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# SPECTRAL EVOLUTION OF A LONG X-RAY BURST

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GREENBELT, MARYLAND

## SPECTRAL EVOLUTION OF A LONG X-RAY BURST

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### ABSTRACT

An X-ray burst-like event with a peak intensity 1 1/2 times that of the Crab and a decay time of  $\sim 100$ s was observed from near  $\ell_{\text{II}} = 356.4^\circ$  and  $b_{\text{II}} = 2.3^\circ$ . Significant spectral changes occurred during the burst. The spectra were best fit by the black body form with  $kT$  ranging from .87 keV to 2.3 keV. They suggest a source with smaller dimensions than a massive black hole. A weak source was observed after the burst with a 10 keV thermal spectrum and an indication of iron line emission.

### I. INTRODUCTION

The time scales of the many X-ray bursts reported in the past year have clustered in the neighborhood of a few seconds. There may also be a clustering of X-ray transient time scales about the value of a few hours (Holt 1976; Rappaport et al. 1976; Cooke 1976). A smaller number of events have been reported with intermediate time scales of a few minutes. Markert et al. (1976) have reported two flares of several minutes from

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near MX 1716-31. A few flares with durations of minutes have been observed from flare stars (Heise et al. 1976). Bursts as long as 50 s have been reported from MXB 1730-335 (Lewin et al. 1976a) and as long as 100 s from a source in Norma (Belian et al. 1976, Grindlay and Gursky 1976). The divisions into classes according to physical origins is not yet clear.

Both the Goddard X-ray Spectroscopy experiment and the Wisconsin Soft X-ray experiment on OSO-8 observed an event several minutes in duration on September 11, 1975 (Swank et al. 1976; Bunner 1976a). The light curve and spectral behavior of this event are similar in some respects to those of short bursts. Because of the duration and intensity of the event we were able to obtain spectra with time resolution on the order of its evolution time. This is the first event on this time scale for which such observations have been reported. We also report the spectrum of a residual flux from the same region which is likely to be associated with the burst source.

## II. OBSERVATIONS

The detectors comprising the Goddard X-ray Spectroscopy experiment have been described before (Serlemitsos et al. 1976). For several days in September 1975 the region near the galactic plane between  $\ell_{\text{II}} = 349^\circ$  and the galactic center was in view of either the xenon detector scanning at  $5^\circ$  about the negative spin axis of the OSO-8 satellite or the argon detector pointed along the negative spin axis. A second xenon detector is pointed along the positive spin axis. The fields of view of the detectors are circular, with half angles of  $3.4^\circ$  for the argon detector and  $5.09^\circ$  for the scanning xenon detector. During the observing time integral rates

were obtained every 160 ms, pulse height information every 2.08s for the scanning detector and 40.96s for the pointed detectors. The satellite spin period was 10.7s.

The long burst (or short flare) we are describing occurred in the scanning detector during an interval when the background level and the pulse height distributions indicated the data was free of electron contamination. No rise in the rates of the other two detectors was observed during the event. A Wisconsin detector similar to our scanning detector also observed the decay of the event (Bunner 1976a) but was not turned on when the burst began. The earth's horizon was 60° away from the field of view. No known solar system object was in view.

The event persisted for more than 50 scans. All but one, the first of the event, were consistent with an azimuthal distribution from a single distant point source. Except at the beginning the intensity appeared to change little during any single scan of the source. The best position determined by the scans subsequent to the first is  $(\ell_{II}, b_{II}) = (356.4^\circ, 2.3^\circ)$ . The 90% confidence error box is shown in Fig. 1 together with the positions reported for other flares and sources in the region. The Wisconsin data on the position and intensity are in agreement with ours (Bunner 1976b). The scan at the beginning of the event was inconsistent with response to a source at the position determined by the subsequent scans in that an excess persisted outside the azimuth range of possible response. Various possibilities have been explored, but the cause of this discrepancy remains unclear.

