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Electron-positron plasma in GRBs and in cosmology

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Summary. — Electron-positron plasma is believed to play an imporant role both in the early Universe and in sources of Gamma-Ray Bursts (GRBs). We focus on analogies and differences between physical conditions of electron-positron plasma in the early Universe and in sources of GRBs. We discuss: a) dynamical differences, namely thermal acceleration of the outflow in GRB sources *vs.* cosmological deceleration; b) nuclear composition differences as synthesis of light elements in the early Universe and possible destruction of heavy elements in GRB plasma; c) different physical conditions during last scattering of photons by electrons. Only during the acceleration phase of the optically thick electron-positron plasma the comoving observer may find it similar to the early Universe. This similarity breaks down during the coasting phase. Reprocessing of nuclear abundances may likely take place in GRB sources. Heavy nuclear elements are then destroyed, resulting mainly in protons with small admixture of helium. Unlike the primordial plasma which recombines to form neutral hydrogen, and emits the Cosmic Microwave Background Radiation, GRB plasma does not cool down enough to recombine.

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1. – Introduction

Electron-positron plasmas are discussed in connection with astrophysical phenomena such as Galactic Center, microquasars, Gamma-Ray Bursts (GRBs), as well as laboratory experiments with high power lasers, for details see [1]. According to the standard cosmological model, such plasma existed also in the early Universe. It is naturally characterized by the energy scale given by the electron rest mass energy, 511 keV. It is interesting that at the epoch when the Universe had this temperature, several important phenomena took place almost contemporarily: electron-positron pair annihilation, the Big Bang Nucleosynthesis (BBN) and neutrino decoupling.

Electron-positron plasma also is thought to play an essential role in GRB sources, where simple estimates for the initial temperature give values in the MeV region. Such plasma is energy-dominated and optically thick due to both Compton scattering and electron-positron pair creation, and relaxes to thermal equilibrium on a time scale less than 10^{-11} s, see [2]. The latter condition results in self-accelerated expansion of the plasma until it becomes either transparent or matter-dominated.

In the literature there have been several qualitative arguments mentioning possible similarities between electron-positron plasmas in the early Universe and in GRB sources. However, until now there is no dedicated study which draws analogies and differences between these two cases. This paper aims at confronting dynamics and physical conditions in both cases.

2. – General equations

The framework which describes electron-positron plasma both in cosmology and in GRB sources is General Relativity. Both dynamics of the expansion of the Universe, and the process of energy release in the source of GRB should be considered within that framework. Hydrodynamic expansion of GRB sources may, however, be studied within a much simpler formalism of Special Relativity.

We start with Einstein equations

$$(1) \qquad R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu},$$

where $R_{\mu\nu}$, $g_{\mu\nu}$ and $T_{\mu\nu}$ are, respectively, Ricci, metric and energy-momentum tensors, G is Newton's constant, c is the speed of light, and the energy-momentum conservation, following from (1)

$$(2) \qquad (T_\mu{}^\nu)_{;\nu} = \frac{1}{\sqrt{-g}} \frac{\partial(\sqrt{-g}\, T_\mu{}^\nu)}{\partial x^\nu} - \Gamma^\lambda_{\nu\mu} T_\lambda{}^\nu = 0,$$

where $\Gamma^\mu_{\nu\lambda}$ are Cristoffel symbols and g is the determinant of the metric tensor. We assume for the energy-momentum tensor

$$(3) \qquad T^{\mu\nu} = p\, g^{\mu\nu} + \omega U^\mu U^\nu,$$

where U^μ, is the four-velocity, $\omega = \rho + p$ is the proper enthalpy, p is the proper pressure and ρ is the proper energy density.

When the plasma is optically thick, radiation is trapped in it and entropy conservation applies. It may be obtained multiplying (2) by the four-velocity

$$(4) \qquad -U^\mu (T_\mu{}^\nu)_{;\nu} = U^\mu \rho_{;\mu} + \omega U^\mu{}_{;\mu} = 0.$$

Using the second law of thermodynamics

$$(5) \qquad \mathrm{d}\left(\frac{\omega}{n}\right) = T\mathrm{d}\left(\frac{\sigma}{n}\right) + \frac{1}{n}\mathrm{d}p,$$

where $\sigma = \omega/T$ is the proper entropy density, T is temperature, one may rewrite 4 as

$$(6) \qquad (\sigma U^\mu)_{;\mu} = U^\mu \sigma_{;\mu} + \sigma U^\mu{}_{;\mu} = 0.$$

