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A POSSIBLE EMISSION FEATURE IN AN X-RAY AFTERGLOW OF GRB 970828 AS A RADIATIVE RECOMBINATION EDGE

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ABSTRACT

A gamma-ray burst (GRB) of 1997 August 28 was localized by the All-Sky Monitor on the *Rossi X-Ray Timing Explorer* satellite, and its coordinates were promptly disseminated. An *ASCA* follow-up started 1.17 days after the burst as a Target-of-Opportunity Observation and detected an X-ray afterglow. The spectral data displayed a *hump* around ∼5 keV and an absorption column of 7.1×10^{21} cm^{-2}. Taking into account the redshift $z = 0.9578$ found for the likely host galaxy of the associated radio flare, this hump structure is likely a recombination edge of iron in the vicinity of the source. The radiative recombination edge and continuum model can interpret the spectrum from highly ionized plasma in a nonequilibrium ionization state. The absorption could also be due to the medium presumably residing in the vicinity of the GRB.

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

1. INTRODUCTION

The sites and the distance scales of gamma-ray bursts (GRBs) are becoming clear owing to the observational breakthroughs made for their afterglows at longer wavelengths (Costa et al. 1997; van Paradijs et al. 1997; Bond 1997; Frail et al. 1997; Sahu et al. 1997; Metzger et al. 1997) together with the extensive theoretical work (Paczyński 1986; Woosley 1993; Rees & Mészáros 1992; Mészáros & Rees 1997; Wijers, Rees, & Mészáros 1997). So far, from the many efforts in multiwavelength study from radio to gamma ray (Kulkarni et al. 1998), we have learned that GRBs are one of the most distant and violent astrophysical phenomena in the universe.

However, the progenitors and sites of GRBs are still unknown; although the merging neutron star binary made in the baryon-clean environment was a popular scenario at the time when GRB afterglows were discovered, recent observations appear to suggest that more "dirty" circumstances are expected for hypernova (Paczyński 1998), collapsar (Woosley 1993), or supranova scenarios (Vietri & Stella 1998). Optical transients (OTs) without GRBs (the so-called "optically dark" GRBs), which are a major part of known GRB samples, are suggested by several authors to be embedded inside the dusty environment in host galaxies, which may be star-forming regions.

The key observation to investigate in GRB environments are probably the strong iron features reported in X-ray afterglows (Piro et al. 1999, 2000; Yoshida et al. 1999; Antonelli et al. 2000). In particular, Piro et al. (2000) report striking results from the *Chandra* for GRB 991216. It clearly revealed both an iron Kα emission line and a recombination edge, which was interpreted to be from highly ionized iron.

A GRB of 1997 August 28.73931 (GRB 970828) is one of the most important events so far because it was an optically dark GRB and showed a spectral feature that was possibly from highly ionized iron together with a large absorption column. It was detected and quickly localized into a small region with $2' \times 5'$ accuracy by the All-Sky Monitor (ASM) aboard the *Rossi X-Ray Timing Explorer* (*RXTE*) satellite (Remillard et a. 1997; Smith et al. 1997). Subsequently, the *RXTE* Proportional Counter Array (PCA) detected an X-ray afterglow of 0.5 mcrab (2–10 keV) about 4 hr after the burst detection (Marshall et al. 1997), *ASCA* detected a fading X-ray source in a prompt follow-up, and *ROSAT* gave a more accurate location of 10″ at a later epoch (Marshall et al. 1997; Murakami et al. 1997; Greiner et al. 1997). Although the X-ray afterglow was rather strong, a corresponding OT was invisible down to $R \approx 23.8$ (Groot et al. 1998). However, a series of VLA observations detected a weak (4.5 σ) radio flare at 8.46 GHz at a period 3.5 days after the GRB inside the *ROSAT* error region. The subsequent optical observation by the Palomar 200 inch telescope revealed extended sources around the radio position (Djorgovski et al. 2001). It shows that the radio source is located between two bright optical peaks; Djorgovski et al. (2001) suggest that the GRB occurred either inside a dust lane (corresponding to a dark gap between two bright peaks referred to as "A" and "B" in their paper) or at an interface of two interacting galaxies. Following a spectroscopic study of the galaxy by the Keck telescope, peak A clearly displayed two emission lines that are interpreted as [O II] and [Ne III] lines. This gives a redshift of $z = 0.9578$ for the galaxy that is likely a host of GRB 970828 (Djorgovski et al. 2001). In this Letter, we report on the properties of an X-ray afterglow of this interesting burst (GRB 970828) with the data obtained by *ASCA* and discuss the emission *hump* and low-energy absorption seen in its spectra.

