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 of 28 August 1997 was localized by the All-Sky Monitor on the Rossi XTE satellite and its coordinates were promptly disseminated. An ASCA followup started 1.17 days after the burst as a Target of Opportunity Observation and detected an X-ray afterglow. The data displayed in spectra an *hump* around ~ 5 keV and an absorption column of 7.1×10^{21} cm^{-2}. This *hump* structure is likely a recombination edge of iron in the vicinity of the source, taking account of the redshift $z = 0.9578$ found for the likely host galaxy of the associated radio flare. Radiative Recombination edge and Continuum model can interpret the spectrum from highly ionized plasma in a non equilibrium ionization state. The absorption could be also due to the medium presumably in the vicinity of the GRB.

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

1. Introduction

The site and the distance scale of γ-ray bursts (GRBs) is becoming clear initiated by the observational breakthroughs made for their afterglows at longer wave lengths (Costa et al. 1997; van Paradijs et al. 1997; Bond et al. 1997; Frail et al. 1997; Sahu et al. 1997; Metzger et al. 1997), together with extensive theoretical works e.g., (Paczyński 1986; Woosley 1993; Rees & Mészáros 1992; Mészáros & Rees 1997; Wijers et al. 1997). We have learned so far that GRB is one of the most distant and violent astrophysical phenomena in the universe from many efforts in multi-wavelengths study from radio to γ-ray (Kulkarni et al. 1998).

However, the mechanism and site 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 are discovered, recent observations appear to suggest more "dirty" circumstances expected for hypernova (Paczyński 1998), collapsar (Woosley 1993), or supranova scenarios (Vietri et al. 1998). Optical Transients (OTs) less GRBs ("optically dark" GRBs), a major part in known GRB samples, are suggested by several authors to be embedded inside the dusty environment in host galaxies, which may be star-forming region.

The key observation to investigate the GRB environment is maybe strong iron features reported in X-ray afterglows (Piro et al. 1999; Yoshida et al. 1999; Piro et al. 2000; Antonelli et al. 2000). Especially Piro et al. (2000) report an striking results from the Chandra for GRB 991216. It clearly revealed both an iron Kα emission line and a recombina-

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tion edge interpreted to be from highly ionized iron.

A GRB of 28.73931 August 1997 (GRB 970828) is one of important events so far because it was an "optically dark" GRB and showed a spectral feature 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 XTE satellite (RXTE) (Remillard et a. 1997; Smith et al. 1997). Subsequently PCA/RXTE found an X-ray afterglow of 0.5 mCrab (2–10 keV) about four hours after the burst detection (Marshall et al. 1997) and ASCA detected a fading X-ray source by a prompt follow-up and ROSAT gave more accurate location of 10 arcsec 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 the 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 occured inside a dust lane (corresponding to a dark gap between two bright peaks "A" and "B" in their paper), or at an interface of two interacting galaxies. Following spectroscopic study by the Keck on the galaxy "A" displayed clear two emission lines which are interpreted as [O II] and [Ne III] lines. This gives a redshift of $z = 0.9578$ for the galaxy which is likely a host of GRB 970828 (Djorgovski et al. 2001).

In this paper we report on properties of an X-ray afterglow of this interesting burst, GRB 970828, with the data obtained by ASCA and discuss an 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 for a 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 ASM/RXTE detection. The observation with net exposure time of $\sim$ 36 ks was performed during a period of August 29.91 – August 30.85 UT beginning at 1.17 days after the GRB. Both two scientific instruments on ASCA, the SIS and the GIS detectors, saw an X-ray source of an average 2–10 keV flux of $F_X \sim 4 \times 10^{-13}$ erg cm^{-2}s^{-1} within the combined source error region given by ASM/RXTE and 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.= $18^h08^m32^s.2$ and Decl.=$+59°18'54''$ (J2000) with a 90 % error radius of $0'.5$ by an image analysis on the datasets.

The X-ray source clearly displayed a fading behavior during the observation. Estimated 2–10 keV fluxes are plotted in Fig.1 together with that measured by PCA/RXTE in the earlier epoch (Marshall et al. 1997). We assume a power-law spectrum with the 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 an elapsed time since the burst. Assuming a power-law fading model, the decay of the X-ray afterglow can be represented by $t^{-1.44 \pm 0.07}$. The solid line in Fig.1 represents this average fading behavior. Note that the error corresponds 90 % confidence throughout this paper.

2.1. Variability

Zooming in the ASCA data, the X-ray flux does not follow a simple decay. A peak-like 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 χ^2 turns out to be 9.82 with the degree-of-freedom (d.o.f.) of 14, while the simple power-law gives $\chi^2 = 21.5$ (17 d.o.f.). Thus this variability is significant with 99 % confidence by an F-test for three additional parameters (i.e., centroid, width and normalization of a line).

The BeppoSAX also saw a variability in the afterglow of GRB 970508 (Piro et al. 1997). It is 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; $\delta t/t \sim 0.05$.

