\mathbf{k}' = d\epsilon'_\gamma \epsilon'^2_\gamma do'_\gamma / c^3$.

Collisional integrals 2: integration over momentum

We can perform one integration over $d\mathbf{p}'$ as $\int d\mathbf{p}'\delta(d\mathbf{k}+d\mathbf{p}-d\mathbf{k}'-d\mathbf{p}')\rightarrow 1$, but it is necessary to take into account the momentum conservation in the next integration over $d\mathbf{k}'$,

$$\int d\epsilon'_\gamma \delta(\epsilon_\gamma+\epsilon_\pm-\epsilon'_\gamma-\epsilon'_\pm)=$$
$$=\int d(\epsilon'_\gamma+\epsilon'_\pm)\frac{1}{|\partial(\epsilon'_\gamma+\epsilon'_\pm)/\partial\epsilon'_\gamma|}\delta(\epsilon_\gamma+\epsilon_\pm-\epsilon'_\gamma-\epsilon'_\pm)\rightarrow$$
$$\rightarrow\frac{1}{|\partial(\epsilon'_\gamma+\epsilon'_\pm)/\partial\epsilon'_\gamma|}\equiv J_{\rm cs},$$

where the Jacobian of the transformation is

$$J_{\rm cs}=\frac{1}{1-\beta'_\pm\mathbf{b}'_\gamma\cdot\mathbf{b}'_\pm}, \tag{4}$$

where $\mathbf{b}_i=\mathbf{p}_i/p$, $\mathbf{b}'_i=\mathbf{p}'_i/p'$, $\mathbf{b}'_\pm=(\beta_\pm\epsilon_\pm\mathbf{b}_\pm+\epsilon_\gamma\mathbf{b}_\gamma-\epsilon'_\gamma\mathbf{b}'_\gamma)/(\beta'_\pm\epsilon'_\pm)$.

Collisional integrals 3: three-particle interactions

Finally, for the absorption coefficient

$$\chi^{\gamma e^{\pm}\to\gamma' e^{\pm\prime}} f_\gamma = -\int do'_\gamma d\mathbf{p} \frac{c\epsilon'_\gamma |M_{fi}|^2}{16\epsilon_\pm \epsilon_\gamma \epsilon'_\pm c^3 (2\pi\hbar)^2} J_{\rm cs} f_\gamma(\mathbf{k},t) f_\pm(\mathbf{p},t),$$

As example of 3-particle reaction consider relativistic bremsstrahlung $e_1 + e_2 \leftrightarrow e'_1 + e'_2 + \gamma'$. For the time derivative, for instance, of the distribution function f_2 one has

$$\dot{f}_2 = \int dp'_2 dk' (2\pi)^4 \delta^{(4)}(P_f - P_i) \frac{|M_{fi}|^2}{2^5 \epsilon_1 \epsilon_2 \epsilon'_1 \epsilon'_2 \epsilon'_\gamma} \times$$
$$\times \left(\int \frac{d\mathbf{p}'_1 f'_k d\mathbf{p}_1 f'_1 f'_2}{(2\pi\hbar)^6} - \int \frac{d\mathbf{p}_1 d\mathbf{p}'_1 f_1 f_2}{(2\pi\hbar)^9} \right).$$

In the case of kinetic equilibrium we have multipliers proportional to $\exp \frac{\varphi}{k_B T}$ in front of the integrals. The calculation is then reduced to the known thermal equilibrium case.

Detailed balance conditions (pure pair plasma)

Consider distribution functions

$$f_\gamma = \frac{1}{\exp\left(\frac{\varepsilon_\gamma - \varphi_\gamma}{\theta_\gamma}\right) - 1}, \qquad f_\pm = \frac{1}{\exp\left(\frac{\varepsilon_\pm - \varphi_\pm}{\theta_\pm}\right) + 1},$$

where $\theta = kT/(mc^2)$ and $\varphi = \mu/(mc^2)$. Suppose $e^\pm\gamma \leftrightarrow e^{\pm\prime}\gamma'$ is in detailed balance. This means reaction rate vanishes

$$f_\pm(1 - f'_\pm)f_\gamma(1 + f'_\gamma) = f'_\pm(1 - f_\pm)f'_\gamma(1 + f_\gamma),$$

which leads to $\theta_\gamma = \theta_\pm \equiv \theta_k$. Analogous results for $e^\pm e^\mp \leftrightarrow \gamma_1\gamma_2$ leads to $\varphi_\gamma = \varphi_\pm \equiv \varphi_k$.

Only triple reactions give $\varphi_k = 0$!