The light curve of the total counts in the response peak for each scan is shown in Fig. 2a. The peak count range was 1 1/2 times that of

the Crab in this detector (sensitive from 1.7-60 keV). Spin 0 is the exceptional spin referred to above. Because of our difficulty in interpreting the data for it we can only specify the rise time to have been  $\lesssim 10$  s. Spins 8-15 can be fit to an exponential decay with a time constant of  $\sim 45$  s. The decay then slowed, proceeding with a longer time constant of  $\sim 215$  s. Even in the period 500-800 s after the initial burst a source remained visible at the level of 25 UHURU cts  $s^{-1}$  that was not present before the burst. Because of occultation by the earth and a change in the pointing direction we cannot follow the evolution beyond that.

The spectrum of the source changed as the event evolved. We computed the ratio of counts from 6-11 keV to the counts from 2-6 keV and divided the burst into intervals with similar hardness ratios. The ratios for these intervals are shown in Fig 2b. Background was taken from the same region prior to the burst. The spectrum during the 20 s peak of the burst is very soft. During the decay the spectrum quickly hardened, but again softened as the decay proceeded.

The spectra fit the model of blackbody emission absorbed by cold matter, i.e. the form

$$f(E) \propto (E^2 / (e^{E/kT} - 1)) e^{-N_H \sigma}$$

with  $\sigma$  the cross section for photoionization of neutral material with the abundances used by Fireman (1974). The parameters of the fits are given in Table I, along with the 90% confidence limits. The parameters for the best fits to thermal bremsstrahlung spectra with absorption are also shown, but these were not acceptable during the hard part of the pulse. Errors are given for the cases when the  $\chi^2$  for the best fit was

less than the 90% confidence  $\chi^2$  for the black body fit. Although we cannot put significant limits on changes in the absorbing column density, the changes in temperature for the black body temperature are statistically significant. The total energy incident from the burst was  $5 \times 10^{-6}$  ergs  $\text{cm}^{-2}$  with a maximum flux of  $6 \times 10^{-8}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$ .

For 6 days following the burst the region was in view of the scanning detector. No further bursts were observed from that position. Because of confusion from nearby sources due to unfavorable spin axis positions the scanning detector can only determine that no source stronger than  $\sim 30$  UHURU cts  $\text{s}^{-1}$  was present there. However, during September 14-15 the pointing argon detector passed over the region. The data is consistent with a steady source at the position of the burst with a flux from 2-6 keV of  $3.4 \times 10^{-10}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$ , equivalent to 20 UHURU cts  $\text{s}^{-1}$ . The spectrum was well fit from 1.6 - 24 keV with a thermal bremsstrahlung spectrum for  $kT = 10 \pm 2$  keV, with an absorbing column density of only  $1.8 \pm 1.8 \times 10^{21} \text{ cm}^{-2}$  and an iron line with an equivalent width of  $313^{+620}_{-223}$  eV, where the errors are 90% confidence limits. At a distance  $d$  the emission measure would have been  $8 \times 10^{55} \left(\frac{d}{1 \text{ kpc}}\right)^2 \text{ cm}^{-3}$ .

### III. DISCUSSION

Although 100 s, the time scale of the event, is a factor of 10 times the life-times of typical bursts from NGC 6624 and MXB 1730-335, for example, this long burst exhibits some qualitative features in common with short bursts. The intensity rose relatively fast compared to the life time of the event, the major part of the decay was exponential, and definite changes in the spectral hardness are similar to the behavior for bursts from NGC 6624 (Clark et al. 1976). The low energy cut-offs

of 2-3 keV which characterize the spectra are similar to those of short bursts (Grindlay et al. 1976c, Lewin et al. 1976c). It seems possible that similar physical situations are involved. A few minutes is also the time scale of optical and radio flares from flare stars. However the observed absorption would not be expected and those few flares observed in X-rays at all had high flux below 1 keV (Heise et al. 1976).