2. *ASCA* OBSERVATION AND PROPERTIES OF THE X-RAY AFTERGLOW

Because of the prompt dissemination of the ASM position and the effort to have very quick operations of the satellite, a Target-of-Opportunity Observation (TOO) by *ASCA* in the 0.5–10 keV range was conducted soon after the alerts, based on the *RXTE*/ASM detection. The observation with net exposure time of ∼36 ks was performed during the period of August 29.91–30.85 UT beginning 1.17 days after the GRB.

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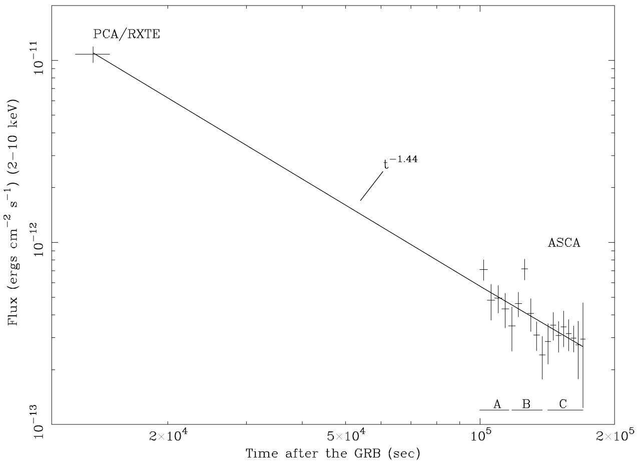

FIG. 1.—X-ray light curve obtained with *ASCA* plotted with the flux reported by Marshall et al. (1997). Here we assume a power-law spectrum with a photon index of −2 for the flux calculation. The simple power-law decay model is indicated by the solid line: $t^{-1.44\pm0.07}$. The lines labeled "A," "B," and "C" indicate the intervals for which spectral studies are made.

Two scientific instruments on *ASCA*, the Solid-State Imaging Spectrometer (SIS) and the Gas Imaging Spectrometer (GIS), detected an X-ray source with an average 2–10 keV flux of $F_X \sim 4 \times 10^{-13}$ ergs cm^{-2} s^{-1} within the combined source error region given by the *RXTE*/ASM and the Interplanetary Network (IPN; Smith et al. 1997; Hurley et al. 1997; Murakami et al. 1997). The position of the X-ray source was determined at R.A. = $18^h08^m32\overset{s}{.}2$ and decl. = +59°18′54″ (J2000) with a 90% error radius of 0′.5 by an image analysis on the data sets.

The X-ray source clearly displayed a fading behavior during the observation. Estimated 2–10 keV fluxes are plotted in Figure 1 together with that measured by the *RXTE*/PCA in the earlier epoch (Marshall et al. 1997). We assume a power-law spectrum with a photon index of −2 for this estimation. The source faded from $\sim 1 \times 10^{-11}$ ergs cm^{-2} s^{-1} (the PCA observation at $t \sim 1.4 \times 10^4$ s) to $\sim 3 \times 10^{-13}$ ergs cm^{-2} s^{-1} (at the end of the *ASCA* observation at $t \sim 1.7 \times 10^5$ s), where t is the elapsed time since the burst. Assuming a power-law–fading model, the decay of the X-ray afterglow can be represented by $t^{-1.44\pm0.07}$. The solid line in Figure 1 represents this average fading behavior. Note that the error corresponds to a 90% confidence throughout this Letter.