The baryon number conservation equation has exactly the same form

$$(7) \qquad (nU^\mu)_{;\mu} = U^\mu n_{;\mu} + nU^\mu{}_{;\mu} = 0.$$

Now recalling that $U^\mu \frac{\partial}{\partial x^\mu} = \frac{\mathrm{d}}{\mathrm{d}\tau}$ and $U^\mu{}_{;\mu} = \mathrm{d}\ln V/\mathrm{d}\tau$, where V is the comoving volume, τ is the proper time, from (4) and (7) we get

$$(8) \qquad \mathrm{d}\rho + \omega \mathrm{d}\ln V = 0, \qquad \mathrm{d}\ln n + \mathrm{d}\ln V = 0,$$

Finally, introducing the thermal index $\gamma = 1 + \frac{p}{\rho}$ restricted by the inequality $1 \le \gamma \le 4/3$ we obtain from (4) the following scaling laws:

$$(9) \qquad \rho V^\gamma = \mathrm{const}, \qquad nV = \mathrm{const}.$$

Both these conservations laws are valid for the early Universe and GRB plasmas.

One can obtain the corresponding scaling laws for comoving temperature by splitting the total energy density into nonrelativistic (with $\gamma = 1$) and ultrarelativistic (with $\gamma = 4/3$) parts with $\rho \to nmc^2 + \varepsilon$, where m is the mass of particles[1], ε is the proper internal energy density. The entropy of the ultrarelativistic component is then $\sigma = \frac{4}{3}\frac{\varepsilon}{T}$, and (6) gives

$$(10) \qquad \frac{\varepsilon V}{T} = \mathrm{const}.$$

For $\varepsilon \gg nmc^2$, which is the energy dominance condition, the internal energy plays a dynamical role by influencing the laws of expansion. For $\varepsilon \ll nmc^2$, which is the matter dominance condition, internal energy does not play any dynamical role, but determines the scaling law of the temperature. In order to understand the dynamics of thermodynamic quantities in both the early Universe and in GRBs, one should write down the corresponding equations of motion.

2'1. *Early Universe.* – For the description of the early Universe we take the Robertson-Walker metric with the interval

$$(11) \qquad \mathrm{d}s^2 = -c^2\mathrm{d}t^2 + a^2(t)\left[\frac{\mathrm{d}r^2}{1-kr^2} + r^2\mathrm{d}\vartheta^2 + r^2\sin^2\vartheta\mathrm{d}\varphi^2\right],$$

where $a(t)$ is the scale factor and $k = 0, \pm 1$ stands for the spatial curvature. In homogeneous and isotropic space described by (11), Einstein equations (1) are reduced to

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[1] The nonrelativistic component is represented by baryons. For simplicity we assume only one sort of baryons, say protons, having mass m. The ultrarelativistic component is represented by photons and electron-positron pairs.

Friedmann equations together with the continuity equation

$$(12) \qquad \left(\frac{\mathrm{d}a}{\mathrm{d}t}\right)^2 + c^2 k = \frac{8\pi G}{3c^2}\rho a^2,$$

$$(13) \qquad 2a\frac{\mathrm{d}^2 a}{\mathrm{d}t^2} + \left(\frac{\mathrm{d}a}{\mathrm{d}t}\right)^2 + c^2 k = -\frac{8\pi G}{c^2}pa^2,$$

$$(14) \qquad \frac{\mathrm{d}\rho}{\mathrm{d}t} + \frac{3}{a}\frac{\mathrm{d}a}{\mathrm{d}t}(\rho + p) = 0,$$

where a is the scale factor. Notice that only two equations in the system above are independent. The continuity equation (14) follows from the Einstein equations (12) and (13) as the energy conservation. In fact, (14) may be also obtained from the entropy conservation (4). The comoving volume in Friedmann's Universe scales with a as $V = a^3$, so (14) and the first equality in (9) are equivalent.

On the radiation-dominated stage of the Universe expansion, one has

$$(15) \qquad \rho \propto V^{-4/3} \propto a^{-4}, \qquad n \propto V^{-1} \propto a^{-3},$$

while on the matter-dominated stage

$$(16) \qquad \rho \propto n \propto V^{-1} \propto a^{-3}.$$

Entropy conservation (10) leads to the unique temperature dependence on the scale factor

$$(17) \qquad T \propto V^{-1/3} \propto a^{-1}.$$

The corresponding time dependence of the thermodynamic quantities may be obtained from solutions of Friedmann equation (12) and continuity equation (14), see, *e.g.* [3].