For spherical emission the total energy output was  $6 \times 10^{38}$  (d/1 kpc)<sup>2</sup> ergs at a distance d, on the same order as that involved in typical short bursts for  $.4 < d < 4$  kpc (Clark et al. 1976; Lewin et al. 1976b,c). If the weak source that we observed a few days after the burst was the same as the burst source the relatively low absorption observed implies a distance less than  $\sim 1$  kpc. The best fits to the burst spectra required as much as an order of magnitude more absorption, but the absorption could occur at the source.

If we assume the source was nearly a black body and the absorption occurred outside the source, at the peak intensity during the first 20 s the radius of a spherical isotropic emitter was  $(1^{+.6}_{-.2}) \times 10^6$  (d/1 kpc) cm. The same assumptions during the remainder of the burst imply a radius within 30% of  $1.5 \times 10^5$  (d/1 kpc) cm. The values could be a few times larger if the radiation were not isotropic. Grindlay and Gursky (1976b) have suggested the hardening of the spectra in bursts from NGC 6624 is caused by scattering in a hot gas which would require a central mass of more than  $100 M_{\odot}$  to bind it. This long burst appears to have involved an emitting area with dimensions less than the Schwarzschild radius of such a mass, unless the distance was greater than seems reasonable on



other grounds ( $> 20$  kpc). The size obtained suggests the source was a neutron star or a black hole of stellar mass. Collapse of mass accumulated at a magnetosphere is considered a possible cause of short bursts (Lewin et al. 1976b,c). The peak luminosity for the long burst would have been  $8 \times 10^{36} (d/1 \text{ kpc})^2 \text{ ergs s}^{-1}$ , so that the source would not have been Eddington-limited for accretion onto a neutron star unless it were  $> 5$  kpc away.

Our observations of the weak source a few days after the burst are consistent with its being the same as the UHURU source "W" (Forman et al. 1976) as well as at the same position as the burst. The possible association with a weak source is similar to the association of one of the flares ("Flare 1") observed by Markert et al. (1976) with another weak relatively unabsorbed source, MX 1716-31. Our error box for the burst intersects the large error box for another flare reported by these authors, "Flare 2". Since little is known about this flare other than that it persisted for 6 minutes as compared with 100 seconds for the burst reported here, we find no compelling reason to associate the two. While the chances per day of observing another burst appear low, more information about the identity might be obtained from the weak source, which is relatively persistent. There are no recorded supernovae remnants near the position, but there are 3 SAO stars in our error box for the burst.