2.2. Spectral Structure

We made a spectral study for the periods which are indicated by lines labeled "A", "B" and "C" in Fig.1. In this analysis, data were jointly fitted with a single model for those from four scientific detectors, SIS-0, SIS-1, GIS-2 and GIS-3, carried by the ASCA. There is an excess feature found around 4.8 keV in the spectrum of "B", which looks like a *hump* or a *broad line* over the continuum. An interpretation of this *hump* as an Fe K_α line was presented in the previous paper (Yoshida et al. 1999). However an inferred redshift of ~ 0.33 did not match to that of the host galaxy reported by Djorgovski et al. (2001). We apply Radiative Recombination edge and Continuum (RRC) structure for this feature as an alternative interpretation.

The RRC model is described as

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

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

Introducing three parameters for RRC, i.e., $E_{\rm edge}$, kT_e and normalization, we achieve a significant reduction of χ^2, $\Delta\chi^2 = 13.2$. Hence a confidence level of the RRC model is found by an F-test to be 99.3 %. The best-fit gives the edge energy of $E_{\rm edge} = 4.76^{+0.19}_{-0.25}$ keV, the electron temperature at the rest frame $kT_e = 0.8^{+1.0}_{-0.2}$ keV and the integrated RRC flux of $F_{\rm RRC} = 1.7^{+6.4}_{-1.3} \times 10^{-5}$ photons cm^{-2}s^{-1}. The 90 % error range of $E_{\rm edge}$ above 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 an expected energy for such ionized plasma. We searched for a 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 the upper limit of $F_{\rm line} \leq 1.5 \times 10^{-6}$ photons cm^{-2}s^{-1}. There also found no significant line structure in "A" nor "B". The best-fit parameters and Upper-limits on iron emission line and the RRC intensities are summarized in table 1 and table 2.

From these fits, we found also that the absorption column density in the best fit for the period "C", and $N_{\rm H}$ indicates to be $7.08^{+0.32}_{-0.27} \times 10^{21}$ cm^{-2} at the observer frame. We have a significant reduction of $\Delta\chi^2 = 20.5$(84 d.o.f.) by adding absorption, which corresponds to a 4.3 σ confidence level. This is significantly larger than the galactic value towards the source direction calculated to be 3.4×10^{20} cm^{-2} by COLDEN 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 red shifted Fe Kα line. Taking an assumption of the line at 6.7 keV at 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 the redshift $z = 0.835$ which was derived from the earlier optical work for GRB 970508 (Metzger et al. 1997). In the case of GRB 970828, on the contrary, an optical transient 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 fluorescence line. For instance, the Chandra observation of GRB 991216 (Piro et al. 2000) has clearly shown a recombination edge with 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. (2000).

There is, however, a sharp difference between the Chandra spectra and the one of ASCA of GRB 970828. The Chandra has seen also an Fe Kα line together with a recombination edge (Piro et al. 2000). However there appears no significant emission feature around the expected energies for the case of ASCA. Inclusion of an additional emission line into a fitting model does not improve fitting at all, and gives an upper bound in a line intensity of $< 1.5 \times 10^{-6}$ photons cm^{-2}s^{-1} (see Table 2). This was puzzling for the ASCA spectra. But it could be understood in the case that plasma in non-equilibrium ionization states are responsible for emission of the RRC and the line. A scenario for emission mechanism of such a line-less recombination edge is described and discussed in the companion paper (Yonetoku et al. 2001).

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 the fitting with the model, $\exp(-N_{\rm H}^{\rm gal}\sigma(E)) * \exp(-N_{\rm H}^{\rm src}\sigma((1+z)E)) * E^{-\alpha}$, to be $N_{\rm H}^{\rm src} = (3.13^{+1.76}_{-1.29}) \times 10^{22}$ cm^{-2} with the galactic density $N_{\rm H}^{\rm gal} = 3.4 \times 10^{20}$ cm^{-2}. Although this column density coupled with the observed change of 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).

Any optical afterglow was not 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 the matter near the source in its host galaxy. Djorgovski et al. (2001) suggest that the GRB source sits inside dusty environment of the host galaxy from the observations of the radio flare and the optical images for its coordinate.

A notable thing is that the intrinsic absorption column appears to be variable in time; it is consistent with zero (i.e., only the galactic absorption is visible) in the pre-flare and during the flare period (period "A" and "B"), but a large value is required for the post-flare period (period "C"). This would suggest that the medium which absorbed the X-ray afterglow was affected by the afterglow and hence located in the vicinity of the source. This would be apart from a dust lane, in a larger scale, which could have obscured an optical transient suggested by Djorgovski et al (2001).