2.1. *Variability*

Focusing on the *ASCA* data, we see that the X-ray flux does not follow a simple decay. A peaklike structure appears around $t = 1.25 \times 10^5$ s. This structure can be represented with a Gaussian-line shape superposed on an overall decaying trend represented by $t^{-1.44}$. From the fit, the χ^2 turns out to be 9.82 with 1.4 degrees of freedom (dof), while the simple power law gives $\chi^2 = 21.5$ (17 dof). Thus, with 99% confidence, this variability is significant when using an F-test for three additional parameters (i.e., the centroid, width, and normalization of a line).

BeppoSAX also saw a variability in the afterglow of GRB 970508 (Piro et al. 1998). It was a rather broad ($\delta t > 10^5$ s at $t \approx 10^5$ s) "bursting activity," while *ASCA*'s "flare activity" is narrow in time ($\delta t/t \sim 0.05$).

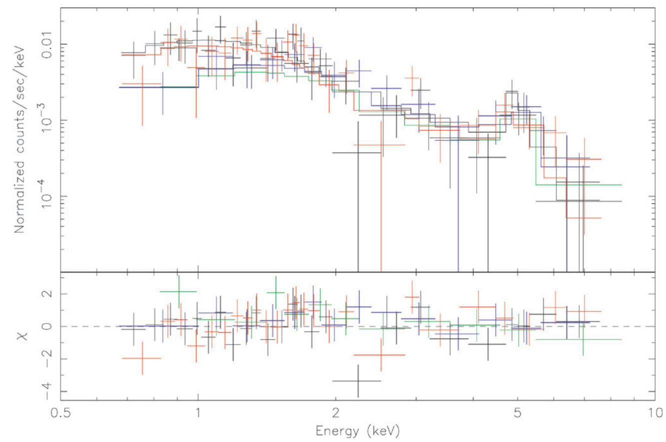

FIG. 2.—X-ray spectrum for the period (B) shown fitted with the model of an "absorbed power law" with an RRC.

2.2. *Spectral Structure*

We made a spectral study for the periods that are indicated by the lines labeled "A," "B," and "C" in Figure 1. In this analysis, data were fitted jointly with a single model for those data from four scientific detectors, SIS0, SIS1, GIS2, and GIS3, aboard *ASCA*. There is an excess feature found at around 4.8 keV in the spectrum of line B, which looks like a *hump* or a *broad line* over the continuum. An interpretation of this hump as an Fe Kα line was presented in a previous paper (Yoshida et al. 1999). However, an inferred redshift of ~0.33 did not match that of the host galaxy reported by Djorgovski et al. (2001). We apply the radiative recombination edge and continuum (RRC) structure for this feature as an alternative interpretation.

The RRC model is described as

$$\frac{dN}{dE} \propto \begin{cases} (kT_e)^{-3/2} \exp(-E/kT_e) & \text{if } E \geq 9.28 \text{ keV}, \\ 0 & \text{otherwise}, \end{cases} \quad (1)$$

where k is Boltzmann's constant and T_e is the electron temperature of the plasma, which can be determined from the width of the RRC structure.

Introducing the three parameters for the RRC, i.e., E_{edge}, kT_e, and normalization, we achieve a significant reduction of χ^2, $\Delta\chi^2 = 13.2$. Hence, the confidence level of the RRC model is found by an F-test to be 99.3%. The best fit gives an edge energy of $E_{edge} = 4.76^{+0.19}_{-0.25}$ keV, an electron temperature at the rest frame of $kT_e = 0.8^{+1.0}_{-0.2}$ keV, and an integrated RRC flux of $F_{RRC} = 1.7^{+6.4}_{-1.3} \times 10^{-5}$ photons cm^{-2} s^{-1}. The above 90% error range of E_{edge} is consistent with the expected edge energy of H-like iron at 4.74 keV and He-like iron at 4.51 keV with a redshift of $z = 0.9578$. Thus, the spectral feature could be explained as a radiative recombination edge with a hard tail (continuum) above the edge energy in highly ionized plasma.

