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NONEQUILIBRIUM IONIZATION STATES OF GAMMA-RAY BURST ENVIRONMENTS

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ABSTRACT

Iron spectral features are thought to be the best tracers of progenitors of gamma-ray bursts (GRBs). The detections of spectral features such as an iron line and/or the radiative recombination edge and continuum (RRC) were reported in four X-ray afterglows of GRBs. However, burst for burst, their properties were different from each other. For example, the *Chandra* observation of GRB 991216 detected a strong H-like iron line together with the RRC. With *ASCA*, on the other hand, Yoshida and coworkers detected only the strong RRC in GRB 970828. Since it is difficult to produce the strong RRC, we have to consider a special condition for the line- and/or RRC-forming regions. In this Letter, we point out the possibility of a "*nonequilibrium ionization state*" for the line- and RRC-forming regions.

Subject headings: gamma rays: bursts — line: formation — X-rays: general

1. INTRODUCTION

Gamma-ray bursts (GRBs) are remote at cosmological distances, and thus their released energies in gamma-ray photons are almost $\sim 10^{52}$ ergs (Kulkarni et al. 1999). Although fireball models (Rees & Mészáros 1992; Piran 1999) or a cannonball model (Dar & De Rújula 2000) can explain many observational properties of GRBs, a progenitor of a GRB is yet to be solved. An important key to probing a progenitor of a GRB is the detection of iron spectral features in X-ray afterglows. Iron is the most abundant heavy element and falls in the middle of the observed energy range of X-ray satellites. Strong iron features can be produced in a dense gas environment. Therefore, the detection is the best evidence of a collapsing model of a massive star such as a hypernova/collapsar or a supranova (Paczyński 1998; Woosley 1993; Vietri & Stella 1998).

The iron features were already reported in four X-ray afterglows. The redshifted iron emission line was discovered in the X-ray afterglow of GRB 970508 by Piro et al. (1999) using *BeppoSAX*, and the redshift was consistent with the distance of a host galaxy. An independent discovery of a redshifted iron emission line was reported for GRB 970828 by Yoshida et al. (1999) using *ASCA*. Assuming an He-like Kα line, the spectral feature was once interpreted as an emission line with a redshift of $z = 0.33$. However, the Keck observation of the host galaxy, which was discovered later in 1998, revealed a redshift of $z = 0.9578$ (Djorgovski et al. 2001). The discrepancy in distance with *ASCA* and, moreover, the temporal detections of both caused us to doubt the reality of the existence of the iron features before the confirmation by the *Chandra* detection.

In 1999, with the ACIS-S/HETG instruments, *Chandra* detected GRB 991216, 37 hr after the GRB, and Piro et al. (2000) reported the detection of both the iron emission line and the radiative recombination edge and continuum (RRC) from fully ionized iron with a high statistical significance of 4.7 σ and 3.0 σ, respectively. The redshift of the line and the RRC were consistent with the host galaxy, and the line was broadened to $\sigma_{\rm line} = 0.23 \pm 0.07$ keV, suggesting a moving ejecta. Soon after the *Chandra* detection, Antonelli et al. (2000) also reported the probable iron emission line in the spectrum of GRB 000214 with an ~ 3.2 σ confidence level. This was the second detection of the iron using *BeppoSAX*. However, the redshift of the host galaxy of GRB 000214 is unknown. Therefore, it remains a question whether the observed feature is the iron emission line or the RRC.

Motivated by the RRC detection with *Chandra*, Yoshida et al. (2001, hereafter Paper I) apply the RRC to the *ASCA* data of GRB 970828 using a redshift of $z = 0.9578$ and obtain the edge energy, which is consistent with 9.28 keV. This possibility was earlier suggested in the paper by Djorgovski et al. (2001). However, there was no iron Kα line detected at the expected energy from GRB 970828. The upper limit of the line flux is less than 1.5×10^{-6} photons cm^{-2} s^{-1} or 120 eV in equivalent width (EW). We must explain the nondetection of the Kα line.

Related to the iron features, we should note that the iron features were only found in a small fraction (<10%) of X-ray afterglows, and sometimes the features were observed only during a certain interval. With *BeppoSAX*, we have tried to search lines in 11 X-ray afterglow spectra, but only one from GRB 970508 was found at the end of 1999 (L. Piro 1999, private communication). Most X-ray afterglows showed only upper limits. In particular, with *ASCA* Yonetoku et al. (2000) set an extremely low upper limit of almost 100 eV in EW for the bright GRB 990123. The published intensities of the observed iron Kα line and the RRC are summarized in Table 1. There is a wide variety in the iron emission and the RRC intensity. In this Letter, we try to explain these varieties of the iron features with the assumption that the line-emitting plasma state is in a "nonequilibrium ionization (NEI) state" that has a low electron temperature as compared with the ionization degree.