2˙**2.** *GRBs.* – A different situation takes place for the sources of GRBs. Assuming spherical symmetry for the case of GRB the interval(^{2}) is

$$(18) \qquad \mathrm{d}s^2 = -c^2\mathrm{d}t^2 + \mathrm{d}r^2 + r^2\mathrm{d}\vartheta^2 + r^2\sin^2\vartheta\mathrm{d}\varphi^2.$$

Being optically thick to Compton scattering and pair production, the electron-positron plasma in GRB sources is radiation-dominated. Its equations of motion follow from the energy-momentum conservation law (2) and baryon number conservation law (7). Initially plasma expands with acceleration driven by the radiative pressure.

In the spherically symmetric case the number conservation equation (7) is

$$(19) \qquad \frac{\partial(n\Gamma)}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 n\sqrt{\Gamma^2 - 1}\right) = 0,$$

(^{2}) General Relativity effects may be included by taking Schwarzschild or Kerr-Newman metric. However, we are interested in optically thick plasma which expands with acceleration and propagates far from its source, where the spatial curvature effects may be neglected. For this reason we simplify the treatment and adopt a spatially flat metric.

Integrating this equation over the volume from certain $r_i(t)$ to $r_e(t)$ which we assume to be comoving with the fluid $\frac{dr_i(t)}{dt} = \beta(r_i, t)$, $\frac{dr_e(t)}{dt} = \beta(r_e, t)$, and ignoring a factor 4π we have

$$(20) \qquad \int_{r_i}^{r_e} \frac{\partial(n\Gamma)}{\partial t} r^2 dr + \int_{r_i}^{r_e} \frac{\partial}{\partial r} \left(r^2 n \sqrt{\Gamma^2 - 1} \right) dr =$$

$$\frac{\partial}{\partial t} \int_{r_i}^{r_e} (n\Gamma) r^2 dr - \frac{dr_e}{dt} n(r_e, t) \Gamma(r_e, t) r_e^2 + \frac{dr_i}{dt} n(r_i, t) \Gamma(r_i, t) r_i^2$$

$$+ r_e^2 n(r_e, t) \sqrt{\Gamma^2(r_e, t) - 1} - r_i^2 n(r_i, t) \sqrt{\Gamma^2(r_i, t) - 1} =$$

$$\frac{d}{dt} \int_{r_i}^{r_e} (n\Gamma) r^2 dr = 0.$$

Since we deal with arbitrary comoving boundaries, this means that the total number of particles integrated over all differential shells is conserved

$$(21) \qquad N = 4\pi \int_0^{R(t)} n\Gamma r^2 dr = \text{const},$$

where $R(t)$ is the external radius of the shell.

Following [4] one can transform (19) from the variables (t, r) to the new variables $(s = t - r, r)$ and then show that

$$(22) \qquad \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 n \sqrt{\Gamma^2 - 1} \right) = -\frac{\partial}{\partial s} \left(\frac{n}{\Gamma + \sqrt{\Gamma^2 - 1}} \right).$$

For ultrarelativistic expansion velocity $\Gamma \gg 1$, the RHS in (22) tends to zero, and then the number of particles in each differential shell between the boundaries $r_i(t)$ and $r_e(t)$ is also conserved with a good approximation, *i.e.*

$$(23) \qquad dN = 4\pi n\Gamma r^2 dr \approx \text{const}.$$

Relations (21) and (23) then imply

$$(24) \qquad 4\pi \int_{r_i}^{r_e} \left(n\Gamma r^2 \right) dr = 4\pi \left[n(r, t)\Gamma(r, t) r^2 \right] \int_{r_i}^{r_e} dr$$

$$= 4\pi (n\Gamma r^2)\Delta \approx \text{const},$$

where the first argument of functions $n(r, t)$ and $\Gamma(r, t)$ is restricted to the interval $r_i < r < r_e$, and consequently $\Delta \equiv r_e - r_i \approx \text{const}$. Taking into account that $r_i(t)$ and $r_e(t)$ are arbitrary, this means that the ultrarelativistically expanding shell preserves its width measured in the laboratory reference frame. This fact has been used in [5] and referred to there as the constant thickness approximation.

