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THERMAL STRUCTURE AND RADIATION SPECTRA OF PHOTOIONIZED GAS IN ACCRETION-POWERED X-RAY SOURCES

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RESUMEN

Se estudia el gas irradiado por rayos-X que circunda a un objeto colapsado. Obtenemos la estructura de la región de emisión ópticamente delgada resolviendo el equilibrio hidrostático acoplado con balance térmico y de ionización.

ABSTRACT

The X-ray irradiated gas around a compact object was investigated. We solved the hydrostatic balance coupling with the ionization and thermal balances to obtain the structure of the optically thin emission region.

Key Words: **ACCRETION — RADIATION MECHANISMS: THERMAL — X-RAYS: GENERAL — X-RAYS: STARS**

1. INTRODUCTION

ASCA has observed emission lines from several X-ray binaries. The line emitting gas must be strongly irradiated by UV and X-rays from the central source to be highly ionized, yet its temperature is relatively low. Therefore, the gas becomes recombining and should have very different thermal properties from the collisionally ionized hot gas. Irradiation also affects the geometrical structure of the emission region. The region is likely quasi-hydrostatic, bound gravitationally against its thermal pressure affected by irradiation, off the optically thick accretion disk. Modelling a disk-fed system, we have carried out the calculations of the thermal and geometrical structures consistently for the gas around a compact object.

2. MODEL

We consider the gas over a geometrically thin and optically thick accretion disk about a compact object. The gas is photoionized by the primary radiation from the compact object and/or the innermost part of the disk, but must be optically thin for the secondary photons born in the gas. The thermal structure of the gas depends on the spectrum as well as the number of ionizing photons. We assume a spectrum in the form

$$\frac{dL}{d\nu}d\nu \propto \nu^{-\gamma} e^{-h\nu/kT_r} \nu d\nu \ , \tag{1}$$

for a point central source; the inner radius of the disk is small enough compared to the emission region concerned here. The ionization structure of the gas can be scaled with a parameter

$$\xi \equiv \frac{\mu m L}{\rho R^2} \ , \tag{2}$$

which is the ratio of the ionizing flux $\sim L/R^2$, at the distance R from the source, to the gas number density $\rho/\mu m$. This is a useful parameter if the local cooling time $t_{cool} \propto T/\Lambda$ is shorter than the crossing time H/c_s, where T is the gas temperature, Λ is the radiative cooling rate per density, and H and c_s are the scale height and the sound speed, respectively, of the gas. Since $t_{cool} > H/c_s$ for most of the region of gas, the gas should have a pressure-constant structure and ξ is no longer a good parameter. Instead, introducing another parameter

$$\Xi \equiv \frac{L}{4\pi c R^2 P} = \frac{\xi}{4\pi c k T} \ , \tag{3}$$

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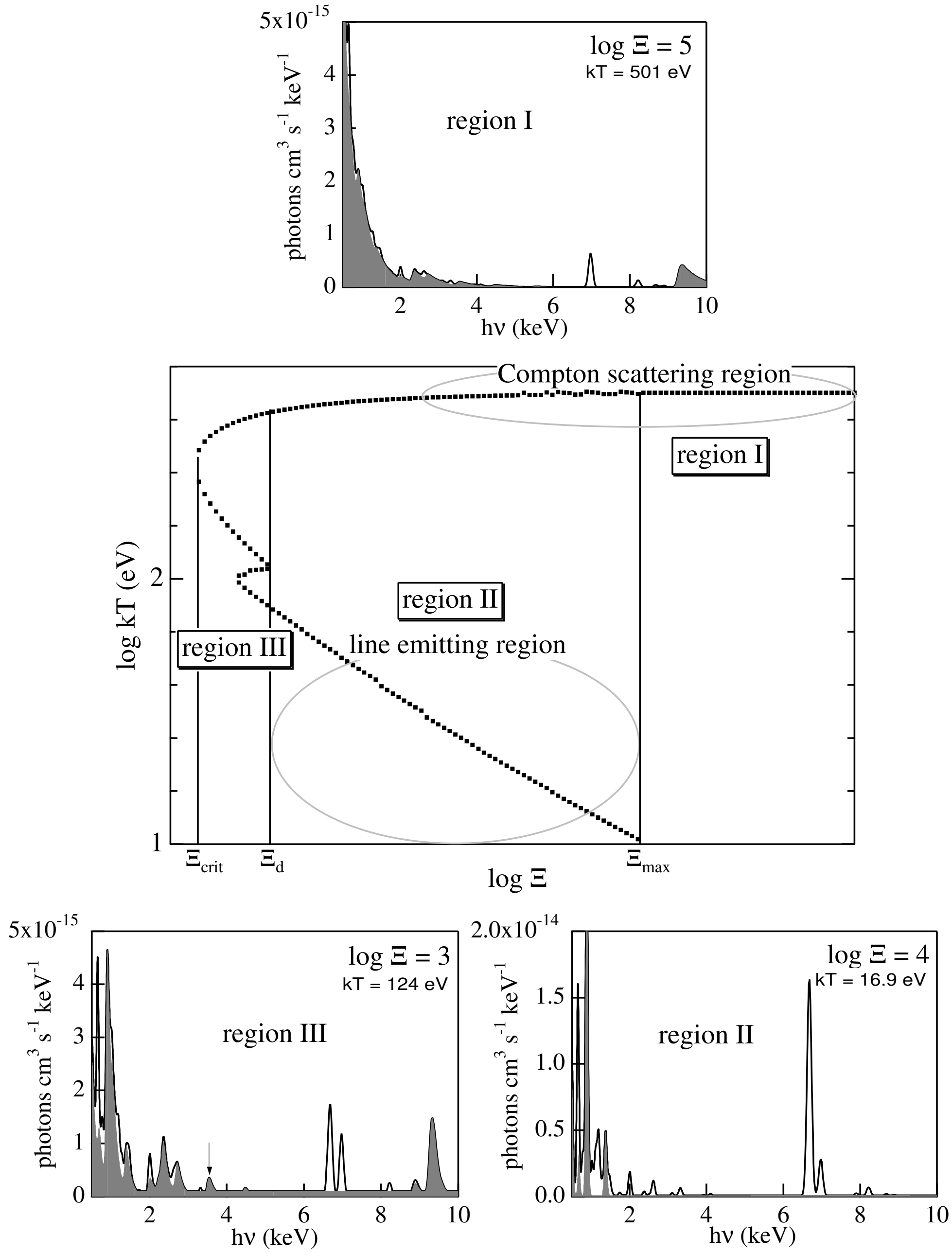

