Theoretical Astroparticle Physics

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2 Participants

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3 Brief description

Astroparticle physics is a new field of research emerging at the intersection of particle physics, astrophysics and cosmology. Theoretical development in these fields is mainly triggered by the growing amount of experimental data of unprecedented accuracy, coming both from the ground based laboratories and from the dedicated space missions.

3.1 Relativistic plasma

Electron-positron plasma is of interest in many fields of physics and astrophysics, e.g. in the early universe, active galactic nuclei, the center of our Galaxy, compact astrophysical objects such as hypothetical quark stars, neutron stars and gamma-ray bursts sources. It is also relevant for the physics of ultraintense lasers and thermonuclear reactions. We study physical properties of dense and hot electron-positron plasmas. In particular, we are interested in the issues of its creation and relaxation, its kinetic properties and hydrodynamic description, baryon loading and radiation from such plasmas.

Two different states exist for electron-positron plasma: optically thin and optically thick. Optically thin pair plasma may exist in active galactic nuclei and in X-ray binaries. The theory of relativistic optically thin nonmagnetic plasma and especially its equilibrium configurations was established in the 80s by Svensson, Lightman, Gould, Haug and others. It was shown that relaxation of the plasma to some equilibrium state is determined by a dominant reaction, e.g. Compton scattering or bremsstrahlung.

Developments in the theory of gamma ray bursts from one side, and observational data from the other side, unambiguously point out on existence of optically thick pair dominated non-steady phase in the beginning of formation of GRBs. The spectrum of radiation from optically thick plasma is usually assumed to be thermal.

Experiments with high intensity laser beams interacting with each other as well as with solid targets aim at creation of relativistic plasmas and their study in laboratory conditions. The goal of such experiments is reproduction of astrophysical plasmas in controlled environment.

In a series of publications we consider kinetic, electrodynamic, hydrodynamic and observational properties of relativistic plasma.

3.1.1 Numerical scheme for evaluating the collision integrals for triple interactions in relativistic plasma

The most general description of relativistic plasma dynamics is given in terms of distribution function, where particle collisions are described by the integrals of differential cross-section (or a matrix element) over the phase space (Cercignani and Kremer, 2012; Groot et al., 1980; Vereshchagin and Aksenov, 2017). The binary interactions between photons and electrons are the subject of classical textbooks in QED. There are some analytic expressions for reaction rates in thermal equilibrium of binary interactions. Most numerical kinetic codes account for binary interactions.

A new fast numerical scheme for computation of collision integrals in relativistic plasmas is developed recently Prakapenia et al. (2020). It is based on the work (Aksenov et al., 2004). This method was applied to the study of thermalization in relativistic plasma of Boltzmann particles (Aksenov et al., 2007, 2009a,b, 2010a), for the computation of relaxation timescales (Aksenov et al., 2010b), and description of electron-positron plasma creation in strong electric fields (Benedetti et al., 2013). Plasma degeneracy has been taken into account in the computational scheme (Prakapenia et al., 2018) which allowed to follow plasma thermalization for degenerate plasmas as well (Prakapenia et al., 2019). Recently generalization of our method for calculation of collision integrals specifically treating triple interactions in relativistic plasma was performed in Prakapenia et al. (2020). In addition, a new approach to compute particle kinematics has been developed, which allowed speed up of the calculations, specifically for triple interactions.