The volume element measured in the laboratory reference frame is $d\mathcal{V} = 4\pi r^2 dr$, while the volume element measured in the reference frame comoving with the shell is

$dV = 4\pi\Gamma r^2 dr$. The comoving volume of the expanding ultrarelativistic shell with $\Gamma \simeq$ const will be

$$(25) \qquad V = 4\pi\Gamma \int_{r-\Delta}^{r} r^2 dr \simeq 4\pi\Gamma r^2 \Delta.$$

Then we rewrite the conservation equations (9) as

$$(26) \qquad \rho^{\frac{1}{\gamma}}\Gamma r^2 = \text{const}, \qquad n\Gamma r^2 = \text{const}.$$

Unlike the early Universe, where both energy and entropy conservations reduce to (14), in the case of GRBs the energy conservation is a separate equation coming from the zeroth component of (2) as

$$(27) \qquad (T_0{}^{\nu})_{;\nu} = \omega U_0 U^{\nu}{}_{;\nu} + U^{\nu}(\omega U_0)_{;\nu} = 0,$$

which independently of γ gives

$$(28) \qquad \rho\Gamma^2 r^2 = \text{const}.$$

From (26) and (28) we then find

$$(29) \qquad \Gamma \propto r^{\frac{2(\gamma-1)}{2-\gamma}}, \qquad n \propto r^{-\frac{2}{2-\gamma}}, \qquad \rho \propto r^{-\frac{2\gamma}{2-\gamma}}.$$

For the ultrarelativistic equation of state with $\gamma = 4/3$ we immediately obtain

$$(30) \qquad \Gamma \propto r, \qquad n \propto r^{-3}, \qquad \rho \propto r^{-4}.$$

Taking into account that the relation between the comoving and the physical coordinates in cosmology is given by the scale factor a, it follows from (30) that both energy density and baryonic number density behave as in the radiation-dominated Universe, see (15). This analogy between the GRB source and the Friedmann Universe is noticed by [6, 4].

In the presence of baryons as the pressure decreases, plasma becomes matter dominated and the expansion velocity saturates. Hence for the nonrelativistic equation of state with $\gamma = 1$, different scaling laws are found:

$$(31) \qquad \Gamma = \text{const}, \qquad n \propto r^{-2}, \qquad \rho \propto r^{-2}.$$

The transition between the two regimes (30) and (31) occurs at the radius $R_c = B^{-1}R_0$, where R_0 is the initial size of plasma.

Therefore, one may reach the conclusion that for a comoving observer the radiation-dominated plasma looks indistinguishable from a portion of the radiation-dominated Universe. However, this is true only in the absence of pressure gradients. Strong gradients are likely present in GRB sources, and they should produce a local acceleration in the radiation-dominated electron-positron plasma, making it distinct from the early Universe, where matter inhomogeneities are known to be weak.

It is easy to get from (26) and (28) for the internal energy density and temperature

$$(32) \qquad \varepsilon \propto r^{-4}, \qquad T \propto r^{-1}, \qquad R_0 < r < R_c,$$

and

$$(33) \qquad \varepsilon \propto r^{-8/3}, \qquad T \propto r^{-2/3}, \qquad R_c < r < R_{tr},$$

where R_{tr} is the radius at which the outflow becomes transparent. The outflow may become transparent for photons also at the acceleration phase, provided that $R_{tr} < R_c$. For instance, a pure electron-positron plasma gets transparent at the acceleration phase.

3. – Heavy elements

Cosmological nucleosynthesis is a well-established branch of cosmology. Classical computations made in the middle of the XX century revealed that heavy elements cannot be built in the early Universe. Hydrogen and helium contribute approximately 3/4 and 1/4, leaving some room, much less than 1 per cent for deuterium, tritium and lithium. All the heavier elements must have been produced in stars.

Some of these stars, as indicated by observations, end their life as progenitors of GRBs. For this reason it is likely that initially in the source of GRBs elements heavier than hydrogen are present. In this section we consider the chemical evolution of plasma in the sources of GRBs.