2. SPECTRAL SIMULATION FOR NONEQUILIBRIUM PLASMA

In Paper I, the observed flux of the RRC and the upper limit for the iron Kα line are given for GRB 970828 with 90% confidence errors. Therefore, we focus on the ratio of the in-

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TABLE 1
INTENSITY OF IRON LINE AND RRC

GRB	z	$F_{\rm line}$ (photons cm^{-2} s^{-1})	σ (keV)	$F_{\rm RRC}$ (photons cm^{-2} s^{-1})	kT (keV)
970508[a]	0.835	$(3.0 \pm 2.0) \times 10^{-5}$	...	...	...
970828[b]	0.958	$<1.5 \times 10^{-6}$	...	$1.7^{+6.4}_{-1.2} \times 10^{-5}$	$0.8^{+1.0}_{-0.2}$
991216[c]	1.020	$(3.2 \pm 0.8) \times 10^{-5}$	0.23 ± 0.07	3.8 ± 2.0	>1.0
000214[d]	...	$(9 \pm 3) \times 10^{-6}$	...	...	...
990123[e]	1.600	$<3.3 \times 10^{-6}$	...	...	...
990704[e]	...	$<4.7 \times 10^{-6}$	...	...	...

[a] The line intensity was variable (Piro et al. 1999).
[b] The RRC was temporal (Paper I).
[c] Piro et al. 2000.
[d] Antonelli et al. 2000.
[e] Yonetoku et al. 2000.

tegrated RRC flux to the iron intensity $F_{\rm RRC}/F_{\rm line}$, which is free from the continuum. The observed ratio of $F_{\rm RRC}/F_{\rm line} > 3.3$ in a 90% statistical lower limit is very hard to reproduce. The case of a strong RRC without a Kα line looks abnormal. In fact, *BeppoSAX* detected the strong Kα line, and the *Chandra* observation showed both features of the H-like iron with the flux ratio $F_{\rm RRC}/F_{\rm line} \sim 1$. Therefore, we are forced to consider a different condition between *ASCA* and other results containing the strong Kα line.

The nondetection of the Kα line of highly ionized iron accompanied by the recombination edge gives us a constraint on the possible emission mechanisms. If the line were produced because of the excitation by an electron impact, the RRC would be hidden by a much more intense thermal bremsstrahlung. Also, the synchrotron emission, which is thought to dominate the afterglow, would be significantly overlaid by the thermal bremsstrahlung. Therefore, we need a condition in which the iron is highly ionized but in which the involved electron energy is low. This would be a radiative recombination in the NEI ($T_e < T_z$) state; otherwise, the charge exchange would be responsible for the iron emission.

In this section, we show spectra using numerical calculations in the NEI plasma state and not depending on the specific model. To explain the observed strong RRC without the Kα line of iron, we calculate the emissivity using the NEI plasma radiation code (Masai 1994). The code employs three mechanisms for the continuum: free-free emission, 2 photon decay, and radiative recombination. For line emissions as well as for excitation by electron impact, fluorescent lines due to ionization and cascade lines due to recombination are taken into account. The radiation properties of a plasma were described by two parameters of the electron temperature (T_e) and the ionization degree represented in units of temperature (T_z), assuming a cosmical abundance. We study the emissivities in the range of 0.1 keV $< kT_e <$ 10 keV and 0.1 keV $< kT_z <$ 100 keV in every 0.1 keV step. We show representative spectra in Figure 1.

The strong RRC compared with the Kα line can be formed only in the regime of $T_e < T_z$, recombining the plasma condition. This condition, however, is attained by several situations that will be discussed later. We intend to find the condition of the plasma in order to account for the observed flux ratio ($F_{\rm RRC}/F_{\rm line}$), which is free from specific modeling with iron abundance, the emission measure, the geometry, and so forth if the line and RRC are emitted from the same site. Thus, for a given T_e and T_z a priori, we carried out calculations of the emissivity ratio in the above wide range of T_e-T_z space.

