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INSTABILITY OF TWO-TEMPERATURE ACCRETION DISK ASSOCIATED WITH COPIOUS PAIR PRODUCTION

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1. Introduction

During the last decade the X-ray source Cyg X-1 is considered as a most likely candidate for a black hole. The crucial arguments for such a hypothesis are rapid time-variability of compact X-ray source and the mass estimate $M \sim 10\, M_{\odot}$ of invisible component of binary system, which is too large for any compact object, except for black hole. The traditional point is that X-rays are produced in the hot accretion plasma surrounding the black hole. The models suggesting a disk accretion are studied most extensively, although the alternative models of unsteady spherical accretion cannot be certainly ruled out (for review, see [2]).

The X-ray source Cyg X-1, assuming distance to the source 2.5 kpc, varies in the limits $3 \cdot 10^{37} - 10^{38}$ erg/s with essential part of luminosity in hard X-rays ($E \gtrsim 50$ keV). Thus in any model of Cyg X-1 containing black hole the accreting plasma should have a temperature more than $5 \cdot 10^{8}$ K.

When the "standard disk" models [3-5] were found as incapable to explain the hard tail of observed X-rays from Cyg X-1, a new modified accretion models were constructed [6-8].

Shapiro, Lightman and Eardley [1] (hereafter SLE) calculated a model of two-temperature disk in which the electron and ion temperatures of plasma in the inner, optically thin region of disk are essentially different. The main result of the model is that the Comptonization of soft photons in the inner, hot region of disk satisfactorily explains the observed hard X-ray spectrum of Cyg X-1. The second important consequence of two-temperature disk model consists in the formation of high ion temperature $T_i \sim 10^{12}$ K, which leads to intense gamma-ray production directly from hot proton-proton interactions $p + p \rightarrow \pi^\circ + \cdots$, $\pi^\circ \rightarrow 2\gamma$ [9] as well as via Penrose process in the ergospheres of massive extreme Kerr black holes [10], widely discussed as the prime energy source of active galactic nuclei.

In this paper we have reexamined the two-temperature disk model of SLE. The revision includes: i) the calculation of disk parameters on the basis of the self-consistent theory of magnetohydrodynamic turbulence [11] instead of standard disk model, providing to dominate the uncertainty associated with magnitude of parameter α characterizing viscosity; ii) the application of correct expression for energy balance between electrons and protons in hot electron plasma as a result of Coulomb interactions.

The calculations indicate a marked discrepancy with SLE disk parameters: a) rather different radius dependence of the parameters; b) higher electron temperature and Thompson scattering depth larger than those obtained by SLE. The high electron temperature $T_e \sim (1\text{-}4) \times 10^9$ K and large scattering depth $\tau_{es} \sim 2 \div 3$, obtained for accretion parameters characterizing Cyg X-1 ($M \sim 10 M_\odot$, $\dot{M} \sim 10^{17}$ g/s) are critical and may lead to instability of disk associated with copious (e^+e^-) pairs production due to $\gamma + \gamma \rightarrow e^+ + e^-$ interactions of comptonized hard photons. Thus the accretion disk may turn out a powerful source of positrons.

2. Basic Parameters of Two-Temperature Disk

The vertical structure of accreting disk with density ρ and halfthickness h , neglecting self-gravitation (i.e. in the approximation $h/r \ll 1$), is defined from the equation of hydrostatic equilibrium

$$\frac{dP}{dh} = -\rho \frac{GM}{r^2} \frac{h}{r} . \tag{1}$$

Gas movement in the disk is described by the equation (e.g. [5])

$$J \dot{M} r V_\varphi = -2\pi r^2 W_{r\varphi} , \tag{2}$$

where $J = (1 - 3r_g/r)^{1/2}$, V_φ is Keplerian velocity and $W_{r\varphi}$ expressed through viscocity is

$$W_{r\varphi} = \int_{-h}^{h} P_{r\varphi} dz \tag{3a}$$

The theory of magnetohydrodynamic turbulence for plasma is the accretion disk developed by Ichimaru [11] allows to define $P_{r\varphi}$:

$$P_{r\varphi} = \left(\frac{2}{\pi}\right)^{3/2} \frac{\rho_r}{2} \left(\frac{\kappa T_i}{m_p}\right)^{1/2} z \frac{d\Omega}{dr} , \tag{3b}$$

where Ω is the angular velocity.

