NON-EQUILIBRIUM IONIZATION STATES OF GRB ENVIRONMENTS

Daisuke Yonetoku[1,2] and Toshio Murakami[1,2]
yonetoku@astro.isas.ac.jp, murakami@astro.isas.ac.jp

Kuniaki Masai[3], Atsumasa Yoshida[4], Nobuyuki Kawai[2], Masaaki Namiki[5]

ABSTRACT

Iron spectral features are thought to be the best tracer of a progenitor of gamma-ray bursts (GRBs). The detections of an iron line and/or a Radiative Recombination edge and Continuum (RRC) were reported in four X-ray afterglows of GRBs. However their properties were different each other event by event. For example, Chandra observation of GRB 991216 reported both the strong H-like iron line together with its RRC. On the contrary, Yoshida et al. (2001) report only the detection of the strong RRC in GRB 970828 with ASCA. Since it is difficult to emit the strong RRC, we have to consider special conditions of the line and/or the RRC forming region. In this paper, we point out a possibility of a *"non-equilibrium ionization state"* for the line and the RRC forming region.

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

1. Introduction

Gamma-Ray Bursts (GRBs) are remote at cosmological distances and thus their released energies in γ-ray photons are almost $\sim 10^{52}$ erg (Kulkarni et al. 1999). Although a fireball model (Rees M.J. & Mészáros P 1992; Piran 1998) or a cannonball model (Dar 2000) can explain many observational properties of GRBs, a progenitor of GRB is yet to be solved. An important key to probe a progenitor of GRB is the detection of iron spectral features in X-ray afterglows. Iron is the most abundant heavy element and fall in the middle of the observed energy range. Strong iron features can be created in the dense gas environment. Therefore, the detection can be the best evidence of a collapsing model of a massive star such as Hypernova/Collapsar or Supranova (Paczyński 1998; Vietri et al. 1998; Woosley 1993).

The strong iron features were reported in four X-ray afterglows. The redshifted iron emission line was discovered in the X-ray afterglow of GRB 970508 with BeppoSAX (Piro et al. 1999), 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 with ASCA (Yoshida et al. 1999). Assuming a He-like Kα line, the line was interpreted as an emission with a redshift of $z = 0.33$. However, the Keck observation of the host galaxy, which was discovered later in 1998, revealed the redshift of $z = 0.9578$ (Djorgovski et al. 2000). The discrepancy in distance forced us to doubt the reality of existence of the iron features. Moreover these detections were temporal.

In 1999, Chandra observed GRB 991216 at 37 hours after the GRB with the ACIS-S/HETG in-

[1]Institute of Space and Astronautical Science, 3-1-1, Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan

[2]Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo 152-0033, Japan

[3]Department of Physics, Tokyo Metropolitan University, 1-1 Minamiosawa, Hachioji, Tokyo 192-0397, Japan

[4]Department of Physics, Aoyama Gakuin University, 6-16-1, Chitosedai, Setagaya, Tokyo, 157-8572 Japan

[5]The Institute of Physical and Chemical Research, 2-1, Hirosawa, Wako 351-0198, Japan

struments, and Piro et al. (2000) reported the detection of both the iron emission line together with the Radiative Recombination edge and Continuum (RRC) from fully ionized (H-like) iron with 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 broaden to $\sigma_{\rm line} = 0.23 \pm 0.07$ keV suggesting a moving ejecta. Antonelli et al. (2000) also reported the probable iron emission line in the spectrum of GRB 000214 with $\sim 3.2\,\sigma$ confidence level. This is the second case of BeppoSAX. However the redshift of a host galaxy 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 paper-I) apply the RRC for the ASCA data using the redshift of $z = 0.9578$, and obtain the edge energy, which is consistent with 9.28 keV. This point was earlier suggested in the paper by Djorgovski et al. (2000). However, there is no iron Kα line at the expected energy. The upper limit of the line flux is $< 1.5 \times 10^{-6}$ photons cm^{-2}s^{-1} or 120 eV in equivalent width (EW).

