PUBLICATIONS OF THE KOREAN ASTRONOMICAL SOCIETY
8: 265 ~ 272

ELECTRON-POSITRON PAIRS IN ACCRETION DISKS

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(Received Oct. 18, 1993)

ABSTRACT

Recent X-ray observations of the accretion disks in stellar black hole candidates have revealed rather complex behavior, which cannot be fully described by the simple picture of the standard disk model. In this paper, therefore, we discuss the effects of e+e− pair creation on the structure and the stability of hot accretion disks, aiming at the thorough understanding of emission properties of X-ray binaries containing black holes.

I. INTRODUCTION

Although it still remains a puzzle if there exist black holes in the universe, there are already plenty of black hole candidates so far known, including Cyg X-1, LMC X-3, and A0620-00. Moreover, the number of black hole candidates has remarkably increased recently owing to the successive discovery of the so-called black-hole X-ray novae by the japanese Ginga satellite (see Tanaka 1992). In Table 1, we list some stellar black-hole candidates. Here HMXB, LMXB, and XN stand for high-mass X-ray binary, low-mass X-ray binary, and (soft) X-ray nova, respectively. (High and low mass refer to the mass of the mass-losing normal stellar companion.

These stellar black-hole candidates have several common features: substantial high-energy (> 100 keV) emission and rapid X-ray variations as short as 1 ms(flickering). In addition, spectral changes between two distinct states are observed in some candidates, such as Cyg X-1. In the soft state (or the high state),

Table 1 : Stellar Black Hole Candidates

Star	Classifications	Comments
Cyg X-1	HMXB	soft-hard transition
GX 339-4	HMXB	soft-hard transition
LMC X-1	LMXB	soft state only
LMC X-3	LMXB	soft state only
A0620-00	XN (1918, 1975)	soft state only
GS1354-64	XN (1987)	soft state only
GS2000+25	XN (1988)	soft state only
GS1826-24	XN (1988)	hard state only
GS2023+338 (V 404 Cyg)	XN (1932, 1989)	hard state only
GS1124-68 (Nova Musca)	XN (1991)	soft-hard transition + 511 keV line
SS433	???	relativistic jet
1E1740.7-2942	?	511 keV source

a black-body component with kT $\sim$ 1 keV is dominant, while in the hard state (or the low state), the spectra are of a power-law type. Here we try to understand such emission properties of high-energy photons from stellar-mass black hole systems in terms of $e^{+}e^{-}$ creation. In next section, we summarize our knowledges on the thermal equilibrium structure of hot accretion disks, and in section 3, we present a new model for the composite disk-corona structure.

II. OPTICALLY THIN, HOT ACCRETION DISKS AND CORONAE

1. Spectral Transition and Origin of Hard X-Rays

We begin our investigation by asking one question; where and how hard X-rays (or power-law spectra) are generated in X-ray binaries. Soft X-rays may be produced in optically thick disks, but they are too cool to generate hard X-rays or γ-rays. Alternatively, two possibilities have been discussed (see Liang and Nolan 1984): two-temperature, optically thin disks (or tori) by Shapiro, Lightman, and Eardley(1976), and accretion disk coronae. However, no matter which may be the case, the stability is a big problem as we will see below. We need optically thin portions of the disks which are hot enough to produce hard X-rays in a quasi-stable fashion, but which, at the same time, should produce rapid X-ray variations on timescales of $\leq$ sec.

In optically thin disks or coronae, the following processes need to be considered. First, the radiation field cannot be a black-body, which was explicitly assumed in the standard model. Especially when the Compton parameter of a plasma is large, $y_C \equiv 4kT_e/(m_ec^2) \cdot \mathrm{Max}(\tau_{es}, \tau^2_{es}) > 1$, inverse Compton scattering is essential when calculating emergent spectra (Rybicki and Lightman 1979). Secondly, hot and low density plasmas may be in a two-temperature state with the electron temperature less than the proton temperature, $T_p > T_e$, by a few orders of magnitude, if coupling between electrons and ions is only through Coulomb collisions. Finally, since the cooling of the plasma is quite inefficient compared with that of optically thick disks, plasma temperatures (both T_e and T_p) can be increased, leading to the electron temperature as high as electron rest-mass energy, i.e., $kT_e \sim 511$keV. Then the influence of e^+e^- pair production cannot be ignored. The presence of magnetic fields in the very hot plasma will also substantially affect the emissivity and stability.