Assume that in the source of a GRB the amount of energy E_0 is released in the volume with linear size R_0 during the time Δt, making this region optically thick to Compton scattering and pair production. The amount of baryons which may be present as well is parametrized by

$$(34) \qquad B \simeq \begin{cases} \dfrac{Mc^2}{E_0}, & \Delta t \ll R_0/c, \\[2mm] \dfrac{\dot{M}c^2}{L}, & \Delta t \gg R_0/c, \end{cases}$$

where $L = \mathrm{d}E/\mathrm{d}t$ is the luminosity, $\dot{M} = \mathrm{d}M/\mathrm{d}t$ is the mass ejection rate and M is the total baryonic mass. The ultrarelativistic outflow is generated through thermal acceleration of baryons by the radiative pressure if plasma is initially energy dominated, *i.e.*

$$(35) \qquad B \ll 1.$$

In the case of instant energy release with time interval $\Delta t \sim R_0/c$ the initial temperature in the source of GRB may be estimated neglecting the baryonic contribution, provided (35) is satisfied as

$$(36) \qquad T_0 \simeq \left(\frac{3E_0}{4\pi a R_0^3} \right)^{1/4} \simeq 6.5 E_{54}^{1/4} R_8^{-3/4} \, \mathrm{MeV},$$

where $a = 4\sigma_{SB}/c$, σ_{SB} is the Stefan-Boltzmann constant and the last value is obtained by substituting the numerical values for $E_0 = 10^{54} E_{54}$ erg and $R_0 = 10^8 R_8$ cm.

As has been shown in [7] for temperatures above $1\,\mathrm{MeV}$ even low-density plasma with density $n = 10^{18}\,\mathrm{cm}^{-3}$ quite quickly destroys all heavier nuclei, and the final state contains just protons and neutrons and some small traces of deuterium and ^{4}He. The

timescale of this process ($\sim 10^{-2}$ s for $T_0 = 1\,\text{MeV}$) strongly depends on temperature, but the rates of almost all reactions increase with temperature, and correspondingly the abundances of nuclei evolve much faster. Therefore, nuclei disintegration is fast enough to occur before plasma starts to expand and cool on the timescale R_0/c.

During the early stages of plasma expansion, its temperature decreases in the same way as it happened in the early Universe. Therefore similar synthesis of light elements to BBN occurs also in sources of GRBs. Most important is, however, another similarity with the early Universe: it is well known that practically all free neutrons have been captured into elements heavier than hydrogen. So we do not expect dynamically important free neutrons present in GRB plasma after it started to expand and cool down unless they are engulfed by the expanding plasma later. The role of such free neutrons has been considered in the literature, see *e.g.* [8] and [9].

4. – Recombination

On the radiation-dominated phase both in the early Universe and in GRB plasma entropy conservation (4) results in a decrease of temperature. When the comoving temperature decreases below the hydrogen ionization energy, $E_i = 13.6\,\text{eV}$, the formation of neutral hydrogen is expected.

4`1. *Early Universe*. – In the early Universe, after the BBN epoch and electron-positron annihilation, cosmological plasma consists of fully ionized hydrogen, helium and small admixture of other light elements. The temperature continues to decrease until it gets sufficiently low to allow formation of neutral atoms: that is the moment in the cosmic history where the formation of the Cosmic Microwave Background Radiation (CMB) happens.

The theory of cosmological recombination of hydrogen, based on three level approximation, has been developed in [10] and [11] in the late 60s. The only modification that such theory underwent in the later years is the account for dark matter and the addition of more levels to the model, currently about 300. There is a basic difference with respect to the equilibrium recombination essentially by the process $e + p \leftrightarrow H + \gamma$, described by the Saha equation

$$(37) \qquad \frac{n_e n_p}{n_H} = \frac{g_e g_p}{g_H} \frac{(2\pi m_e kT)^{3/2}}{h^3} \exp\left(-\frac{E_i}{kT}\right),$$

where g_i are statistical weights, h is Planck's constant. This difference is due to the presence of the $2p$ quantum level, which produces Ly-α photons. The absorption of such photons is very strong. However, ionization from the $2p$ level requires only $E_i/4$. Therefore the formation of neutral hydrogen proceeds through the $2s$-$1s$ transition in the presence of abundant Ly-α photons.