Figures 1*c* and 1*d* are the simulated plasma emissivities with a cosmical abundance explaining the ratio $F_{\rm RRC}/F_{\rm line}$ of GRB 991216 and GRB 970828, respectively. The ratios of an integrated RRC flux to Kα lines of the simulated ionization state are $F_{\rm RRC}/F_{\rm line} \sim 1$ and ~ 4 for Figures 1*c* and 1*d*, respectively, and the ratios are within the observational values in a 90% statistical error. In the calculation of the ratios, the line components (mostly a blend of Fe and Ni) very close to the edge of the RRC are included in the RRC component because of the limited energy-resolving power of the Solid-State Imaging Spectrometer (SIS) on board *ASCA*.

3. THE REASON FOR STRONG RRC AND WEAK Kα LINE

To produce the strong RRC in quantum number $n = 1$, the iron must be almost fully ionized. The H-like Kα line, which was observed with *Chandra*, dominates other ionization states at a temperature of $kT_z > 20$ keV. Above this temperature, Fe XXVII consists of more than 70% iron; thus, we assume that $kT_z > 20$ keV in the following discussion. In a condition with a high electron temperature of $kT_e \sim kT_z > 20$ keV, i.e., equilibrium ionization, the capture rate of free electrons is small, and the emissivity of the line and the RRC also becomes small. Moreover, the free-free emission from high-T_e electrons dominates at the hard X-ray band. Therefore, the RRC may not be observed because it can be obscured by the free-free component.

The cross section of the electron capture into the nth quantum state can be expressed as

$$\sigma_n \propto \frac{1}{n^3}\left(\frac{3}{2}\frac{kT_e}{\epsilon} + \frac{1}{n^2}\right)^{-1}, \qquad (1)$$

where ϵ is an ionization energy of 9.28 keV for H-like iron (e.g., Nakayama & Masai 2001). Thus, the best condition to form the strong RRC would be the case of $kT_e \sim \epsilon (\ll kT_z)$. In such a plasma state, $\sigma_n \propto n^{-3}$, and then most of the free electrons recombine directly into the ground state ($n = 1$), compared with the $n \geq 2$ levels. However, free-free emission dominates the continuum.

With decreasing kT_e, the recombination rate increases, while free-free emission becomes suppressed. Recombination into $n \geq 2$ increases relatively and produces line emission. Thus, the Kα line can be enhanced by cascades from $n \geq 3$ excited levels. This is the case for He-like Kα, but H-like Kα (Lyα) is little affected; a considerable fraction comes to direct transition to the ground state.

We summarize the above discussions in view of the intensity of the RRC and Kα line. The plasma state with the strong RRC but a weak Kα line, which was observed with *ASCA*, is realized