Conservation laws

Energy conservation

$$\frac{d}{dt}\sum_i \rho_i = 0, \quad \text{or} \quad \frac{d}{dt}\sum_{i,\omega} Y_{i,\omega} = 0, \quad \text{where} \quad Y_{i,\omega} = \int_{\epsilon_{i,\omega}-\Delta\epsilon_{i,\omega}/2}^{\epsilon_{i,\omega}+\Delta\epsilon_{i,\omega}/2} E_i d\epsilon.$$

Particle's conservation for binary reactions

$$\frac{d}{dt}\sum_i n_i = 0, \quad \text{or} \quad \frac{d}{dt}\sum_{i,\omega} \frac{Y_{i,\omega}}{\epsilon_{i,\omega}} = 0.$$

Baryonic number and charge conservation respectively

$$\frac{dn_p}{dt} = 0, \quad n_- = n_+ + n_p,$$

The condition for the chemical potentials

$$\varphi_+ + \varphi_- = 2\varphi_\gamma.$$

Kinetic equilibrium 1

For photons we have

$$n_\gamma = \frac{1}{V_0}\exp\left(\frac{\nu_\gamma}{\theta}\right)2\theta^3, \qquad \frac{\rho_\gamma}{n_\gamma mc^2} = 3\theta, \qquad V_0 = \frac{1}{8\pi}\left(\frac{2\pi\hbar}{mc}\right)^3$$

for pairs

$$n_\pm = \frac{1}{V_0}\exp\left(\frac{\nu_\pm}{\theta}\right)j_1(\theta), \qquad \frac{\rho_\pm}{n_\pm mc^2} = j_2(\theta),$$

and for protons

$$n_p = \frac{1}{V_0}\sqrt{\frac{\pi}{2}}\left(\frac{M}{m}\right)^{3/2}\exp\left(\frac{\nu_p - M/m}{\theta}\right)\theta^{3/2}, \qquad \frac{\rho_p}{Mn_p c^2} = 1 + \frac{3}{2}\frac{m}{M}\theta,$$

$$j_1(\theta) = \theta K_2(\theta^{-1}) \rightarrow \begin{cases} \sqrt{\frac{\pi}{2}}e^{-\frac{1}{\theta}}\theta^{3/2}, & \theta \rightarrow 0 \\ 2\theta^3, & \theta \rightarrow \infty \end{cases},$$

$$j_2(\theta) = \frac{3K_3(\theta^{-1}) + K_1(\theta^{-1})}{4K_2(\theta^{-1})} \rightarrow \begin{cases} 1 + \frac{3}{2}\theta, & \theta \rightarrow 0 \\ 3\theta, & \theta \rightarrow \infty \end{cases}.$$

Kinetic equilibrium 2

Summing up energy densities

$$\sum_i \rho_i = \frac{mc^2}{V_0}\left\{6\theta^4 \exp\left(\frac{\nu_+}{\theta}\right)\left[1-\frac{n_p V_0}{j_1(\theta)}\exp\left(-\frac{\nu_+}{\theta}\right)\right]^{\frac{1}{2}} + \right.$$
$$\left. + j_2(\theta)\left[2j_1(\theta)\exp\left(\frac{\nu_+}{\theta}\right) - n_p V_0\right] + \frac{M}{m}\left(1+\frac{3}{2}\frac{m}{M}\theta\right) n_p V_0\right\},$$

and analogously for number densities

$$\sum_i n_i = \frac{1}{V_0}\left\{6\theta^4 \exp\left(\frac{\nu_+}{\theta}\right)\left[1-\frac{n_p V_0}{j_1(\theta)}\exp\left(-\frac{\nu_+}{\theta}\right)\right]^{\frac{1}{2}} + 2j_1(\theta)\exp\left(\frac{\nu_+}{\theta}\right)\right\},$$

so that two unknowns, ν_+ and θ can be found.

Kinetic equilibrium 3

$$\exp\left(\frac{\nu_-}{\theta}\right) = \exp\left(\frac{\nu_+}{\theta}\right) + \frac{n_p V_0}{j_1(\theta)},$$

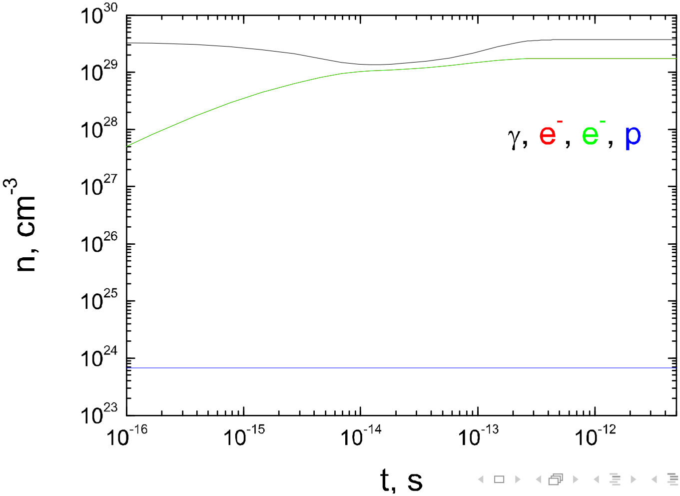
$$\exp\left(\frac{\nu_\gamma}{\theta}\right) = \exp\left(\frac{\nu_+}{\theta}\right)\left[1 + \frac{n_p V_0}{j_1(\theta)}\exp\left(-\frac{\nu_+}{\theta}\right)\right]^{\frac{1}{2}},$$