In fact, the early Universe would become transparent for radiation even if formation of hydrogen would have been forbidden, see *e.g.* [12]. The optical depth to Thomson scattering is

$$(38) \qquad \tau = \int_t^{t_0} \sigma_T n_b c \mathrm{d}t$$
$$\simeq 4 \times 10^{-2} \frac{\Omega_b}{\Omega_m} h \left\{ \left[\Omega_\Lambda + \Omega_m(1+z)^3\right]^{1/2} - 1 \right\},$$

where σ_T is the Thomson cross-section, $\Omega_i = \rho_i/\rho_c$, $\rho_c = 3H^2c^2/8\pi G$, $H = 100h\,\mathrm{km\,s/}$ Mpc and b, m, Λ stand for, respectively baryons, dark matter and cosmological constant contributions to the total energy density of the Universe. For large z we have

$$\tau(z_*) = 1, \qquad z_* \simeq 8.4\Omega_b^{-2/3}\Omega_m^{1/3}h^{-2/3}.$$

For typical values $\Omega_b h^2 \simeq 0.02$, $\Omega_m \simeq 0.3$, and $h \simeq 0.7$ we have $z_* \simeq 60$. At such redshift the Universe would be expected to become transparent to Thomson scattering. That is exactly what happens in plasma in GRB sources. Below we show that, unlike radiation-dominated cosmological expansion where comoving quantities also fulfill relations (32), the comoving temperature in GRB outflows remains always high enough to prevent recombination of hydrogen.

$4\dot{}2$. *GRBs.* – During both acceleration and coasting phases the comoving temperature decreases with radius, see (32) and (33). The optical depth to Compton scattering may be computed and the corresponding photospheric radius may be obtained, see [13] where ultrarelativistic outflows were analysed in details. In particular, the comoving temperature at the photosphere decreases with the baryonic loading B both at acceleration and coasting phases. However, when the outflow reaches the radius $R_s = B^{-2}R_0$, the comoving temperature becomes independent of B. In that regime the expression for the photospheric radius is

$$(39) \qquad R_{tr} = \left(\frac{\sigma E_0 B}{4\pi m_p c^2}\right)^{1/2},$$

where m_p and σ are proton mass and Thompson cross-section, respectively. Indeed, using (36), (39), (32) and (33) in the case of an instant energy release we have

$$(40) \qquad T_{\min} = BT_0 \left(\frac{R_c}{R_{tr}}\right)^{2/3}$$

$$(41) \qquad = \left(\frac{3}{4\pi a}\right)^{1/4}\left(\frac{\sigma}{4\pi m_p c^2}\right)^{-1/3}(E_0 R_0)^{-1/12}.$$

Notice how extremely insensitive this value is with respect to the remaining parameters E_0 and R_0! Expressed in units of typical energy and size

$$(42) \qquad T_{\min}^{(s)} \simeq 42(E_{54}R_8)^{-1/12}\,\mathrm{eV}.$$

In the case of a gradual energy release with $\Delta t \gg R_0/c$ and constant luminosity and mass ejection rate the initial temperature is

$$(43) \qquad T_0 \simeq \left(\frac{L}{16\pi\sigma_{SB}R_0^2}\right)^{1/4}$$

and a similar expression to (40) may be derived:

$$(44) \qquad T_{\min} = \left(\frac{1}{16\pi\sigma_{SB}}\right)^{1/4}\left(\frac{\sigma}{4\pi m_p c^2}\right)^{-1/3}L^{-1/12}R_0^{1/6}\Delta t^{-1/3},$$

which may be rewritten, introducing $L = 10^{50} L_{50}$ erg/s and $\Delta t = 1 \Delta t_1$ s, as

$$(45) \qquad T_{\min}^{(w)} \simeq 17 L_{50}^{-1/12} R_8^{1/6} \Delta t_1^{-1/3} \text{ eV}.$$

Even if (45) appears to be less stringent that (42), they are both quite insensitive to initial parameters. As a result, even if the comoving temperature decreases very much compared to its initial value, typically on the order of MeV, at the photospheric radius it is always well above the characteristic temperature 0.3 eV at which recombination happens [14], thus preventing formation of neutral hydrogen. In fact, if such hydrogen were formed, the cross-section of interaction of expanding particles with the circumburst medium would drastically decrease. As a consequence no aferglow would be observed.