Following SLE we admit that the gas pressure exceeds the radiation one and thus the pressure in the disk is

$$P = \frac{\rho}{m_p} \kappa (T_i + T_e) ,$$

where T_i and T_e are ion and electron temperatures, respectively. Hereafter we limit our consideration with pure hydrogen plasma only.

In the case of polytropic disk with index n = 3 Eq.(3a) might be written in the form [12]

$$W_{r\varphi} \simeq 10 \left(\frac{2}{\pi}\right)^{1/2} \left(\frac{GM}{r^3}\right)^{-1/2} P \frac{hr}{2} \frac{d\Omega}{dr} . \tag{3c}$$

The two additional equations together with Eqs.(1)-(3) determining the disk structure are energy balance equations for protons and electrons.

In the case of nonrotating black hole the maximum proton energy is determined by the gravitational binding energy of a proton in the inner edge of the disk

$$E_{max} \sim \frac{1}{6} m_p c^2 \sim 120\, MeV,$$

hence we may consider protons in the disk as nonrelativistic without any noticeable error. On the other hand, the electrons depending on physical conditions may turn out nonrelativistic as well as relativistic. Therefore in the inner region of disk the proton cooling rate due to proton-electron Coulomb collisions may be correctly described by expression (e.g. [13])

$$\frac{d\varepsilon_{ei}}{dt} = \frac{4\pi r_0^2\, mc^3\, \Lambda}{(2kT_i/m_p c^2)^{1/2}}\, S\left(\sqrt{\frac{m_e}{m_p}\,\frac{T_i}{T_e}}\right) \tag{4}$$

where

$$S(x) = \psi(x) - x\,\psi'(x)$$

and $\psi(x)$ is the error function, r_0 is the elctron classical radius, Λ is the Coulomb logarithm.

The Coulomb cooling rate of protons must be equal to disk heating due to viscous dissipation. Therefore the energy balance equation for protons is

$$\frac{d\varepsilon_{ei}}{dt} = \left(\frac{3}{8\pi}\,\frac{GM\dot{M}}{r^3}\right)\frac{J}{h} \tag{5}$$

The last equation determining the disk structure is the equation of energy balance for electrons: the heating rate of electrons due to Coulomb (p-e) collisions be equal to radiation cooling rate. Following SLE on the possible solutions of disk accretion plasma instabilities are assumed absent and the electrons cool dominantly by unsaturated Comptonization. In this case we have

$$\left(\frac{3}{8\pi}\ \frac{GM\dot{M}}{r^3}\right)J = \frac{4\kappa T_e}{m_e c^2}\,\tau_{es}\,U_r\,c \tag{6}$$

or

$$4\left(\frac{\kappa T_e}{m_e c^2}\right)\max\left(\tau_{es},\ \tau_{es}^2\right) = 1, \tag{7}$$

where photon density is $U_r = \left(\frac{3}{8\pi}\ \frac{GM\dot{M}}{r^3}\ \frac{J}{c}\right)\mathrm{Max}\left(1, \tau_{es}\right)$, and is the optical depth with respect to electron scattering.

From Eqs.(1)-(5) and (7) we obtain the main physical parameters of the disk near its inner edge:

$$T_i \simeq 6\cdot 10^{11}\,\dot{M}_o^{1/3}\,M_o^{1/6}\quad K \tag{8}$$

$$T_e \simeq 4\cdot 10^{9}\,\dot{M}_o^{-5/3}\,M_o^{-5/6}\quad K \tag{9}$$

$$h \simeq 2\cdot 10^{6}\,\dot{M}_o^{1/3}\,M_o^{-1/3}\quad cm \tag{10}$$

$$\rho \simeq 1.2\,10^{-6}\,\dot{M}_o^{1/2}\,M_o^{3/4}\quad g/cm^3 \tag{11}$$

$$\tau_{es} \simeq 3\cdot \dot{M}_o^{5/6}\,M_o^{5/12}\ . \tag{12}$$

Here we use the following normalization for the variables: black hole mass $M_o = M/10M_{\odot}$ and accretion rate $\dot{M}_o = \dot{M}/10^{17}\,gs^{-1}$.

The radius dependence of electron and ion temperatures, together with the density of the disk is shown in Fig.1. We see that the ion temperature is nearly constant. Note that solution by SLE give physically nonexplainable result, namely increasing with radius ion temperature. The other parameters differ, too.

It is easy to convince that for disk parameters (8)-(12) absorption depth of plasma $\tau_* = (\tau_{es}\ \tau_{ff})^{1/2} \ll 1$, and thus the disk is optically thin.