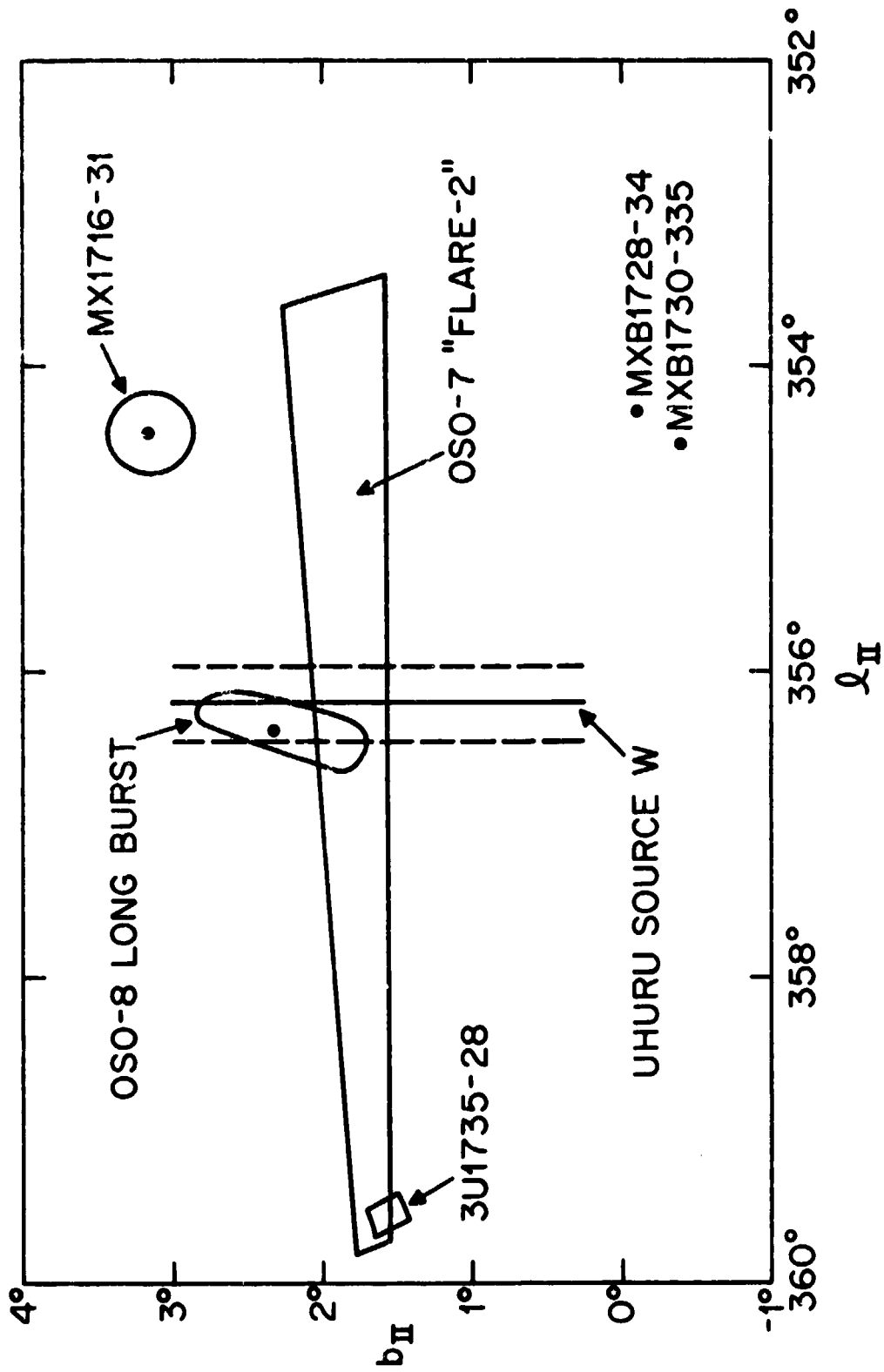
## FIGURE CAPTIONS

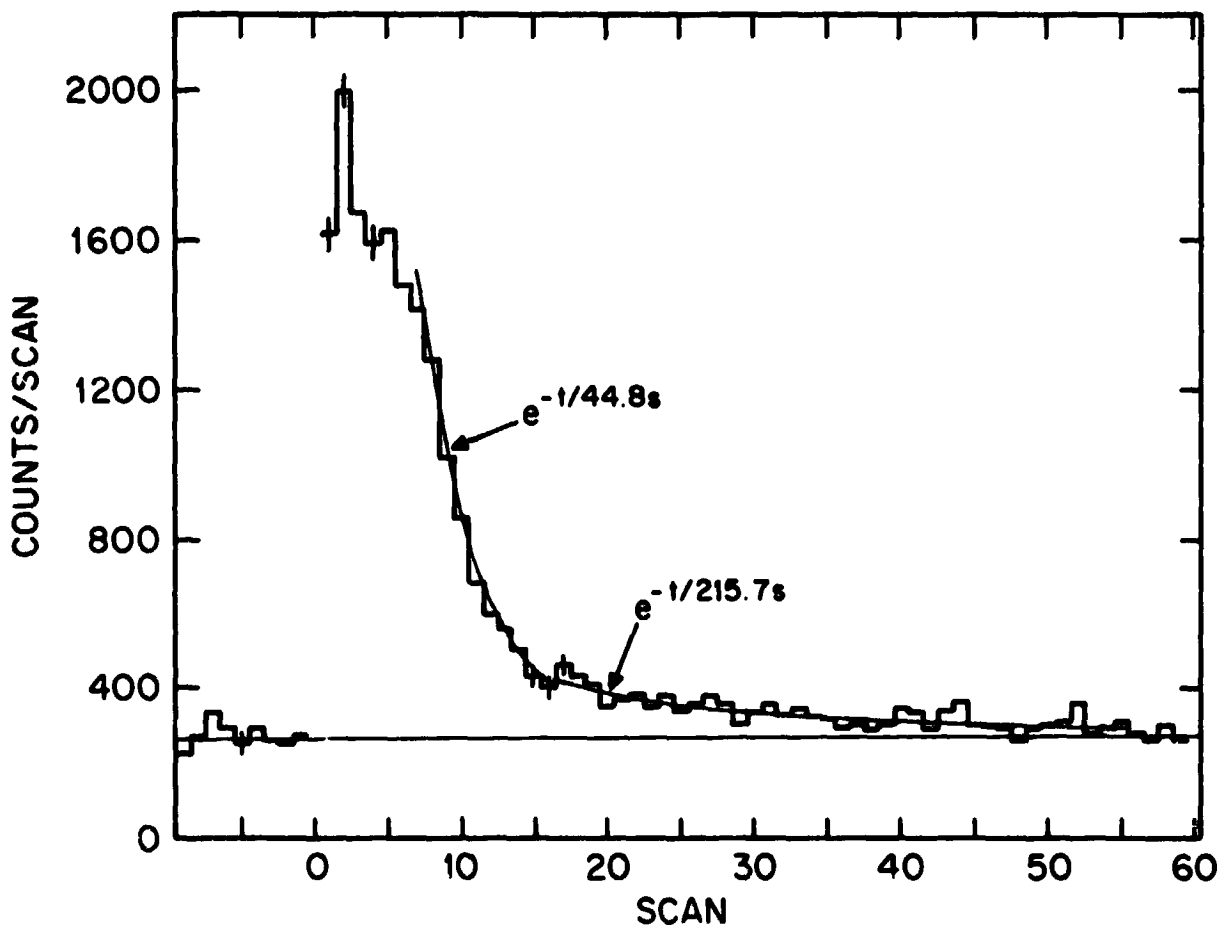
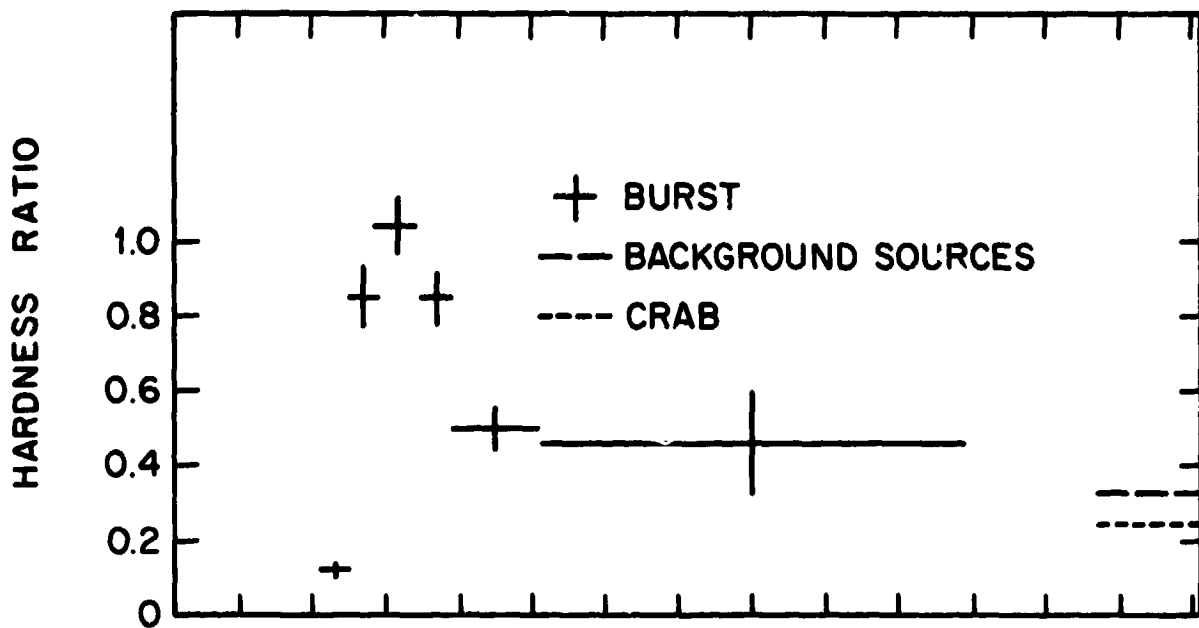
**Figure 1** Position determined for the long burst observed by OSO-8. The 90% confidence error box and the best position are shown with the error boxes for some other sources reported nearby. W is from Forman et al. (1976). The dashed lines indicate the error on the longitude. The latitude is poorly known. "Flare 2" observed by OSO-7 is discussed in the text.