$$\exp\left(\frac{\nu_p - M/m}{\theta}\right) = n_p V_0 \sqrt{\frac{2}{\pi}}\left(\frac{m}{M}\right)^{3/2}\theta^{-3/2}.$$

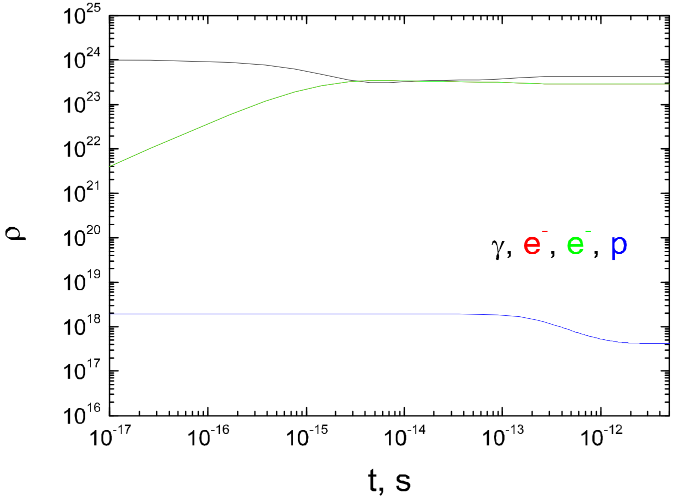
In thermal equilibrium $\nu_\gamma = 0$ and $\nu_+ = -\nu_-$.
For $n_p > 0$ one always has $\nu_- > 0$ and $\nu_+ < 0$ in thermal equilibrium.

Concentrations

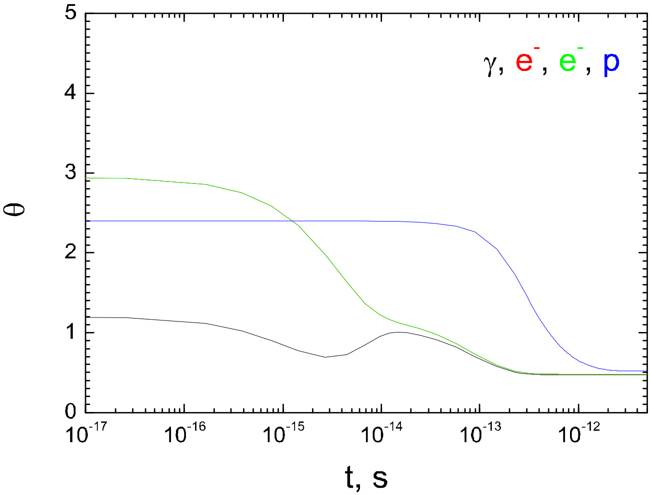
Initial conditions: $\rho = 10^{24}$ erg/cm^3, $\rho_\pm = 10^{-5}\rho$, $B = 10^{-3}$



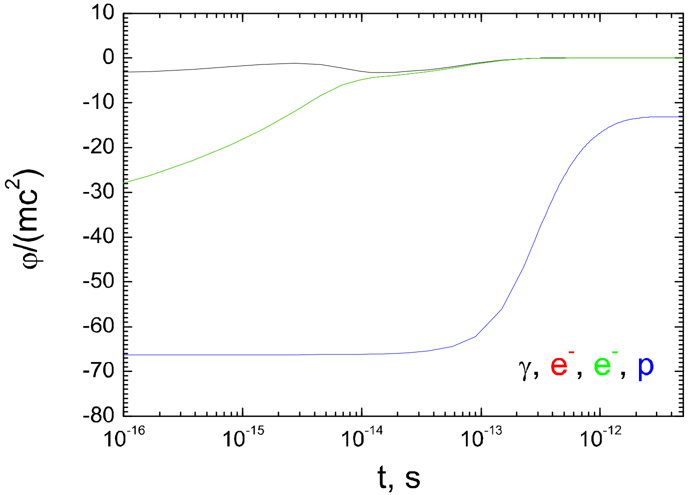
Energy densities



Temperatures



Chemical potentials



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2. Kinetic equilibrium is obtained from the first principles.
3. Protons thermalize with other particles by proton-electron scatterings; proton-proton scattering is inefficient.
4. **The timescale of thermalization is always shorter than the dynamical one.**