Here the results of numerical calculations are presented. We compare our results for three-particle collision integral with analytical expressions, which appear to use only Boltzmann statistics, without quantum corrections. So that further all comparisons are made for such a case that is $\xi = 0$. Svensson Svensson (1984) gives analytical expressions for thermal photon emission coefficients η_γ in the soft photon limit ($\varepsilon_\gamma \ll k_B T_\gamma$) for the double Compton scattering, electron-electron bremsstrahlung, three-photon annihilation and radiative pair production. We note that Svensson formula for electron-electron bremsstrahlung does not correctly describe the non-relativistic and ultrarelativistic limits. Therefore we use the formula of Haug Haug (1975), which represents non-relativistic limit and the formula of Alexanian Alexanian (1968) for ultrarelativistic limit. One should keep in mind that Svensson formulas represent an interpolation between non-relativistic and ultra-relativistic limits and the rates are inversely proportional to the photon energy $\eta_\gamma \sim \epsilon^{-1}$, and their accuracy for the intermediate plasma temperatures is not estimated. For this reason we compare our results only in a non-relativistic domain, selecting for $k_B T = 0.1 m_e c^2$ and relativistic domain with $k_B T = 3 m_e c^2$. Below dimensionless energy $\epsilon \equiv \varepsilon / m_e c^2$ and temperature $\theta = k_B T / m_e c^2$ are used.

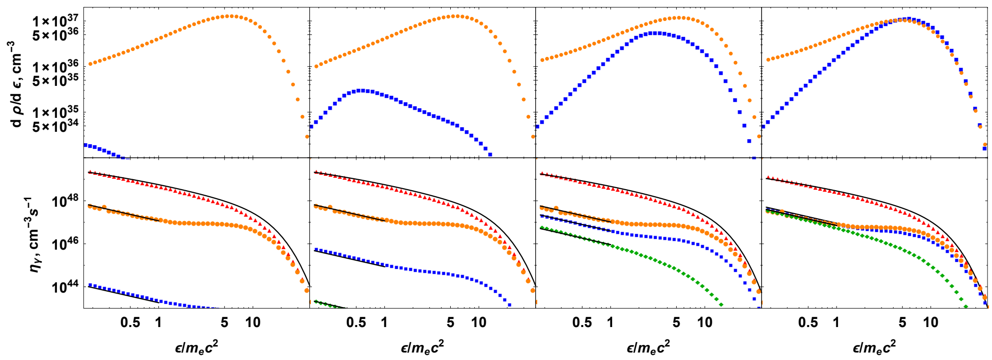

Figure 3.1: Energy density spectrum and photon emisivity at selected time moments for the photon production process. From left to right: $t = 10^{-22}$ s, $t = 10^{-20}$ s, $t = 10^{-18}$ s, $t = 10^{-16}$ s. Top: orange circles represent pairs, blue squares represent photons. Bottom: photon emissivity for e-e bremsstrahlung (red triangle), three-photon (orange circles), double Compton scattering (blue squares), radiative photon production (green rhombs). Black solid lines correspond to analytical expressions of Svensson (1984) and Alexanian (1968).

We present the results for relativistic energy domain. In particular, for plasma energy density $\rho = 2.1 \times 10^{27}$ erg cm^{-3} and final temperature $\theta = 3$

the photon production process was simulated. Figure 1 shows time evolution of particle number density of photons and electron-positron pairs. Initially pairs have Maxwellian distribution with zero chemical potential and temperature $\theta = 3.3$; photons are absent. Energy density spectrum and photon emissivity at selected time moments (10^{-22} s, 10^{-20} s, 10^{-18} s, 10^{-16} s) are shown on figure 2. The final thermal state with zero chemical potential and final temperature $\theta = 3$ establishes at time moment $t = 10^{-16}$ s. It is clear from the figure that at early times ($t < 10^{-18}$s) double Compton scattering and radiative pair production processes are negligible because of a small photon number and the most intense processes are bremsstrahlung and three-photon annihilation. Analytical expressions of Svensson Svensson (1984) and Alexanian Alexanian (1968) are well reproduced at all stages of thermalization (see the bottom row in fig. 2) because of establishment of equilibrium for pairs and insignificant deviations from equilibrium for photons (see the top row in Fig. 3.1).

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Results of this work were reported at the 107 SIF congress, 13-17 September 2021. These results are published in Astronomy Reports, 2021.