In the following, we briefly see some of these effects, which were neglected in the standard model. We still neglect the effects of magnetic fields and regard the physical picture sketched here as a prelude to adding that complication.

2 Thermal Equilibrium Curves of Hot Disks

The thermal equilibrium solutions are obtained by equating the cooling rate due to bremsstrahlung/Compton cooling with the viscous heating rate, when we assume the hydrostatic balance in the direction perpendicuar to the disk plane and adopt the α viscosity for the $r\phi$ component of the shear-stress tensor (Shakura and Sunyaev 1973). In what follows, we see the influence of the high energy processes on the equilibrium structure.

When α is small, e.g., $\alpha < 0.1$, most part of the standard disk solution lies in the region where effective optical thickness, τ_*, is greater than unity. In such a case the effect of Compton scattering is small. However, when α is large, this is not the case. Most part of the radiation pressure-dominated branch has large values of the Compton parameter and small values of τ_*. The relation between the surface density, Σ, and $\dot{M}$ or T_c, of such disks is depicted in Fig. 1 by a line (dot - dash) labeled with MSS (modified Shakura-Sunyaev). Parameters are $M = 10M_\odot$, $\alpha = 1.0$, and $r = 5r_s$.

At higher temperatures, the disk plasma could be in a two-temperature state. We first illustrates the two-temperature solutions for the case without e^+e^-pairs by the short-dashed line (with a label NPR) in Fig. 1. The 2-T optically thin solutions connect the 1-T P_{rad} dominated branch and the 1-T optically thin P_{gas} dominated branch. We also depict the solutions with pairs by the solid line (labeled by PR) in

Fig. 1. It is clear in this figure that the equilibrium curves are substantially modified by the presence of e+e-pair production. Three pair-equilibrium solutions are found for a fixed value of Σ in the range $0.6 \le \Sigma \le 6.0$ (g cm^{-2}).

Here, we must emphasize that, when pair production is substantial the two-dimensional (Σ,T) plane is not sufficient to understand the physics; we need one more axis, the z (pair density ratio) axis. In fact, the right panel of Fig. 1 corresponds to the projection of the pair-thermal equilibrium solutions in the (Σ,T,z) space onto the (Σ,T) plane. To see this situation clearly, it is helpful to display the two equilibrium lines in the (T_p, z)plane for a fixed value of Σ. In Fig. 2, the thermal equilibrium curve is indicated by the dashed line, and the pair equilibrium curve by the solid line at Σ = 6.0 g cm^{-2} and $\gamma = 5\gamma_s$. We find three pair-thermal equilibrium solutions, corresponding to three pair dominated branches in Fig. 1.

Note that for solutions with e+e-pairs, the critical accretion rate should be reduced by a factor of 1 + 2z (see Lightman and Zdziarski 1987). The accretion rate then easily exceeds this limit on most of the PR branch, leading to the formation of e+e-jets or winds, unless strong Coulomb force by protons prevents pair escape. So far, we restricted our studies on disk plasmas in hydrostatic balance, but certainly there is a possibility that coronal plasmas are out of hydrostatic balance.

3. Stability

It is widely known (e.g., Pringle, Rees, and Pacholczyk 1973) that all the optically thin branches are thermally unstable (in the absence of pair production). We need to check if this is still the case even with abundant pair generation. The stability analysis of the 2-T, pair dominated branch is rather complicated, because the proton thermal timescales can be comparable to the timescales for the pair creation or annihilation (Bjornsson and Svensson 1991) at $kT_e \sim 0.1 m_e c^2$. We thus need to discuss the pair and the thermal instabilities simultaneously. That is, the thermal instability may trigger the pair instability, and vice versa.