It should be notable that there is no redshifted iron emission line seen at the expected energy for such ionized plasma. We searched for an H-like iron emission line (6.97 keV at the rest frame) in the spectrum at B. As shown in Figure 2, we found no emission line around $6.97/(1+z) = 3.56$ keV with an upper limit of $F_{line} \leq 1.5 \times 10^{-6}$ photons cm^{-2} s^{-1}. No significant line structure was found in A or C. The best-fit parameters and the upper limits on the iron emission line and the RRC intensities are summarized in Tables 1 and 2.

From these fits, a significant absorption column density is found only in the spectrum of period C, of which N_H is eval-

TABLE 1
FITTING RESULTS OF GRB 970828

Period	N_H^{gal} ($\times 10^{20}$ cm^{-2})	N_H ($\times 10^{20}$ cm^{-2})	Power-Law Γ	RRC E_{RRC} (keV)	RRC kT_e (keV)	χ^2 (dof)
A ……	3.4 (fixed)	<36.5	$1.6^{+0.2}_{-0.3}$	…	…	34.7 (48)
B ……	3.4 (fixed)	<55.4	$2.1^{+0.3}_{-0.3}$	$4.76^{+0.19}_{-0.25}$	$0.8^{+1.0}_{-0.2}$	70.3 (72)
C ……	3.4 (fixed)	$70.8^{+32.1}_{-27.5}$	$2.9^{+0.7}_{-0.4}$	…	…	94.0 (84)

uated to be $7.08^{+0.32}_{-0.27} \times 10^{21}$ cm^{-2} at the observer frame. We get a significant reduction of $\Delta\chi^2 = 20.5$ (84 dof) by adding an absorption, which corresponds to a 4.3 σ confidence level. This is significantly larger than the Galactic value toward the source direction that is calculated to be 3.4×10^{20} cm^{-2} by the COLDEN program at the *Einstein* On-Line Service, Smithsonian Astrophysical Observatory. The fitting results are summarized in Table 1.

3. DISCUSSIONS

In the previous paper (Yoshida et al. 1999), we proposed that the hump was likely corresponding to a redshifted Fe Kα line. Assuming that the line was 6.7 keV from the source (i.e., He-like iron), the redshift was estimated to be $z \sim 0.33$. Piro et al. (1998) reports a similar emission-line feature from the *BeppoSAX* observations of the GRB 970508 afterglow (Piro et al. 1999). They imply that it is possibly an Fe line at a redshift $z = 0.835$ that was derived from the earlier optical work done on GRB 970508 (Metzger et al. 1997). In the case of GRB 970828, however, an OT corresponding to the GRB was invisible down to $R = 23.8$ (Groot et al. 1998), and one could not know its redshift from an OT.

However, recently published work on a radio transient and a possible host galaxy of GRB 970828 shows that the burst source likely sits in a distant galaxy of $z = 0.9578$. This is inconsistent with the interpretation of the X-ray spectral structure as an Fe Kα line. An alternative interpretation is that the structure could be due to an iron recombination edge instead of a fluorescent line. For instance, the *Chandra* observation of GRB 991216 (Piro et al. 2000) has clearly shown a recombination edge with a rest energy of 9.28 keV (H-like iron) as well as a Kα line at $z = 1.020$, which is consistent with the optical spectroscopy reported by Vreeswijk et al. (1999).