3.2 Photospheric emission

Emission from optically thick stationary plasma is an important topic in astrophysics. Such plasma confined by the gravitational field constitutes stars, accretion disks and other objects. The light from these systems is coming from the photosphere defined as a region where the optical depth computed from the interior of the optically thick plasma outwards reaches unity.

There are also dynamical sources where bulk velocities of plasma reach ultrarelativistic values such as microquasars, active galactic nuclei and gamma-ray bursts (GRBs). While in the former two objects there is clear evidence for jets which contain optically thin plasma, in the latter objects the issue of jets is controversial, and the source is required to be optically thick. This observational fact poses a new problem: the emission from (spherically) expanding plasma which initially is optically thick. Such plasma eventually becomes optically thin during its expansion, and initially trapped photons should be released. We have developed a new theory of photospheric emission in GRBs, reviewed in Vereshchagin (2014) and recently applied it also to the emission observed in their early afterglows Vereshchagin and Siutsou (2020).

This year we focused in the implications of observed photospheric emission on the composition of relativistic outflows producing GRBs.

3.2.1 Is magnetically dominated outflow required to explain GRBs?

The composition of relativistic outflows producing gamma-ray bursts is a long standing open question. One of the main arguments in favor of magnetically dominated outflows is the absence of photospheric component in their broadband time resolved spectra, with such notable example as GRB 080916C Zhang and Pe'er (2009).

In this paper we present the new spectral analysis of GRB 080916C, and confirm the previous results on the presence of additional spectral component in the time resolved spectra Guiriec et al. (2015). By interpreting this spectral component as photospheric emission and by applying the method of ref. Pe'er et al. (2007) we estimate the Lorentz factor of the baryonic outflow, the nozzle radius and the photospheric radius of the outflow. Our results indicate that observations of GRB 080916C can be naturally accounted for in the standard baryonic fireball model, provided that the high energy emission, detected in this GRB originates not at the photosphere, but at larger radii. This is consistent with the earlier proposals of high energy emission emerging in the external shock. We argue that the main assumption behind the conclusions in Zhang and Pe'er (2009) is the origin of the broadband non-thermal emission in the same zone (one-zone approximation). This is clearly not required by the data, and cannot provide evidence for the outflow composition.

4 Publications

1. M. A. Prakapenia and G. V. Vereshchagin, “Numerical scheme for evaluating the collision integrals for triple interactions in relativistic plasma”, Astronomy Reports, volume 65 (2021), pp. 1011–1014.

We perform calculations of nonequilibrium reaction rates for all triple interactions in relativistic plasma including: relativistic bremsstrahlung, double Compton scattering, radiative pair production, triple pair production/annihilation and their inverse processes. Reaction rates are computed out of first principles, numerically integrating exact QED matrix elements over the phase space of particles. Example is given for photon emission by hot thermal electron-positron pairs.

1. D. Begue, L. Li and G. V. Vereshchagin, “Is magnetically dominated outflow required to explain GRBs?”, arXiv:2201.05062, submitted to MNRAS.

The composition of relativistic outflows producing gamma-ray bursts is a long standing open question. One of the main arguments in favor of magnetically dominated outflows is the absence of photospheric component in their broadband time resolved spectra, with such notable examples as GRB 080916C. Here we perform accurate analysis of time resolved spectra of this GRB and confirm the previous detection of additional spectral component in GRB 080916C. We show that this subdominant component is consistent with the photosphere of ultrarelativistic baryonic outflow, deep in the coasting regime. We argue that, contrary to previous statements, the magnetic dominance is not required for interpretation of observations of this GRB. Moreover, simultaneous detection of high energy emission in its prompt phase requires departure from a simple one-zone emission model.

4.1 Invited talks at international conferences

1. “Diffusive photospheres in gamma-ray bursts”, 16th Marcel Grossman Meeting, July 5, 2021, online.

2. “Kinetic effects in nonequilibrium electron-positron plasmas”, 107 SIF National Congress, 13-17 September 2021, online.

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