3. Photoproduction of Electron-Positron Pairs in the Two-Temperature Disk

In the previous section we have ensured that in the case of two-temperature disk-type accretion regime onto the black hole the electron plasma becomes very hot with temperature exceeding 10^9 K in the inner region of the disk.

The results obtained for self-consistent model of the disk with more accurate consideration of energy balance between electrons and protons sufficiently differ from those of SLE. As it was mentioned in Sec.2, the most important difference is the high temperature and large scattering depth of electron plasma. The importance of these results is not limited by quantitative arguments only. As it will be shown below, the electron plasma with temperature $T_e \gtrsim 10^9$ K and with Thompson optical depth $\tau_{es} > 1$ appears critical with respect to $(e^+ e^-)$ pair production and leads to instability of the disk. The photoproduction in the accretion disks was earlier discussed by Stoeger[14] and Liang[15].

The self-consistent solution (8)-(12) of equation system (1)-(7) was found under assumption that the main source of electron cooling is the unsaturated Comptonization. However, beginning from the temperatures $T_e \sim 10^9$ K the electron cooling via processes with production and subsequent annihilation of positrons become rather important. At subrelativistic temperatures of the electron plasma the photoproduction $\gamma + \gamma \to e^+ + e^-$ is the main source of positrons.

At higher temperatures ($kT_e \gg m_e c^2$) the reactions of pair production by (e-e) and (e-p) collisions have remarkable contribution, too. Positrons are generated in inelastic nuclear collisions of hot ions as well, especially in the interactions of protons and α -particles with CNO group nuclei (1 MeV $\leq \kappa T_i \leq$ 100 MeV) and in inelastic (p-p) and (p-α) π -meson production at higher temperatures ($\kappa T_i \gtrsim$ 100 MeV).

The main process of generating high energy photons associated with plasma electron component is the Comptonization of low frequency photons. The spectrum of escaping radiation depends on electron scattering depth τ_{es} and temperature T_e of plasma only and is described by the following expression [16]

$$\phi_{\tau_{es},\kappa T}(\omega) \sim \frac{x^2}{\kappa T_e} e^{-x/2} W_{2,\sqrt{\frac{9}{4}+\gamma}}(x); \qquad (13)$$

$$x \equiv \frac{\omega}{\kappa T}; \qquad \gamma = \frac{\pi^2}{3\kappa T_e} \quad \frac{1}{(\tau_{es}+\frac{2}{3})^2}$$

where $W_{\lambda\mu}(x)$ is the Witteker function.

Function (13) characterizes the escaping radiation spectrum of plasma. The photon spectrum within the plasma generally varies from point to point depending on mutual disposition of the external low-frequency photon source and plasma configuration. Note, that the solution (13) derived from nonrelativistic transfer equation is correct for temperatures $\kappa T_e <$ 100 keV. However, Monte-Carlo calculations by Pozdnyakov et al. [17] show that at higher temperatures the behaviour of Comptonization spectrum does not vary essentially.

On the other hand, as it is seen from (8), the temperature depends on radius as well. Nevertheless, for qualitative estimations we suggest the radiation spectrum inside the disk being invariable and described by function (13).

Then the production rate of (e^+e^-) pairs by means of photoproduction process is

$$Q_{\gamma\gamma}(\tau_{es}, T_e) = \int \phi_{\tau_{es},T_e}(\omega)\, \phi_{\tau_{es},T_e}(\omega')\, \bar{\sigma}(\omega, \omega')\, d\omega\, d\omega', \tag{14}$$

where $\bar{\sigma}(\omega, \omega')$ is the photoproduction cross section averaged by all directions of interacting photons. For isotropic distribution of photons $\bar{\sigma}$ was obtained by Aharonian and Atoyan [18]. It depends on energies of colliding photons and has a maximum at $\omega\omega' = 3(mc^2)^2$. The rate of photoproduction for comptonized radiation spectrum (13) was calculated, too. The Table represents some results from that paper for a number of values of plasma temperatures and optical depths. Values presented in the Table are normalized so that the energy density of $\omega \gtrsim 0.1mc^2$ photons be $1\ erg/cm^3$, i.e.

$$u_{\gamma_1} = \int_{0.1mc^2}^{\infty} \omega\, \phi_{\tau_{es},T_e}(\omega)\, d\omega = 1\, \frac{erg}{cm^3}. \tag{15}$$

Then knowing or taking the luminosity of the disk L_γ in this energy band (i.e. more than $0.1\ mc^2$) it is easy to estimate the rate of (e^+e^-) pair production.