Related to the iron features, we should note the fact that the iron features were found only in a small fraction ($<$ 10 %) of X-ray afterglows, and sometimes observed during a certain interval. BeppoSAX has tried to search lines in eleven X-ray afterglow spectra, but found only one from GRB 970508 at the end of 1999 (Piro; private communication). The most X-ray afterglows do show only upper limit. Especially, Yonetoku et al. (2000) set an extremely low upper limit of almost 100 eV in EW for the bright GRB 990123 with ASCA. 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 paper, we try to explain these varieties of the iron features in view point of the line-emitting plasma state such as in "non-equilibrium ionization (NEI) state" which has a low electron temperature as compared to the ionization degree.

2. Spectral Simulation for Non-equilibrium Plasma

In paper-I, the fluxes of the RRC and the upper limit for the iron line are given for GRB 970828 with 90 % confidence errors. Thus the flux ratio of the RRC to the line: $F_{\rm RRC}/F_{\rm line} > 3.3$ in 90 % statistical lower limit. It is very hard to imagine a case of strong RRC with no Kα line. In fact, BeppoSAX showed the strong Kα line (Piro et al. 1999, Antonelli et al. 2000) and the Chandra observation showed both features with the flux ratio of nearly $F_{\rm RRC}/F_{\rm line} \sim 1$ (Piro et al. 2000). We are forced to consider a different condition between ASCA and other cases with a strong Kα line. We think that the variety may be realized in the NEI plasma state of a combination of high ionization degree and relatively low electron temperature. In this section, we show spectra of numerical calculations in the NEI state. After that, we consider probable processes to form these plasma state.

To explain the strong RRC with the weak Kα line of iron, we simulate the emissivity using an NEI plasma radiation code (Masai 1994). The code employs three mechanisms, such as free-free emission, two-photon decay and radiative recombination for the continuum. Radiation properties can be described by two parameters of the electron temperature (T_e) and the ionization degree represented in units of temperature T_z. We study the emissivities in the range of $0.1 < T_e < 10$ keV and $0.1 < T_z < 100$ keV in every 0.1 keV step. We show representative spectra in figure 1.

The strong RRC as compared with the Kα line can be formed only in the regime of $T_e < T_z$, recombining plasma condition. Figure 1-c and -d are simulated emissivities to explain the spectrum of GRB 991216 and GRB 970828 respectively. The ratio 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 figure 1-c and -d respectively, and they are consistent with observational results in 90 % statistical error. In the calculation of the ratios, the lines (the blend of Fe and Ni) very close to the edge of the RRC are included to the RRC component, due to the limited energy resolving power of the SIS detector with ASCA.

You should take cautions to compare these simulations with the observed spectra directly, due to following reasons ; (a) The observed spectra consist of mostly the non-thermal X-ray afterglow component but the simulated spectra do not contain it. (b) The calculations demonstarate not the intensity but the emissivity. The intensity is subject to radiative transfer. (c) The Kα line observed with Chandra were broad, but any kinetic effects of the line broadening are not included in these simulations. However the energy response of the SIS detectors is included.

3. The Reason for Strong RRC and Weak Kα Line

To produce the strong RRC with quantum number $n = 1$, the iron must be almost fully ionized. Since the H-like Kα line, which was observed with Chandra, dominates the Kα of other ionization states at a temperature of $T_z > 30$ keV, we assume $T_z > 30$ keV in the following discussions. In a condition of high electron temperature of $T_e \sim T_z > 30$ keV, i.e., equilibrium ionization, the capture rate of free electrons is small and the emissivity of the line and 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 n level can be expressed as

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

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 $kT_e \sim \epsilon\,(\ll T_z)$. In such a plasma state, $\sigma_n \propto n^{-3}$ and then the most of free electrons recombine into the ground state ($n = 1$) directly compared to 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 point of the intensity of the RRC and Kα line. The plasma state with the strong RRC but the weak Kα line, which was observed with ASCA, is realized when kT_e is slightly less than ϵ but in high T_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 the function of T_e and T_z. The peak of the ratio appears at around $T_e = 4$ keV and $T_z = 100$ keV in the calculated range. The condition of $F_{\rm RRC}/F_{\rm line} > 3.3$ of GRB 970828 can be explain by this result.