The physical reasons are obvious; since cooling of the plasma depends on the number of pairs, the cooling rate is sensitive to the pair generation/annihilation rates, while the pair creation rate is a function of the photon density which is sensitive to the plasma cooling rate.

The time development of the disk plasma basically follows two equations,

$$\frac{\partial T_p}{\partial t} \propto Q_p^{+} - Q_p^{-} \tag{1}$$

and

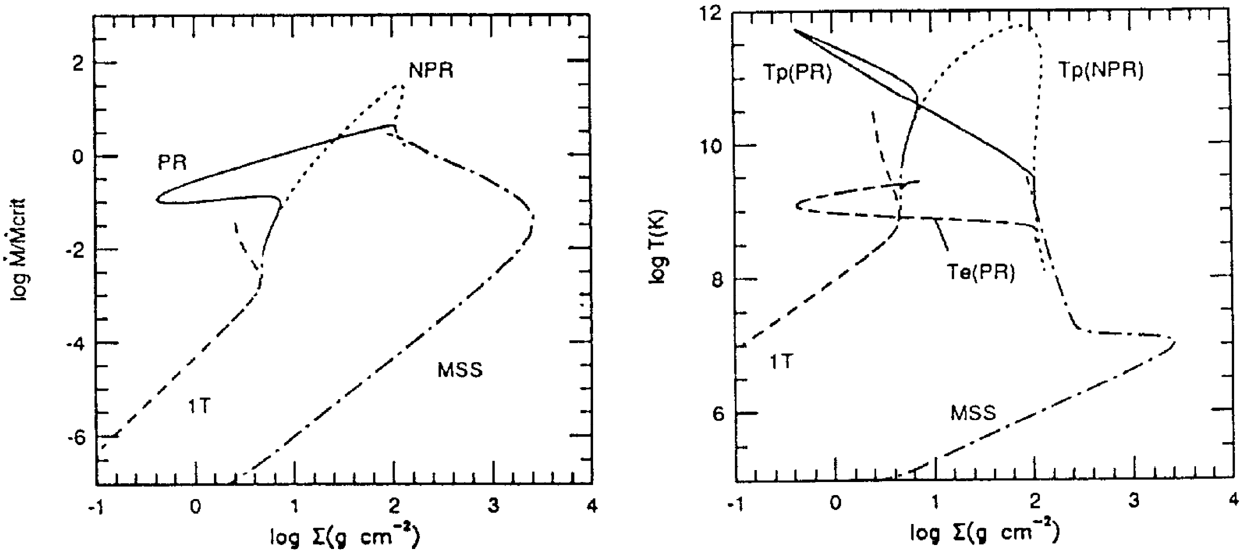

Fig. 1. Complete network of thermal equilibrium curves of hot disks in the (Σ, $\dot{M}$) plane (left) and in the (Σ, T) plane (right) taken from Kusunose and Mineshige (1992). Parameters are $M = 10\ M_\odot$, $\alpha = 1$, and $r = 5\ r_s$. MSS (dash-dot line) represents the modified Shakura-Sunyaev solution, 1T (long-dashed line) is the optically thin, one temperature solution, PR (solid line) and NPR (short-dashed line) are the optically thin, two-temperature solution with and without pairs, respectively.