Let ℓ be the characteristic size of radiation region considered (of order of magnitude 10 rg).

Then the photon energy density is

$$u_\gamma \simeq \frac{L_\gamma}{V} \quad \frac{h}{c}(1+\tau_{es}) \sim \frac{L_\gamma}{2\pi\ell^2 c}(1+\tau_{es}), \tag{16}$$

and respectively

$$\nu_{\gamma\gamma} \equiv u_\gamma^2\, Q(\tau_{es}, T_e) \sim \frac{L_\gamma^2}{4\pi^2} \frac{(1+\tau_{es})^2}{\ell^4 c^2} Q_{\gamma\gamma}(\tau_{es}, T_e). \tag{17}$$

The (e^+e^-) pair annihilation rate is determined by density and temperature of plasma only

$$\nu_{e^+e^-} = n_+ n_- Q_{e^+e^-}(T_e) \tag{18}$$

The function $Q_{e^+e^-}(T_e)$ at $T_e > 10^7$ K is completely determined by free annihilation without preliminary formation of bound system-positronium. As the calculations of Aharonian et al.[19] show, $Q_{e^+e^-}(T_e)$ depends weakly on temperature up to $kT_e \sim \frac{1}{2} m_e c^2$ and by the order of magnitude equals to $\pi r_o^2 c$, hence, for electron temperature of interest

$$\nu_{e^+e^-} \simeq n_+ n_- \pi r_o^2 c \, .$$

From the condition of plasma neutrality we have

$$n_p = n_- - n_+ \tag{19}$$

where n_p is proton density.

From the stationarity condition assuming that there is no positron escape it follows that the pair production and annihilation rates must be equal to $\nu_{\gamma\gamma} = \nu_{e^+e^-}$, i.e.

$$\frac{L_\gamma^2}{4\pi^2} \frac{(1+\tau_{es})^2}{\ell^4 c^2} Q_{\gamma\gamma}(\tau_{es}, T_e) = \pi r_o^2 n_-(n_- - n_p). \tag{21}$$

Solving this equation with respect to n_- we have

$$n_-^2 - n_p n_- - \frac{L_\gamma^2 (1+\tau_{es})^2}{4\pi^2 \ell^4 c^3} \frac{Q_{\gamma\gamma}(\tau_{es}, T_e)}{\pi r_o^2} = 0 \tag{22a}$$

and

$$n_- = \frac{n_p + \sqrt{n_p^2 - 4G}}{2} \tag{22b}$$

Hence equation (22a) has solution if

$$n_p \gtrsim 2\, G^{1/2} \tag{23a}$$

where

$$G = \frac{L_\gamma^2}{4\pi^2} \frac{(1+\tau_{es})^2}{\ell^4 c^3} \frac{Q_{\gamma\gamma}(\tau_{es}, T_e)}{\pi r_0^2} . \tag{23b}$$

Using characteristic values of parameters $\tau_{es} \sim 3$, $T_e \sim 3 \cdot 10^9$ K, $\ell \sim 10^7$ cm from Eqs.(8), (10). (12) and the corresponding values of $Q_{\gamma\gamma}(\tau_{es}, T_e)$, taking luminosity $L \sim 10^{37}$ erg/s, we find the density $n_p \sim 10^{18}$ cm^{-3}, i.e. of the order exceeding that determined from (11). Evidently, the account of photons generated at the annihilation of pairs will still enhance this contradiction.

4. Discussion

From the results obtained above we conclude that the accretion disk wit parameters (8)-(12) following from the system of equations (1)-(7) cannot be stationary due to copious (e^+e^-) pair production. The instability may result in the following: the intense pair production and formation of nearly pure electron-positron plasma with a density

$$n_+ \simeq n_- \gtrsim G^{1/2}$$

will lead to fast cooling of the plasma due to photoproduction and annihila tion up to $T \lesssim 10^8$ K, after which these processes become ineffective. The returning to a stationary state may take place through a flare (as a result of annihilation) with luminosity maximum in the region of $\sim 1\ mc^2$. Due to thermal motion of electron-positron pairs the annihilation line undergoes ultraviolet shifting: $\Delta E \sim \alpha \kappa T_e$, where $\alpha \sim 1$ in a wide region of temperatures, besides, the line will have a strong broadening (e.g. at

$T_e \simeq 10^9$ K the width of the line is ~ 300 keV)[19, 20].