4. Discussion

There are two probable ways to achieve the NEI ($T_e < T_z$) state. One is a strong photoionization process and another is rapid cooling due to adiabatic expansion. In case of the photoionization of neutral gas by the initial bright flash of GRB, the strong 6.4 keV lines are expected but not observed. The emission line observed with Chandra was purely H-like (Piro et al. 2000). Therefore, the region was high temperature enough to ionize iron atoms to H-like at the time of the iron emission. If the line and the RRC emitting region is illuminated continuously by a hidden intense beam, discussed by Rees et al. (2000), it can achieve the NEI ($T_e < T_z$) state by the photoionization.

The observed T_e from the RRC are cool of $kT_e > 1$ keV for Chandra and $T_e = 0.8^{+1.0}_{-0.2}$ at the rest frame for ASCA respectively. These are a little bit lower than the best T_e for the maximum ratio at around 4 keV in figure 2.

In any case, the extremely high $T_z \sim 100$ keV and low T_e are required when we consider the high ratio of the RRC to the line more than 3.3. Thus another efficient mechanism to cool electrons might be rapid adiabatic expansion of a highly ionized hot plasma. This sort of mechanism has already been discussed by Itoh & Masai (1989) for a supernova which explodes in the circumstellar matter ejected in the past. They show that when the blast wave breakes out of the dense circumstellar matter into a rarefied interstellar medium, the shocked matter cools rapidly and emits strong RRC as well as Kα. If the iron emission plasma initially has a high temperature of $T_e = T_z \sim 100$ keV, it should undergo a rapid cooling to achieve the NEI ($T_e < T_z$) state. The electron and ion temperature are cool but the ionization degree T_z remains high temporally because the recombination time scale is longer than the cooling time scale.

Finally, one curious thing should be explained is that most of X-ray afterglow did not show any line and/or the RRC feature. It is easy to say too cool to produce lines in both T_e and T_z or too hot to recombine. However, what causes the differences in temperature burst by burst? We have no answer but the RRC structure will play an important role of tracing the environment of a GRB progenitor.

5. Acknowledgment

We would like to thank Shri Kulkarni and George Djorgovski for their comments and suggestions about the distance of the host galaxy before the publication. This work was done under the support of Grant-in-Aides for the Scientific Research (Nos. 12640302) by the Ministry of Education.

REFERENCES

Antnelli, L. A. et al. 2000, ApJ, 545, L39

Dar A. & De Rújula A., 2000, astro-ph/0008474 (A & A submitted)

Djorgovski S. G. et al. 2000, ApJ (submitted)

Itoh, H. & Masai, K. 1989, MNRAS 236, 885

Kallman, T. R. & McCray, R., 1982, ApJS 50, 263

Kulkarni, S et al. 1999, Nature 398, 389

Masai, K. 1994, ApJ 437, 770

Murakami, T. et al. 1997, IAU Circ., # 6732

Nakayama, M. & Masai, K., 2001, A & A Submitted

Paczyński B. 1998, ApJ 494, L45

Piran T 1998, Phys. Rep. 314, 575

Piro L. et al. 1999, ApJ 514, L73

Piro, L. et al. 2000, Science 290, 955

Rees M.J. & Mészáros P 1992, MNRAS 258, L41

Rees M.J. & Mészáros P 2000, ApJL 545, L73

Vietri M. et al. 1998, ApJ 507, L45

Vreeswijk P. M. et al. 2000, GCN Circular 496

Woosley S. E. 1993, ApJ 405, 273

Yonetoku, D. et al. 2000, PASJ 52, 509

Yoshida, A. et al. 1999, A & A Sup. 138, 433

Yoshida et al. 2001, ApJL, (submitted) (companion paper)

Fig. 1.— Simulated emissivities, convolved with the energy resolution of the ASCA-SIS for the 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, $T_e = 1.5$ keV and (d) $T_z = 100$ keV, $T_e = 1$ keV. The solid lines represent emissivity of continuum and the dotted ones are for lines.

Fig. 2.— Ratios of the integrated emissivity of the RRC structure to the Kα lines ($F_{\rm RRC}/F_{\rm line}$) for several ionization state in 3-dimensional axis.

