THE ASTROPHYSICAL JOURNAL, 212:L73–L76, 1977 March 1

SPECTRAL EVOLUTION OF A LONG X-RAY BURST

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Received 1976 September 13; revised 1976 November 15

ABSTRACT

An X-ray burst–like event with a peak intensity $1\frac{1}{2}$ times that of the Crab and a decay time of ~100 s was observed from near $l^{\text{II}} = 356\overset{\circ}{.}4$ and $b^{\text{II}} = 2\overset{\circ}{.}3$. Significant spectral changes occurred during the burst. The spectra were best fitted by the blackbody form with kT ranging from 0.87 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.

Subject headings: X-rays: bursts — X-rays: spectral

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, Beckman, and McClintock (1976) have reported two flares of several minutes from near MX 1716−31. A few flares with durations of minutes have been observed from flare stars (Heise *et al.* 1975). Bursts as long as 50 s have been reported from MXB 1730−335 (Lewin 1976) and as long as 100 s from a source in Norma (Belian, Conner, and Evans 1976; Grindlay and Gursky 1976*a*). 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 1975 September 11 (Swank *et al.* 1976; Bunner 1976*a*). 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 1975 September the region near the galactic plane between $l^{\text{II}} = 349°$ and the galactic center was in view of either the xenon detector scanning at 5° 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 $3\overset{\circ}{.}4$ for the argon detector and $5\overset{\circ}{.}09$ for the scanning xenon detector. During the observing time integral rates were obtained every 160 ms, and pulse height information was obtained every 2.08 s for the scanning detector and 40.96 s for the pointed detectors. The satellite spin period was 10.7 s.

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 were 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 1976*a*) 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 $(l^{\text{II}}, b^{\text{II}}) = (356\overset{\circ}{.}4, 2\overset{\circ}{.}3)$. The 90% confidence error box is shown in Figure 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 1976*b*). 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 Figure 2*a*. The peak count range was $1\frac{1}{2}$ times that of the Crab in this detector (sensitive from 1.7 to 60 keV). Spin 0 is the

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† Work supported by University of Maryland grant NGR 21-002-316.

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* counts 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 to 11 keV to the counts from 2 to 6 keV and divided the burst into intervals with similar hardness ratios. The ratios for these intervals are shown in Figure 2*b*. 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

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

with σ the cross section for photoionization of neutral material with the abundances used by Fireman (1974). The parameters of the fits are given in Table 1, 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 χ^2 for the best fit was less than the 90% confidence χ^2 for the blackbody fit. Although we cannot put significant limits on changes in the absorbing column density, the changes in temperature for the blackbody temperature are statistically significant. The total energy incident from the burst was 5×10^{-6} ergs

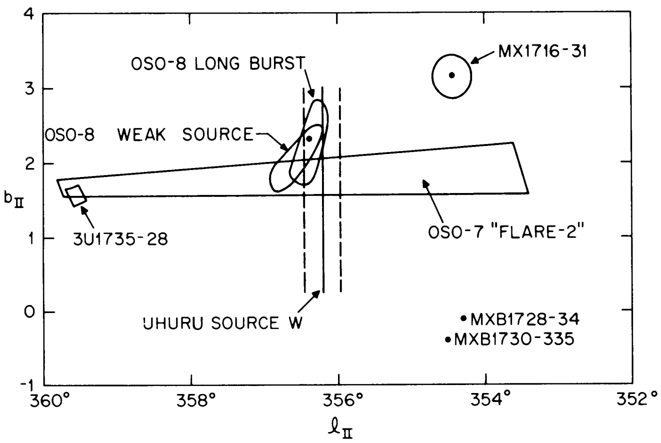

FIG. 1.—Positions determined for the burst and the weak source by OSO-8. The 90% confidence error box and the best position are shown with those of other sources reported in the region. W is from Forman *et al.* (1976). The dashed lines indicate the error on the longitude. The latitude is poorly known. "Flare 2" observed by OSO-7 is discussed in the text.