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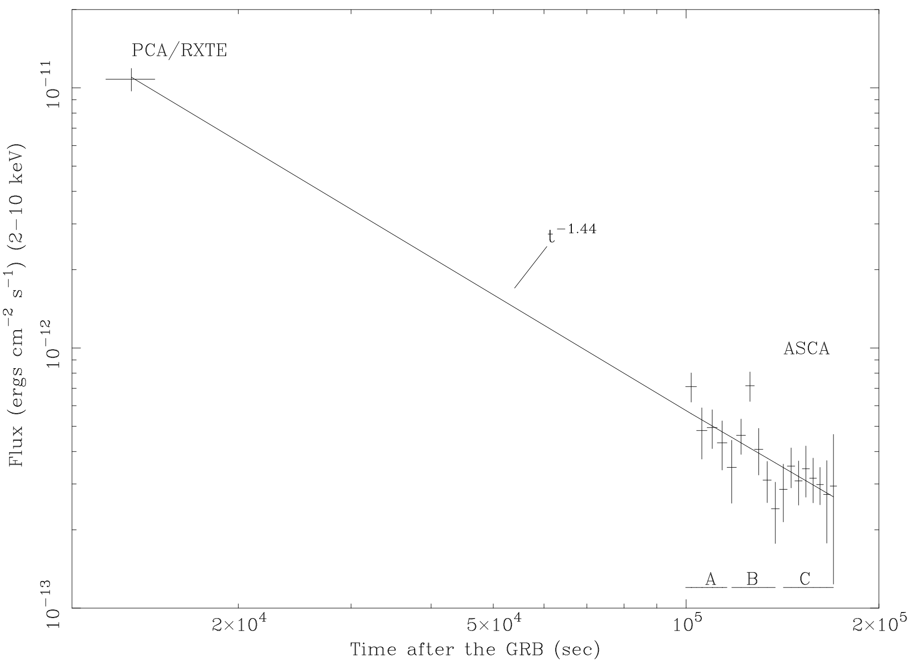
Fig. 1.— The X-ray light curve obtained with ASCA is plotted together with the flux reported by Marshall et al (1997). Here we assume a power-law spectrum with the photon index of -2 for the flux calculation. The simple power-law decay model is indicated by the solid line: $t^{-1.44\pm0.07}$. The lines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

Fig. 2.— The X-ray spectrum for the period (B) shown in Fig.2 fitted with the model of "absorbed power-law" with a Radiative Recombination edge and Continuum (RRC).


PCA/RXTE
$t^{-1.44}$
ASCA
A
B
C
Flux (ergs cm^{-2} s^{-1}) (2–10 keV)
10^{-11}
10^{-12}
10^{-13}
2×10^4
5×10^4
10^5
2×10^5
Time after the GRB (sec)

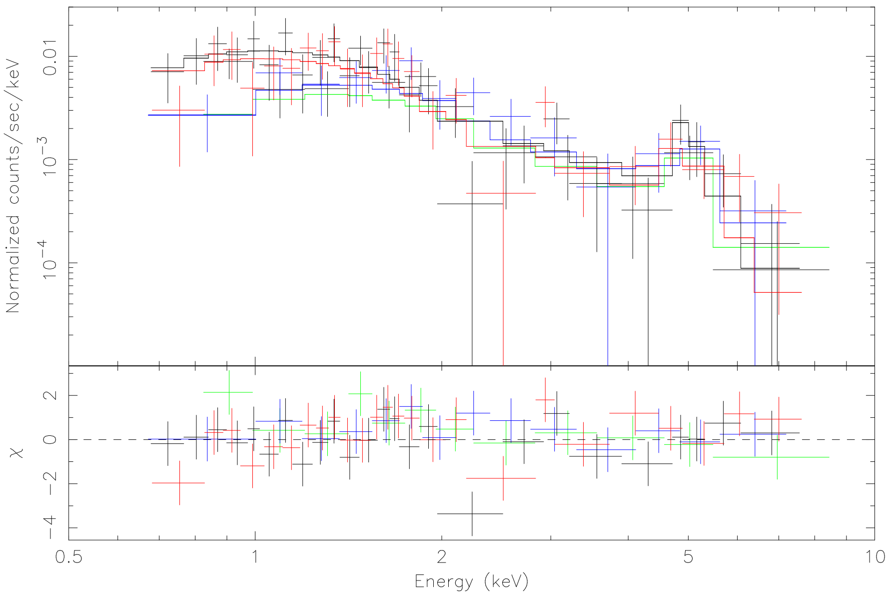

Normalized counts/sec/keV
0.01
10^{-3}
10^{-4}
χ
2
0
−2
−4
0.5
1
2
5
10
Energy (keV)

Table 1: Fitting Results of GRB 970828

Period	$N_{\mathrm{H}}^{\mathrm{gal}}$ (10^{20} cm^{-2})	N_{H} (10^{20} cm^{-2})	power-law Γ	RRC E_{RRC} (keV)	RRC kT_e (keV)	χ^2 (d.o.f)
A	3.4 (fix)	—	$1.6^{+0.2}_{-0.3}$	—	—	34.7(48)
B	3.4 (fix)	—	$2.1^{+0.3}_{-0.3}$	$4.76^{+0.19}_{-0.25}$	$0.8^{+1.0}_{-0.2}$	70.3(72)
C	3.4 (fix)	70.8^{+32}_{-27}	$2.9^{+0.7}_{-0.4}$	—	—	94.0(84)

Table 2: Iron Line and RRC Flux of GRB 970828

period	Line (6.97 keV) (photon cm^2s^{-1})	R.R.C (9.28 keV) (photon cm^2s^{-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	$< 3.0 \times 10^{-5}$	$< 7.0 \times 10^{-6}$