A simplified way to look at this lower bound on the comoving temperature at the photosphere is to say that if a fraction ϵ of solar mass is released in the volume having radius δ solar Schwarzschild radii, then its minimum comoving temperature before transparency is

$$(46) \qquad T_{\min}^{(s)} \simeq 66 (\epsilon \delta)^{-1/12} \text{ eV},$$

in the case of instant energy release and

$$(47) \qquad T_{\min}^{(w)} \simeq 2.8 \epsilon^{-1/12} \delta^{1/6} \Delta t_1^{-1/4} \text{ eV},$$

in the case of gradual energy release during time Δt_1. Clearly in both cases $\delta > 1$, and likely $\epsilon < 1$. Notice that, while in the case of instant energy release the lower bound on temperature decreases with increasing δ, it instead increases in the case of gradual energy release.

The baryon-to-photon ratio in GRB plasma like in cosmology is large. This ratio may be estimated as

$$(48) \qquad \frac{n_\gamma}{n_B} = \frac{m_p}{m_e} \frac{1}{B \langle \varepsilon \rangle} \simeq 1.8 \times 10^5 B_{-2}^{-1} \langle \varepsilon \rangle^{-1},$$

where $B_{-2} = 10^{-2} B$, and $\langle \varepsilon \rangle$ is the average photon energy in the source of GRB in units of electron rest mass energy. Thus the optical depth of electrons is much larger than the one of photons and it is given in [15]

$$(49) \qquad \frac{\tau_e}{\tau_\gamma} = \log \Lambda + \frac{n_\gamma}{n_e} \simeq \frac{n_\gamma}{n_B},$$

where Λ is the Coulomb logarithm. It means that electrons are kept in equilibrium with photons when the latter already decoupled from them [16]. In other words, electrons are forced to keep the local temperature of photons. This may lead to efficient Comptonization of the photon flow when it is decoupled from plasma and is passing through electrons having a locally different temperature.

As soon as plasma gets collisionless, laboratory spectrum of photons, baryons and electrons is maintained. If it were thermal at decoupling it will remain so. This shows

another difference with respect to cosmology, where the energy of all particles decoupled from the thermal bath decreases due to the cosmological expansion. For that reason in cosmology only the shape of the spectrum is conserved with expansion, but not the temperature.

Therefore, we have reached the conclusion that hydrogen recombination which is responsible for transparency of cosmological plasma does not occur in GRB plasma. This difference in physical conditions may result in deviations from black-body spectrum, as observed in GRBs. Available studies of photospheric emission in GRBs in the literature show that deviations from the perfectly thermal spectrum come mostly from three effects: a) dynamical and ultrarelativistic character of plasma outflows and geometric effects [13]; b) "fuzzy photosphere" effect [17, 18] and c) possible dissipation mechanisms at the photosphere [9, 19, 20].

Recently we presented a theory of photospheric emission from relativistic outflows, see [13]. Assuming that the spectrum of radiation in the comoving reference frame is the perfect black-body one, we have shown that the spectrum seen by a distant observer may be essentially nonthermal due to both geometric and dynamical special relativistic effects. The possibility that the spectrum of photospheric emission is nonthermal also in the comoving frame is under investigation.

5. – Conclusions

Regarding the dynamical aspects, there is an apparent similarity between the electron-positron plasma in the early Universe and the one in GRB sources. For an observer comoving with the radiation-dominated plasma in GRB source it may look indistinguishable from a portion of radiation-dominated Universe. However, this is true only in the absence of pressure gradients. Strong gradients are likely present in GRB sources, and they should produce local acceleration in the radiation-dominated electron-positron plasma, making it distinct from the early Universe, where matter inhomogeneities are known to be weak.

There is also an apparent similarity with respect to the nucleosynthesis phenomenon. Given that the temperature reached in GRB sources, see eq. (36), may be as high as several MeV, nuclear reactions are expected to operate on timescales of 10^{-2} s or shorter. That is, on the order of magnitude of dynamical timescale of the GRB sources. It means that reprocessing of nuclear abundances may likely take place in GRB sources. Since observations imply that GRBs may originate from compact stellar objects, elements heavier than helium are likely to be present in GRB sources. Such heavy elements are then destroyed, resulting mainly in protons with small admixture of helium. Thus, similarly to the early Universe, we do not expect dynamically important free neutrons present in GRB plasma after it started to expand and cool down unless they are engulfed by the expanding plasma later.

Finally, there is an important difference between the electron-positron plasma in the early Universe and the one in GRB sources. We show in this paper that unlike the primordial plasma which recombines to form neutral hydrogen, and emits the Cosmic Microwave Background Radiation, GRB plasma does not cool down enough to recombine. Therefore GRB plasma always becomes transparent due to Compton scattering.

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