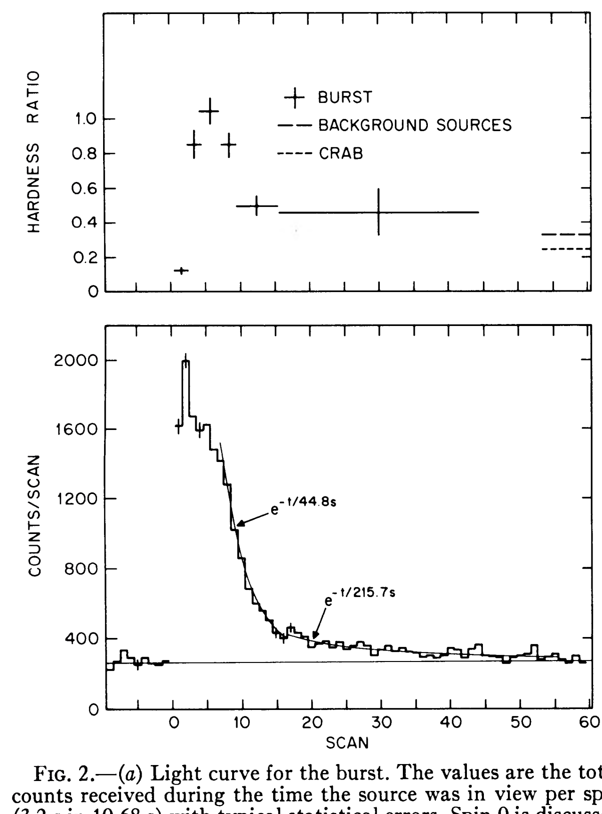

FIG. 2.—(*a*) Light curve for the burst. The values are the total counts received during the time the source was in view per spin (3.2 s in 10.68 s) with typical statistical errors. Spin 0 is discussed in the text. (*b*) The ratio of the counts in the 6–10.6 keV channels to those in the 2–6 keV channels. For the excess counts in spin 0 the ratio was 0.43 ± 0.03.

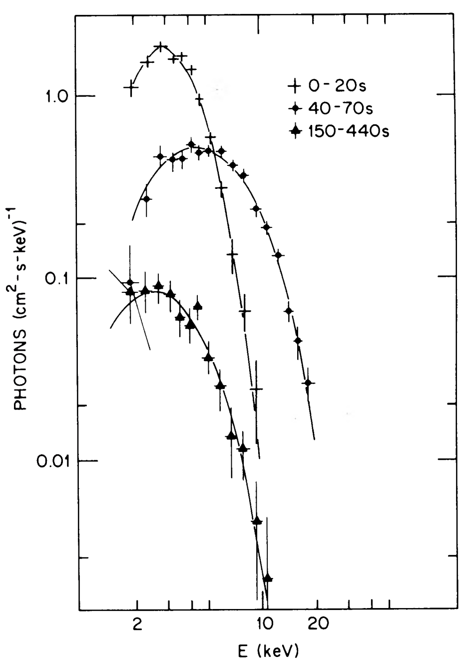

FIG. 3.—Incident spectra of the burst for the initial pulse, the hardest interval, and the tail of the decay. The solid curves show the best blackbody fits.