There is, however, a sharp difference between the *Chandra* spectra and the *ASCA* spectrum of GRB 970828. *Chandra* has also detected an Fe Kα line together with a recombination edge (Piro et al. 2000). However, there appears to be no significant emission feature around the expected energies for the detections by *ASCA*. Inclusion of an additional emission line in a fitting model does not improve the fitting at all and gives an upper bound of less than 1.5×10^{-6} photons cm^{-2} s^{-1} to the line intensity (see Table 2). This was puzzling for the *ASCA* spectra, but it could be understood for the case in which plasmas in nonequilibrium ionization states are responsible for the emission of the RRC and the line. A scenario for the emission mechanism of such an apparently lineless recombination edge is described and discussed in the companion paper (Yonetoku et al. 2001).

TABLE 2
IRON LINE AND RRC FLUX OF GRB 970828

Period	Line (6.97 keV) (photons cm^2 s^{-1})	RRC (9.28 keV) (photons cm^2 s^{-1})
A ……	$<4.7 \times 10^{-6}$	$<1.2 \times 10^{-5}$
B ……	$<1.5 \times 10^{-6}$	$1.7^{+6.4}_{-1.2} \times 10^{-5}$
C ……	$<3.0 \times 10^{-5}$	$<7.0 \times 10^{-6}$

A large absorption column is the other puzzle in the X-ray afterglow. Taking $z = 0.9578$ for the GRB source, the intrinsic column density of the period C is derived by fitting it with the model, $\exp[-N_H^{gal}\sigma(E)] \times \exp\{-N_H^{src}\sigma[(1+z)E]\} \times E^{-\alpha}$, so that $N_H^{src} = 3.13^{+1.76}_{-1.29} \times 10^{22}$ cm^{-2} with Galactic density $N_H^{gal} = 3.4 \times 10^{20}$ cm^{-2}. Although this column density is coupled with the observed change in the power-law index, the large absorptions were measured in several other X-ray afterglows, even the famous "optically bright" GRB 990123 (Yonetoku et al. 2000).

No optical afterglow was discovered for GRB 970828 down to $R = 23.8$ (Groot et al. 1998). The *R*-band extinction should be large from the above column density. This would imply that the matter is near the source in its host galaxy. From the observations of the radio flare and the optical images for its coordinate, Djorgovski et al. (2001) suggest that the GRB source sits inside the dusty environment of the host galaxy.

It is also notable that the intrinsic absorption column is apparently variable. An absorption is not necessary for the preflare or in-flare spectra (A and B) with 90% upper bounds of 3.65×10^{21} and 5.54×10^{21} cm^{-2}, respectively, while a large N_H is required for the postflare period C ($7.08^{+3.21}_{-2.75} \times 10^{21}$ cm^{-2}). Although the variability is marginal and the absorption column is coupled with the continuum, this implies that the medium that absorbed the X-ray would have been changed during the periods A–C. Some authors have studied the time-dependent absorption in the GRB environments (Perna & Loeb 1998; Böttcher et al. 1999). For instance, Perna & Loeb (1998), considering an H I cloud with a density of 100 cm^{-3} within ~1 pc from the source, suggest that the afterglow radiation ionizes the matter around the source and that therefore the absorption should decay in the later epoch instead of *increase*. The inferred density from the current observation is much larger, $\sim 10^{22}$ cm^{-2}, and could imply a much denser medium. The blast wave moving nearly with the light speed would have been $\sim 4 \times 10^{15}$ cm from the source at the period C [$(1.4–1.7) \times 10^5$ s from the burst]. The size of the observable *beam* of afterglow radiation increases proportional to $1/\Gamma$ as the bulk Lorentz factor Γ decreases. If the dense matter was near the edge of the *beam*, it might have caused the increase of absorption, as observed. The *variable* absorption might be an indication of a strong inhomogeneous matter distribution in the vicinity of the GRB source. This is likely separate from a dust lane in a larger scale, which could have obscured an OT (Djorgovski et al. 2001).

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