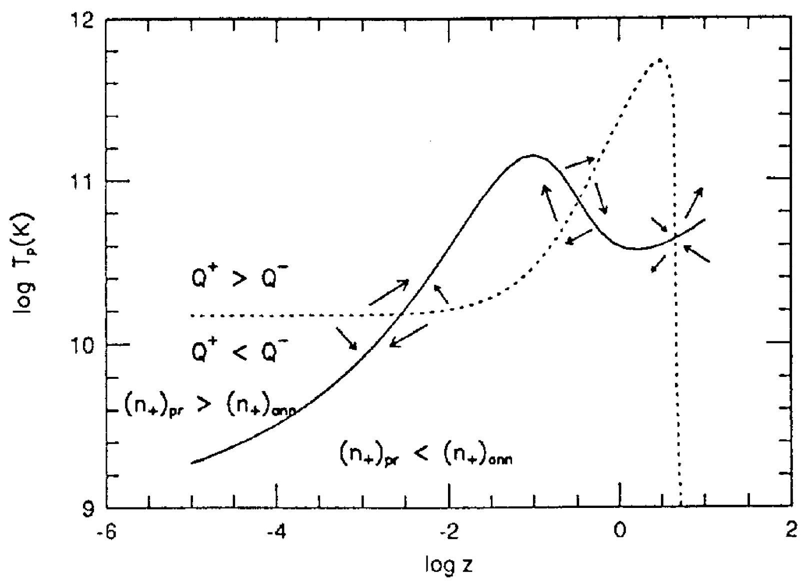

Fig. 2. The pair equilibrium curve (solid line) and the thermal equiibrium curve (dashed line) in two-temperature disks at $\Sigma = 6.0$ g cm^{-2} and $r = 5\ r_s$ (from Kusunose and Mineshige 1992)

$$\frac{\partial z}{\partial t} \propto (\dot{n}_+)_{pr} - (\dot{n}_+)_{ann} \qquad (2)$$

where Q_p^+ and Q_p^- are the proton heating rate and cooling rate, respectively, z is the positron number density devided by the proton number density, and $(\dot{n}_+)_{pr}$ and $(\dot{n}_+)_{ann}$ are the pair production and annihilation rates, respectively. The arrows in Fig. 2 indicate the expected evolutionary direction of the plasmw; for example, in the region where $Q_p^+ > Q_p^-$ and $(\dot{n}_+)_{pr} > (\dot{n}_+)_{ann}$, both of T_p and z should increase (cf. Eq. 1 and 2), so the evolutionary paths should be upward (towards the region of large T_p) and rightward (towards the region of high z). We then find a possibility for a limitcycle behavior around the second solution (cf. Moskalik and Sikora 1986). Suppose the disk is in thermal balance but in pair imbalance near the second solution. Since the pair generation rate is greater (or less) than the pair annihilation rate, numerous numbers of pairs are being generated (annihilated). The number of coolants (i.e.,pairs) then rapidly increases (decreases), causing a rapid increase (decrease) in the cooling rate. This in turn leads to a thermal imbalance; the temperature of the protons decreases (increases) rapidly. Fewer (more) bremsstrahlung photons will be generated, which in turn decreases (increases) the pair production rate. This limit cycle behavior is suggested to cause rapid X-ray variabilities in black-hole candidates (Kusunose and Mineshige 1991).

Through this analysis, we assumed no variation in Σ, which may not be the case. Possibilities to have pair winds or jets should also be taken into account. Further investigation is required towards thorough understanding of global, time-dependent developments of the instabilities (cf. White and Lightman 1990).

3. A Composite Model for Disk-Corona Systems

In section 2, we obtained solutions for geometrically thin disks with α -viscosity,assuming the stress tensor is proportional to the total pressure. There appear a variety of branches, depending on whether the disk is optically thick or thin, whether Compton scattering is appreciable or not, and whether e^+e^--pair production is substantial or not. These branches form a network of solutions. The lower portions of the optically thin branch and the optically thick branch are smoothly connected through a branch of neutral hydrogen (Mineshige and Wood 1990). We see the remarkable influence of the various physical mechanisms which were not considered in the standard model.

It seems that the black-body (soft)spectra of black-hole candidates are generated in the optically thick part of the disk (main body), while the power-law(hard) spectra are formed in the optically thin part of the disk (disk coronae). If the fraction f of the total energy release by the mass accretion flow goes to the main body, then the remaining fraction $(1-f)$ should be dissipated in the disk coronae (cf. Haardt and Maraschi 1991). The fraction f is then a key factor to determine the spectral state, but at present we have no conclusive ideas how to change f during the soft-hard spectral transition. Obviously, the mass-flow rate cannot solely determine f, because some X-ray novae stay in the soft state in which f=1, even when the X-ray luminosity decreases by more than four orders of magnitude, while other novae are in the hard state in which f=0 throughout the decay.