Besides this, for ion temperatures $T_i \sim 5 \cdot 10^{11}$ K from Eq.(8) many other nuclear gamma-ray lines generated in inelastic nuclear reactions should be expected[21, 22]. Evidently these lines will be strongly broadened due to high ion temperature. In the model we have obtained for pure hydrogen plasma we omit the discussion of contribution of these lines to the resulting spectrum. It is obvious that all these processes will make our arguments still more convinced.

On the basis of results obtained by Gurzadyan and Ozernoy[23] for characteristic evolution time scale of the disk we find

$$\tau \sim 5 \left(\frac{M}{10 M_\odot} \right)^{1,84} \left(\frac{\dot{M}}{10^{17} g s^{-1}} \right)^{-0.3} yr ,$$

which excludes fast (with a time scale shorter than the X-ray fluctuation ones for compact X-ray sources) recovery of the two-temperature disk described in Sec.2.

This instability can lead also to injection of a large number of positrons[24, 25]. We do not discuss the dynamics of this process , only noting that the positive charge of a black hole may essentially promote this injection. Thus an accreting disk around a black hole may appear an intense source of positrons. This possibility is of special interest associated with great difficulties in the explanation of the observed annihilation line from the centre of Galaxy[26].

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Tabl

T_e / τ_{es}	0.05	0.1	0.2	0.5	1
0.01	-	-	$6.3 \cdot 10^{4}$	$1.2 \cdot 10^{10}$	$1.3 \cdot 10^{12}$
1	$1.1 \cdot 10^{-2}$	$5.4 \cdot 10^{6}$	$7.4 \cdot 10^{10}$	$7.9 \cdot 10^{12}$	$9.9 \cdot 10^{12}$
10	$2.7 \cdot 10^{2}$	$4.5 \cdot 10^{9}$	$2.4 \cdot 10^{12}$	$1.5 \cdot 10^{13}$	$8.3 \cdot 10^{12}$

Photproduction rate $Q_{\gamma\gamma}$ for comptonized radiation obtained by Aharonian and Atoyan [18] in the units of $10^{-16}\ cm^{-3}\ sec^{-1}$. T_e is plasma temperature in mc^2, τ_{es} is electron scattering depth. Photon energy density is U = 1 erg/cm .

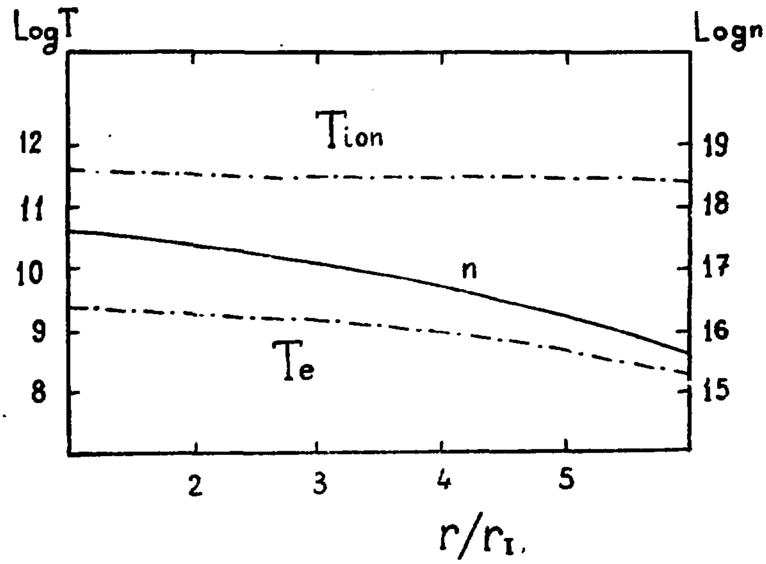

Figure. Density and ion and electron temperatures profiles in the emission zone for a black hole with $M = 10M_{\odot}$ and accretion rate $\dot{M} = 10^{17}\ gs^{-1}$.

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Ф.А. АГАРОНЯН, В.Г.ГУРЗАДЯН

НЕУСТОЙЧИВОСТЬ ДВУХТЕМПЕРАТУРНОГО АККРЕЦИОННОГО ДИСКА, СВЯЗАННАЯ С ОБИЛЬНЫМ РОЖДЕНИЕМ (e^-e^-) ПАР

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