**Figure 2(a)** Light curve for the burst. The values are the total counts received during the time the source was in view per spin (3.2 s in 10.68 s) with typical statistical errors. Spin 0 is discussed in the text.

(b) The ratio of the counts in the 6-10.6 keV channels to those in the 2-6 keV channels. For the excess counts in spin 0 the ratio was  $.43 \pm .03$ .

**Figure 3** Incident spectra of the burst for the initial pulse, the hardest interval and the tail of the decay. The solid curves show the best black body fits.





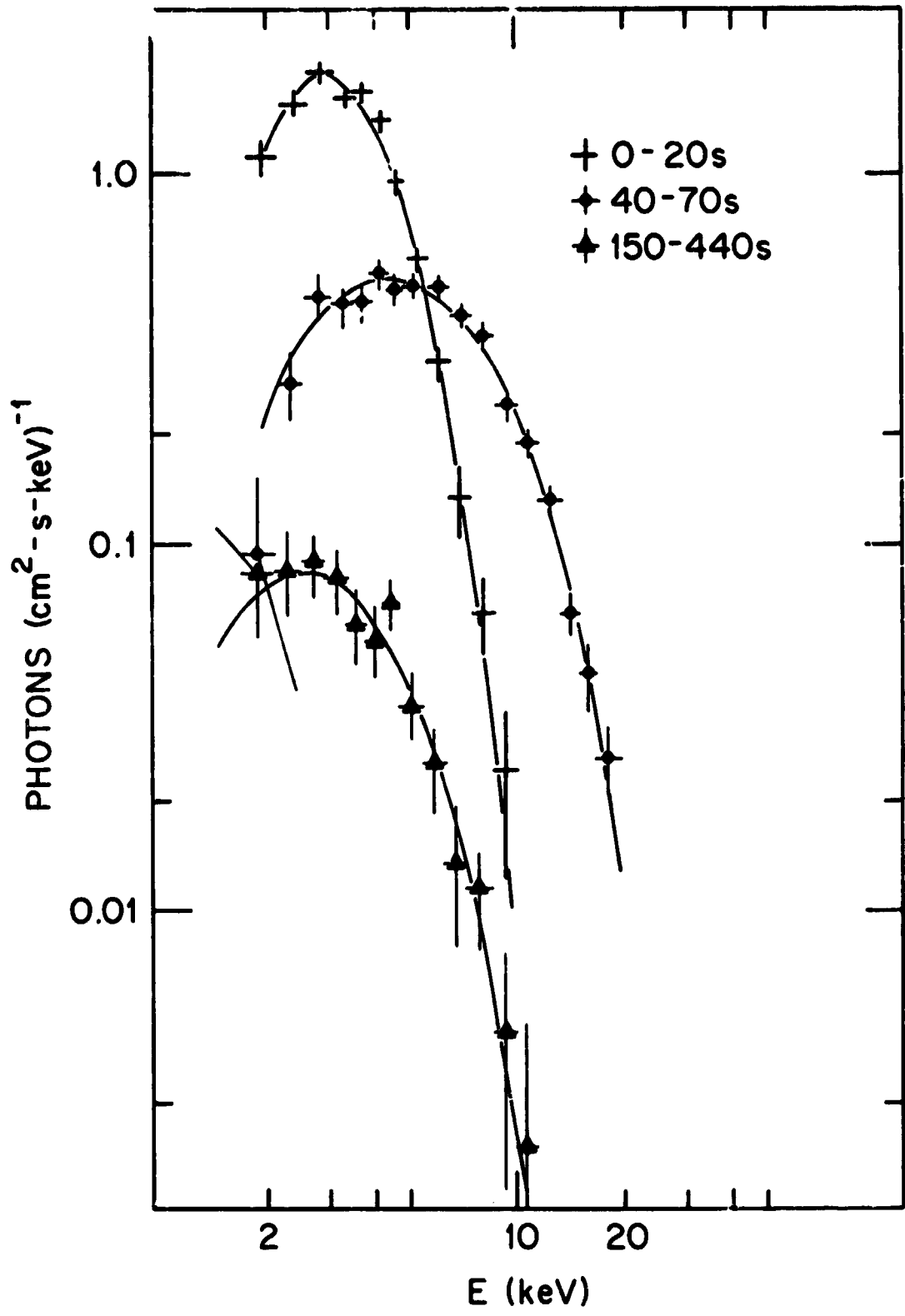


TABLE I  
Parameters of Spectral Fits

Time after start(s)	Black Body			Thermal Bremsstrahlung <sup>†</sup>		
	kT(keV)	N <sub>H</sub> (10 <sup>22</sup> cm <sup>2</sup> )	χ <sup>2</sup> <sub>r</sub> *	kT(keV)	N <sub>H</sub> (10 <sup>22</sup> cm <sup>2</sup> )	χ <sup>2</sup> <sub>r</sub>
0 - 20	.87 <sup>+0.07</sup> -.09	3 <sup>+2</sup> -1	1.1	1.8 <sup>+0.09</sup>	7.4 <sup>+5</sup>	1.6
20 - 40	2.04 <sup>+0.16</sup>	3 <sup>+3</sup>	.92	7.6	13.5	2.2
40 - 70	2.33 <sup>+0.07</sup> -.1	2 <sup>+2</sup>	.99	9.5	14.4	6.2
70 - 90	1.74 <sup>+0.2</sup> -.14	5 <sup>+3</sup> -3	1.1	5.1	14.4	3.2
90 - 150	1.37 <sup>+0.15</sup> -.21	6 <sup>+4</sup> -3	1.1	3.4 <sup>+0.6</sup>	13.5 <sup>+3</sup>	1.3
150 - 440	1.2 <sup>+0.25</sup> -.19	.8 <sup>+0.5</sup> -.7	1	3.2 <sup>+1.8</sup> -1.4	4.7 <sup>+3</sup> -2	.94

\*  $\chi^2_r = \chi^2/\text{degrees of freedom}$ . For a 3 parameter fit the 90% confidence limit was taken to be an increase in  $\chi^2$  by 6.1 from the best fit value. The degrees of freedom ranged from 9 to 17. Channels were not used which were sensitive to dead time corrections to background subtraction.

<sup>†</sup>The energy dependence of the Gaunt factor was taken to be  $E^{-.4}$ .

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