Fig. 1. The gas temperature vs Ξ (mid panel) and a typical radiation spectrum of each region. It is noted that the line center of the He-like iron $K\alpha$-blend slightly shifts toward the forbidden line ^{1}S–^{3}S (6.63 keV) and the intercombination line ^{1}S–^{3}P (6.67 keV) from the resonance line ^{1}S–^{1}P (6.70 keV) in comparison with a spectrum of collisionally ionized hot gas. The arrow in region III spectrum indicates the recombination edge detected by the *ASCA* Cyg X-3 observation (Kawashima & Kitamoto 1996). Our model predicts more intense narrow recombination continua in the 2–3 keV range covered by *ASCA*, but those were not claimed by the authors. This is likely because the authors could identify the narrow continuum with a real line. In fact, our calculations show that a line exists close to each continuum edge in 2–3 keV, while the detected 3.5 keV edge (and also faint 4.5 keV edge) is free from intense lines.

which is the ratio of the radiation pressure to the gas pressure P, we write the hydrostatic equation as,

$$\frac{\partial \ln P}{\partial h} = -\left(\frac{GM\mu m}{R^2 kT} - \frac{\rho\sigma_T}{\mu m}\Xi\right)\frac{h}{R} \ . \tag{4}$$

Here σ_T is the Thomson scattering cross section, h is the height from the disk plane with $R = (r^2 + h^2)^{1/2}$ at a disk radius r, and the gravitational force by the compact object of mass M is taken into account; the self-gravity of the gas is negligible. We solved equation (4) coupling the ionization/recombination and heating/cooling equations by iteration; the radiation spectrum was calculated every step and fed back.

3. RESULTS AND DISCUSSION

The time t_{cool} becomes significantly longer in the recombining gas (Masai 1999). This favors a pressure-constant structure, where $t_{cool} \propto T^2/\Lambda$. Incorporating hydrostatic balance, we can divide the thermal structure of the gas into four regimes: (I) high T and continuum emission, (II) low T and radiative recombination (RR) cascade line, (III) medium T and narrow RR continuum, (IV) not bound gravitationally. These regions are geometrically located in the order of I, II and IV from the compact object over the disk, and region III forms around the interface of I and II (Nakayama 1999). Figure 1 shows the thermal structure for the case $M = 1.4\,M_\odot$, $L = 1 \times 10^{36}$ erg s^{-1}, $\gamma = 1$ and $kT_r = 2$ keV, where region IV is at $r \gtrsim 2 \times 10^{11}$ cm. The value of Ξ is minimum at $\log \Xi_{crit} \approx 2.8$, and moves back and forth along the low T branch, reflecting the cooling dominated by bound/free-bound emissions sensitive to the temperature and ionization state. The largest leap appears at $kT \sim 100$ eV due to iron. Region III is thermally unstable (e.g., Hess, Kahn, & Paerels 1997) and the high T and low T phases coexist. Also between $\log \Xi_d \approx 3.0$ and $\log \Xi_{max} \approx 4.4$ the temperature exhibits multi-values, but the high T and low T regimes are geometrically separated from each other. Region II corresponds to the lower T branch.

In the photoionized gas, RR is enhanced to play a role for atomic level populations and the resultant thermal emission. The captures into excited levels increase more than those directly into the ground state, and are followed by cascades to the ground state. Since the kinetic energies of free electrons are relatively low compared to the ionization state, the photons emitted during the captures into an excited level fall into a quite narrow energy band, while the photons emitted through the cascades dominate the line spectra. The narrow RR continua look like lines (Liedahl & Paerels 1996), and the cascades enhance multiplet lines more than the resonance line (Masai 1994, see Fig. 1). These are seen in the spectra of regions III and IV, where the continuum is represented by the filled area to be distinguished from the real lines. Our model predicts many line-like RR continua around 1 keV. The width of the RR continuum is narrower in region IV than in region III because T is lower in region IV. The emission lines are more intense in region IV than in region III. From this it is also inferred that the line emission is dominated by RR cascade processes (Masai 1994).

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