TABLE 1

PARAMETERS OF SPECTRAL FITS

TIME AFTER START(s)	BLACKBODY kT(keV)	BLACKBODY $N_H(10^{22}\ cm^2)$	BLACKBODY χ^2_r*	THERMAL BREMSSTRAHLUNG† kT(keV)	THERMAL BREMSSTRAHLUNG† $N_H(10^{22}\ cm^2)$	THERMAL BREMSSTRAHLUNG† χ^2_r
0–20	0.87 (+0.07, −0.09)	3 (+2, −1)	1.1	1.8±0.09	7.4±5	1.6
20–40	2.04±0.16	3±3	0.92	7.6	13.5	2.2
40–70	2.33 (+0.07, −0.1)	2±2	0.99	9.5	14.4	6.2
70–90	1.74 (+0.2, −0.14)	5±3	1.1	5.1	14.4	3.2
90–150	1.37 (+0.15, −0.21)	6 (+4, −3)	1.1	3.4±0.6	13.5±3	1.3
150–440	1.2 (+0.25, −0.19)	0.8 (+0.5, −0.7)	1	3.2 (+1.8, −1.4)	4.7 (+3, −2)	0.94

* $\chi^2_r = \chi^2$ per degree of freedom. For a 3 parameter fit the 90% confidence limit was taken to be an increase in χ^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.

† The energy dependence of the Gaunt factor was taken to be $E^{-0.4}$.

cm^{-2} with a maximum flux of 6×10^{-8} ergs cm^{-2} 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* counts s^{-1} was present there. However, during September 14–15 the pointing argon detector passed over the region and observed a weak flux. The error box for the position is shown in Figure 1. The data are consistent with a steady source at the position of the burst with a flux from 2 to 6 keV of 3.4×10^{-10} ergs cm^{-2} s^{-1}, equivalent to 20 *Uhuru* counts s^{-1}. Such a source could also have been present before the burst (part of the background for the burst spectra). The spectrum was well fitted from 1.6 to 24 keV with a thermal bremsstrahlung spectrum for $kT = 10 \pm 2$ keV, with an absorbing column density of only $1.8 \pm 1.8 \times 10^{21}$ 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 8×10^{55} $(d/1\ \text{kpc})^2$ cm^{-3}.

III. DISCUSSION

Although 100 s, the time scale of the event, is a factor of 10 times the lifetimes 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 lifetime 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 cutoffs of 2–3 keV which characterize the spectra are similar to those of short bursts (Grindlay *et al.* 1976; Lewin *et al.* 1976*b*). 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.* 1975).

For spherical emission the total energy output was 6×10^{38} $(d/1\ \text{kpc})^2$ ergs at a distance d, on the same order as that involved in typical short bursts for $0.4 < d < 4$ kpc (Clark *et al.* 1976; Lewin *et al.* 1976*a*, *b*). 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. In that case, since the best fits to the burst spectra required as much as an order of magnitude more absorption, the absorption during the burst occurred at the source.

If we assume that the source was nearly a blackbody, absorbed by some material outside itself, at the peak intensity during the first 20 s the radius of a spherical isotropic emitter was 1 (+0.6, −0.2) $\times 10^6$ $(d/1\ \text{kpc})$ cm. The same assumptions during the remainder of the burst imply a radius within 30% of 1.5×10^5 $(d/1\ \text{kpc})$ cm. The values could be a few times larger if the radiation was not isotropic. Grindlay and Gursky (1976*b*) have suggested that 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 that 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.* 1976*a*, *b*). The peak luminosity for the long burst would have been 8×10^{36} $(d/1\ \text{kpc})^2$ ergs s^{-1}, so that the source would not have been Eddington-limited for accretion onto a neutron star unless it were $\gtrsim$5 kpc away.

If the burst source and the weak source observed a few days after the burst are the same, the difference in the spectra indicates a complex source. The possible association of the burst source with a weak nonburst source is similar to the association of one of the flares ("Flare 1") observed by Markert, Backman, and McClintock (1976) with another weak relatively unabsorbed source, MX 1716−31. Our error boxes intersect 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 s for the burst reported here, we find no compelling reason to associate the two. Our error boxes also intersect that of the weak *Uhuru* source W (Forman, Jones, and Tananbaum 1976). While the chances per day of observing another burst appear low, more information about the identity might be obtained from the weak and more persistent source or sources in the region. There are no recorded supernova remnants near the position, but there are three SAO stars in our error box for the burst.

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