Table 1: Intensity of Iron Line and RRC

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

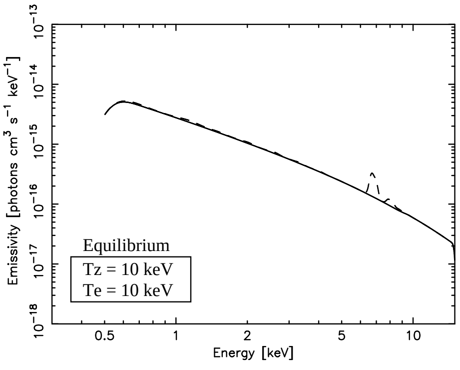
* Piro et al. 1999 ; the line intensity was variable.

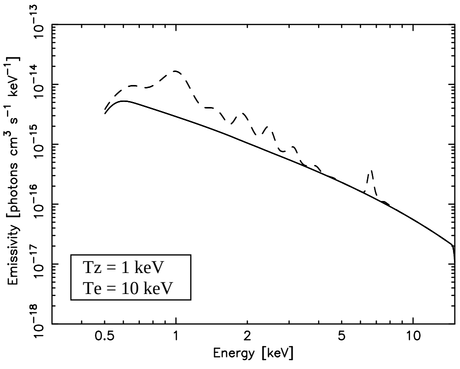
† Yoshida et al. 2001 ; the RRC was temporal.

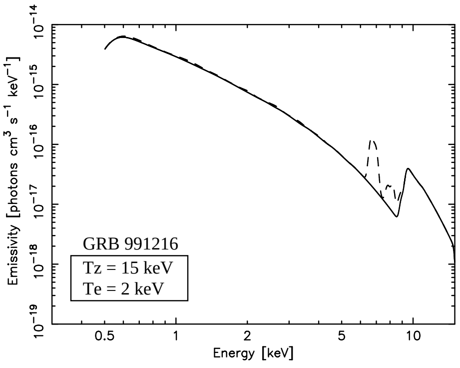
$^{\sharp}$ Piro et al. 2000

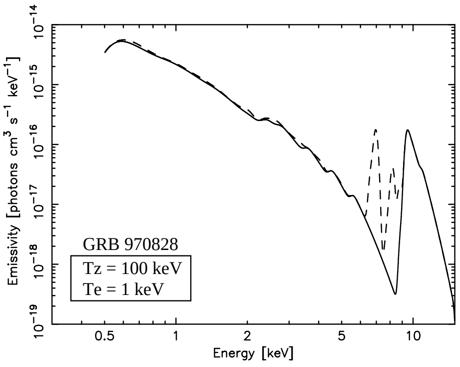
$^{\natural}$ Antonelli et al. 2000

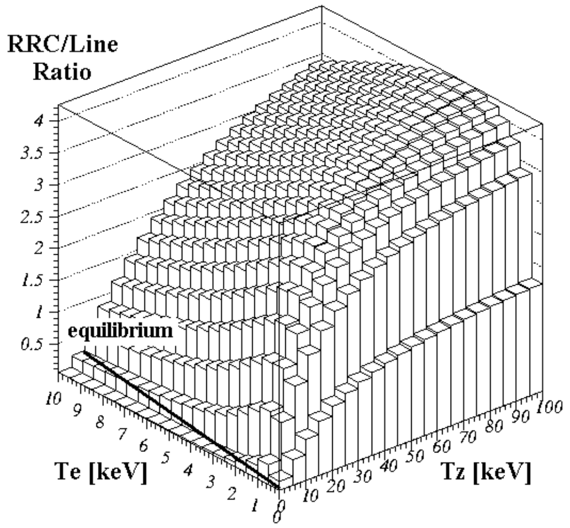
* Yonetoku et al. 2000


Emissivity [photons cm^3 s^{-1} keV^{-1}]
Energy [keV]
Equilibrium
Tz = 10 keV
Te = 10 keV


Emissivity [photons cm^3 s^{-1} keV^{-1}]
Energy [keV]
Tz = 1 keV
Te = 10 keV


Emissivity [photons cm^3 s^{-1} keV^{-1}]
Energy [keV]
GRB 991216
Tz = 15 keV
Te = 2 keV


Emissivity [photons cm^3 s^{-1} keV^{-1}]
Energy [keV]
GRB 970828
Tz = 100 keV
Te = 1 keV


RRC/Line
Ratio
4
3.5
3
2.5
2
1.5
1
0.5
equilibrium
10
9
8
7
6
5
4
3
2
1
0
Te [keV]
0
10
20
30
40
50
60
70
80
90
100
Tz [keV]