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Radiative properties of pair-plasma in accretion disc around black holes

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Abstract. We study the equilibrium properties of thermal pair plasma in the accretion disc around black hole. We mostly concentrate on the properties of the radiation dominated pair plasma and have calculated the electron density profile along the disc under the pair equilibrium condition. The radiation spectrum from the disc shows significant high energy contribution due to the presence of pair in such conditions.

Keywords : black hole physics – accretion – plasmas – radiation mechanisms: thermal

1. Introduction

Study of the properties of pair plasma has been shown of immense astrophysical importance over last several decades. The observations towards active galactic nuclei (AGNs), gamma ray bursts (GRBs), quasars etc. indicate the existence of semi-relativistic to relativistic plasma. In such a plasma, pairs related physical processes are unavoidable. The properties of static thermal plasma in pair equilibrium was studied in 80's by several authors (Svensson 1982; Lightman 1982; Svensson 1984). Bjornsson and Svensson (1990) tried to explain the AGNs variabilities using instabilities in pair plasma. Kusunose and Takahara (1985) included the effect of magnetic filed and Svensson (1987) studied the effect of non thermal processes in a static spherical cloud.

In this paper, we attempt to apply pair equilibrium plasma properties in an accretion disc close to compact objects. This can change the spectral characteristic of the radiation spectrum from accretion disc. Also other motivation toward this study is that the composition of the pair-plasma, in particular composition of the astrophysical jets can be self-consistently calculated from the accretion solution. Also the nature

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of the annihilation line in the systems like GRBs, AGNs etc. can be understood. In the next two sections, we describe the radiation processes, and pair-equilibrium in a static thermal plasma. Finally, we present the application onto an accretion disc and conclusion respectively.

2. Radiation processes and pair production

We consider a thermal plasma at temperature T ($\theta = kTm_e^{-1}c^{-2}$, where k is Boltzmann constant, m_e is mass of electron and c is speed of light). We assume that the medium is optically thin under Thomson scattering and the typical plasma electron temperature is $\sim 10^8 - 10^{10}$K. In this temperature range, plasma consists of electrons (e), protons (p) and positrons (e^+). Hence, the charge neutrality condition is $n_e = n_p + n_{e^+}$, where n_i represents the number density of particles with $i = e, e^+$ and p. In absence of magnetic field, the major sources of radiations are due to bremsstrahlung and ee^+ pair annihilation. We have considered the following pair production and annihilation processes in this paper:

1. Photon-photon ($\gamma\gamma$) pair production: $\gamma + \gamma \rightarrow e + e^+$;
2. Photon-particle pair production:
   photon-electron/positron (γe & γe^+) pair production:
   $\gamma + e \rightarrow e + e^+ + e$;
   photon-proton (γp) pair production: $\gamma + p \rightarrow e + e^+ + p$;
3. Particle-particle pair production:
   proton-electron/positron (pe & pe^+) pair production:
   $p + e \rightarrow e + e^+ + p + e$;
   electron-electron (ee & e^+e^+) pair production:
   $e + e \rightarrow e + e^+ + e + e$;
4. electron-positron (ee^+) pair annihilation: $e + e^+ \rightarrow \gamma + \gamma$;

The $\gamma\gamma$ interactions involve photons from 4 different processes ($\gamma_A, \gamma_{ep}, \gamma_{ee}$ and γ_{ee^+}) with a total of 16 terms, where 'A' represents annihilation. Similarly photon-particle interactions provide 8 terms and the same for particle-particle interactions contain 2 terms. Hence, pair production processes consists of 26 terms which need to be balanced with pair annihilation to get a pair equilibrium solution.