Finally, we construct a composite model for the disk-corona structure, by combining an optically thick solution and an optically thin solution with the same pressure and α. The total surface density is calculated as

$$\Sigma = \Sigma(\text{opt. thin}) + \Sigma(\text{opt. thick}) \approx \Sigma(\text{opt. thick}), \tag{3}$$

whereas the mass accretion rate is given by

$$\dot{M} = \dot{M}(\text{opt. thin}) + \dot{M}(\text{opt. thick}) \approx \dot{M}(\text{opt. thin}) \tag{4}$$

By changing the value of pressure, we successively obtain one sequence of the equilibrium solutions in the $(\Sigma, \dot{M})$plane, illustrated in Fig. 3.

We now find three solutions which give the same disk luminosity, corresponding to the three solutions which give the same disk luminosity, corresponding to the three pair-dominated branches in Fig. 1. The middle branch is quasi-stable in the sense of limit-cycle behavior. The disk-corona system on this branch will give rise to persistent power-law spectra (f<<1) via inverse-Compton scattering of soft photons in the corona. The other branches are, on the other hand, thermally unstable. The disk-corona systems on these branches will either blow up to form a jet because of heating instability or shrink and cool down to merge with the cool main body, giving rise to the soft, black body spectra ($f \sim 1$). We therefore suggest that these branches may in this way be related to the distinct spectral behavior observed in black hole candidates. To make a more realistic model for disk coronae, however, nonthermal processes should be considered. Future work should investigate the role of winds, advective cooling, and magnetic fields as well.

The author (S.M.) acknowledges Professors C.H.Kim, K.T.Kim, and other stuff members of Chungnum University for the hopitalities during his stay in Korea. He is also greatful to the Korean Astronomical Society for support.

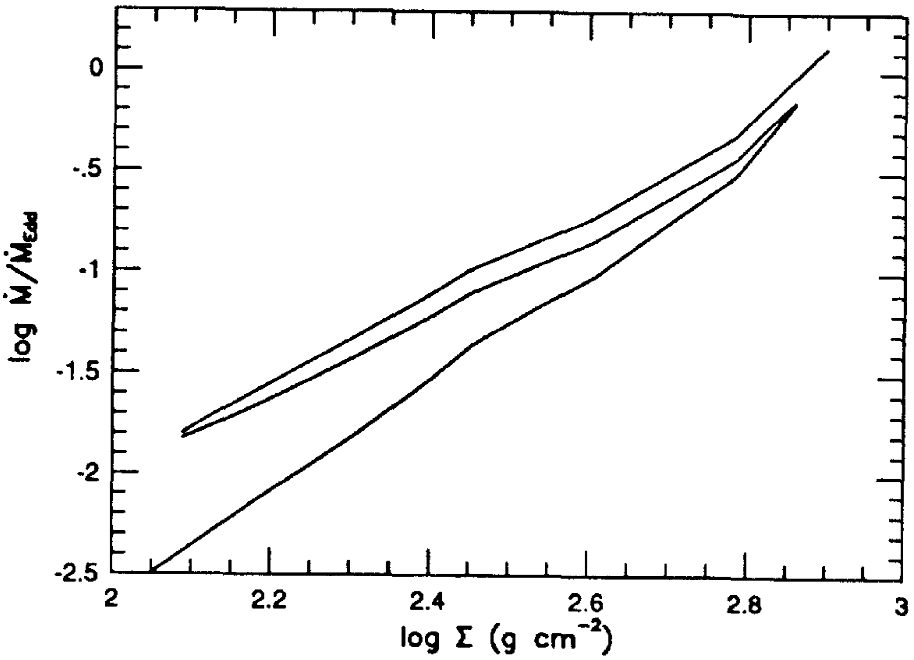

Fig. 3. Same as Fig. 1 but for the composite disk-corona model. Parameters are $M = 10M_\odot$, $\alpha = 1$, and $r = 5\ r_s$.

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