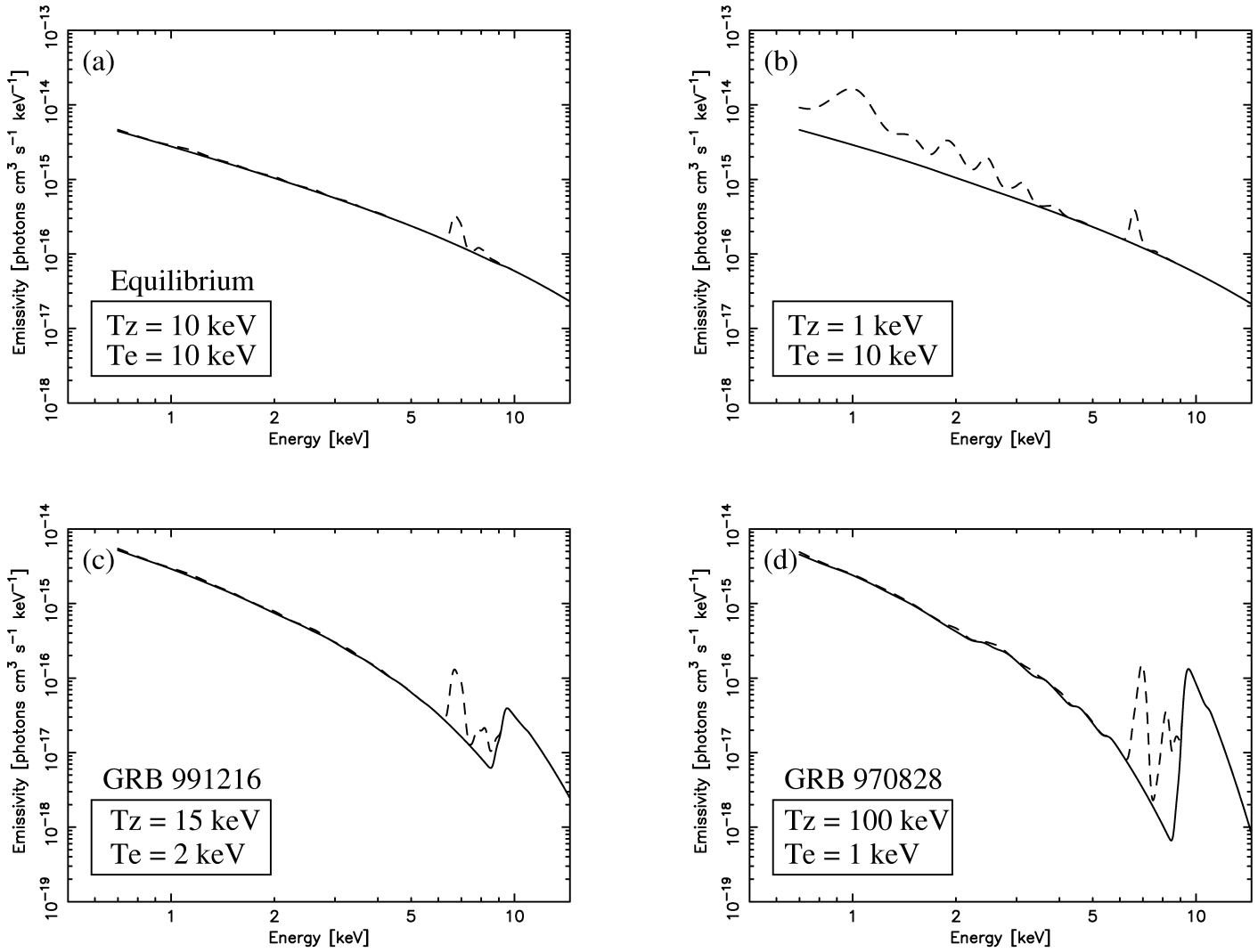

FIG. 1.—Simulated emissivities convolved with the energy resolution of the *ASCA* SIS for the following cases: (*a*) $T_z = 10$ keV, $T_e = 10$ keV (equilibrium); (*b*) $T_z = 1$ keV, $T_e = 10$ keV; (*c*) $T_z = 15$ keV, $T_e = 2$ keV; and (*d*) $T_z = 100$ keV, $T_e = 1$ keV. The solid lines represent the emissivity of the continuum, and the dashed lines represent the emission lines. Panels *c* and *d* are simulated to represent the cases of GRB 991216 and GRB 970828, respectively, but only in view of the observed ratios of $F_{\rm RRC}/F_{\rm line}$. We do not intend to reproduce the spectral shapes, which mostly consist of a nonthermal component.

when kT_e is slightly less than ϵ but in high kT_z. The ratio of the RRC to Kα lines ($F_{\rm RRC}/F_{\rm line}$) from the numerical calculations is shown in Figure 2 as a function of T_e and T_z. The peak of the ratio appears at around $kT_e = 4$ keV and $kT_z = 100$ keV in the calculated range. The condition of $F_{\rm RRC}/F_{\rm line} > 3.3$ of GRB 970828 can be explained by this result.

4. DISCUSSION

A high-ionization degree of $kT_z \sim 100$ keV and a low electron temperature of $kT_e \sim 1$ keV are required when we reproduce the high ratio of the RRC to the iron line of more than 3.3. This condition may be attained in (1) the photoionizations by X-rays or (2) the rapid cooling due to rarefaction.

Case 1 is also likely accompanied by a fluorescent Kα line with 6.4–6.5 keV energies of partially ionized iron. In particular, for the photoionizations of a neutral circumstellar gas by the initial bright flash of a GRB, iron lines in the low-ionization states are expected but not observed. The line observed using *Chandra* was purely H-like (Piro et al. 2000). Therefore, the iron atoms should be fully ionized by the time of the observed iron emission. However, if the line- and RRC-emitting regions are illuminated continuously by a hidden intense beam, discussed by Rees & Mészáros (2000), they can achieve the NEI ($T_e < T_z$) state by the photoionization process. Even if this process is realized, the mean energy of the hidden-beam photons that illuminate the line-emitting region should not be significantly greater than the edge energy of 9.28 keV since the observed values of T_e were low; $kT_e = 0.8^{+1.0}_{-0.2}$ keV at the rest frame for *ASCA* and $kT_e \gtrsim 1$ keV for *Chandra*.