3. Pair balance in spherical plasma

We consider an optically thin spherical plasma of constant temperature and proton number density. In presence of pair processes the electron and positron densities are not constant and hence we characterize the plasma via proton density or through a

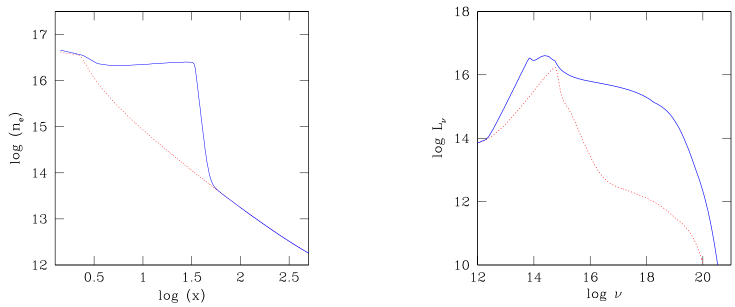

Figure 1. Left Panel: Density profile with radial distance (x) in absence of pair-production (red-dotted) and in presence of pair-equilibrium (blue-solid). Right Panel: A general representation of the radiation spectrum corresponds to the density profile (left panel) in presence (solid-blue) and absence (red-dotted) of pair production.

characteristic optical depth $\tau_p = n_p \sigma_T R$, where σ_T is Thomson cross-section, R is the size of the cloud. We define a dimensionless positron density z (=n_{e^+}/n_p) and electron Thomson depth can be expressed as $\tau_T = (1 + 2z)\tau_p$. We have taken care the spatial diffusion of photons by simply including the prolonged pathway of photons before escaping with time scale $t_c = \frac{R}{c}(1 + \tau_T)$ (Rybicki and Lightman 1979). Finally, we express the pair production rate in terms of τ_p, z, t_c and spectral emissivity (Svensson 1982). Initially we assume that electron number density is same as proton number density and we need to solve the pair balance equation $\dot{z} = \dot{z}_P - \dot{z}_A$, where $\dot{z}_P$ is the rate of pair production and $\dot{z}_A$ is the rate of pair annihilation, to calculate the electron density $n_e = (1 + z)n_p$ under pair equilibrium. For a given value of τ_p, there are two branches of solutions (Svensson 1982), one for particle dominated pair production balancing the annihilation (lower branch) and the other due to photon dominated pair production balancing the annihilation (higher branch). We are interested to study the pair properties in radiation dominated situation and have consider only the higher branch of the solution in this paper.

4. Radiation spectrum from accretion disc in pair-equilibrium

We consider an accretion disc around a 10 $M_\odot$ black hole. We define the radial coordinate x in units of $\frac{2GM}{c^2}$, where G is gravitational constant, M is mass of the black hole and c is speed of light. The angular momentum distribution in the accretion disc is assumed to be sub-Keplerian. We consider a radial flow and solve the steady state hydrodynamic equations (Das 2007) in the accretion disc for a given set boundary values. The solution provides radial distribution of temperature and density in the disc. The hydrodynamic solutions are considered in absence of pair-production/annihilation but we have taken into account the heating (Coulomb coupling) and cooling (bremsstrahlung) for electrons. We solve the pair balance equation in every annuli of the disc with the initial electron density and temperature to calculate the electron density under pair balance. Such a solution is shown in the left panel of Fig. 1 for accretion rate 0.017 (Eddington rate). The red-dotted line represents the initial hydrodynamic solution whereas blue-solid line is the electron density under pair balance. As we have mentioned earlier that we are interested to study the pair properties under radiation dominated situation and hence we consider the higher branch of the solution. We see that far away from the central object pair contribution is negligible and central part is pair dominated. In Fig. 1, right panel shows the radiation spectrum (Mandal and Chakrabarti 2008) from the accretion disc corresponds to the solution shown in the left panel. Here, we have included the Comptonization effects as well just to represent the enhanced effect of pair contribution in the spectrum. The integrated radiation spectrum in the disc without pair contribution is shown by red-dotted line whereas blue-solid line shows the spectrum in pair equilibrium. The spectra clearly indicate that pair contribution in high energy part which is coming from the central region of the disc is dramatic and this can change the observed luminosity significantly.

5. Conclusion

Study of pair production and annihilation is important to understand the high energy contribution in the radiation spectrum from the accretion disc. Plasma in pair balance may help to understand the physics of steady production of jet and the acceleration of the jet around compact object. But Pair balance throughout the entire disc may not always possible, rather it is limited to a range of temperatures and this may leads to instability in plasma. In this paper, we have put our attention only towards pair equilibrium plasma and calculate the radiation spectrum. Of course, our calculation is not completely self-consistent because we did not include the pair-balance in hydrodynamics which may suppress the high energy part of the spectrum. This work is under investigation and will be published elsewhere in future.

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