In case 2, we pay attention to the rapid adiabatic expansion of a highly ionized hot plasma. This sort of mechanism has already been investigated by Itoh & Masai (1989) for a supernova exploded in the circumstellar matter that was ejected during its progenitor's supergiant phase. They show that when the blast shock breaks out of the dense circumstellar matter into a low-density interstellar medium, a rarefaction wave propagates inward into the shocked hot plasma. Then the hot plasma expands adiabatically and loses its internal energy quickly. The electron temperature T_e decreases, but the ionization degree T_z temporally remains high, because the recombination timescale becomes much longer as a result of the low density. The mean temperature of the shocked matter, $kT \sim 100(v_s/10^9 \text{ cm s}^{-1})^2$ keV, where v_s

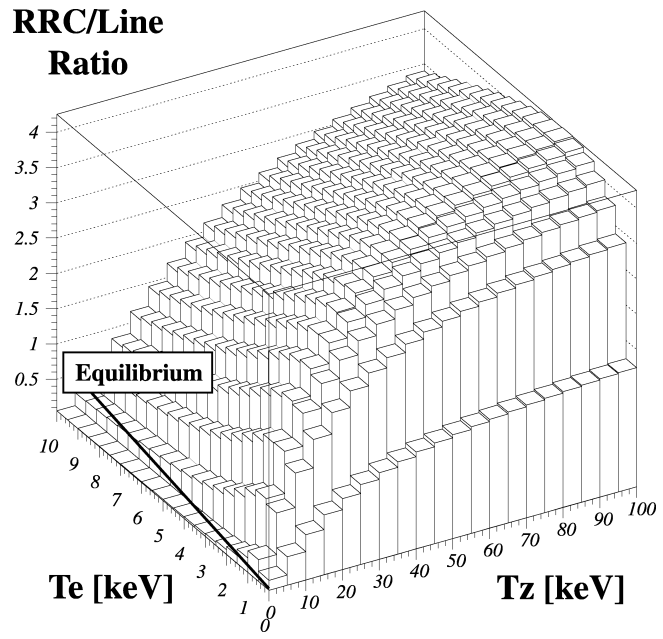

FIG. 2.—Ratios of the integrated emissivity of the RRC structure to the Kα lines ($F_{\rm RRC}/F_{\rm line}$) for several ionization states in a three-dimensional axis. We calculate the ratio of the emissivity for each $T_z = 5$ keV and $T_e = 0.5$ keV step. The thick solid line labeled "equilibrium" indicates the condition of $T_e = T_z$. The recombination process is only enhanced in the $T_e < T_z$ region. Within our calculated range, the observed ratio of $F_{\rm RRC}/F_{\rm line} > 3.3$ for GRB 970828 can be attained in the range of more than $T_z = 80$ keV, limiting the $T_e = 1$ keV, which is observed in the RRC structure.

is the shock velocity, drops by about 2 orders of magnitude for the density contrast (ratio) of the dense matter to the ambient medium of $\sim 10^3$ in their hydrodynamic calculations. Therefore, the plasma can achieve the NEI ($T_e \sim 1$ keV, $T_z \sim 100$ keV) state naturally and can emit the strong RRC with a weak Kα line of $F_{\rm RRC}/F_{\rm line} \sim 4$.

If these mechanisms work, we can estimate an emission measure for GRB 970828 using the observed photon flux of the RRC ($\mathcal{F}_{\rm RRC}$), the distance (D) and the integrated emissivity ($\varepsilon_{\rm RRC}$), shown in Figure 2, with the cosmical abundance,

$$n^2 V \sim 10^{68} \left(\frac{D}{3\ \mathrm{Gpc}}\right)^2 \left(\frac{\mathcal{F}_{\rm RRC}}{1.7 \times 10^{-5}}\right) \left(\frac{\varepsilon_{\rm RRC}}{2 \times 10^{-16}}\right)^{-1}. \quad (2)$$

Although these n and V are coupled with each other and depend highly on the specific model, we may conclude that the density of line-emitting region is considerably high.

The RRC and/or the line of a large EW suggest a recombined ($T_e < T_z$) condition, which can be realized by photoionization or rarefaction. It should be noted that most of the X-ray afterglow did not show both emission features; the NEI state is not always the case.

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