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HEAO 1 OBSERVATION OF A TYPE I BURST FROM MXB 1728−34[1]

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ABSTRACT

We present the results of a *HEAO 1* observation of a type I X-ray burst, observed from MXB 1728−34 over the energy range 2–150 keV with a time resolution of 5 ms. The rise of the burst is distinctly resolved, lasting several tenths of a second and showing a marked flattening as burst maximum is approached. Intensity changes with scales of tens of milliseconds are resolved as are spectral changes on a time scale of hundreds of milliseconds. A simple, smoothly evolving spectral model cannot fit the rapid temporal and spectral changes at the start of the burst. The relatively smooth decay of the burst is well described by a cooling blackbody model. The data can also be fitted by a model with significant Compton scattering and lower emissivity. If the emission is blackbody, the apparent radius of the emission region is ~6 km, with the source at a distance of ~5 kpc. The largest apparent radius allowed for lower emissivity models is about twice the blackbody radius. The hydrogen column density to MXB 1728−34 is $\sim 2 \times 10^{22}$ cm^{-2}. Hard X-ray emission from 85 to 180 keV is <6% of the total observed X-ray flux at energies <25 keV and has a spectrum steeper than gamma-ray burst spectra.

Subject heading: X-rays: bursts

I. INTRODUCTION

The average properties of X-ray bursts have been determined over the past 3 years by a variety of satellite instruments (see Lewin and Joss [1978] and Lewin [1979] for recent reviews of the subject, and references therein). Most bursts are characterized by a rise time of $\lesssim 1$ s, a decay time of ~10 s, a peak luminosity of $\sim 10^{38}$ ergs s^{-1}, a total radiant energy of $\sim 10^{39}$ ergs, and a blackbody spectrum whose temperature decreases during the decay phase. Bursts of this nature have been categorized by Hoffman, Marshall, and Lewin (1978) as type I, to distinguish them from the "rapid bursts" (type II) observed from MXB 1730−335.

Previous observations of bursts were made with instruments of relatively small area (at most, several hundred cm^2). The small area has limited the ability to determine such characteristics of individual bursts as rise time, unusual temporal features, and spectral evolution. Superpositions of several normal type I bursts (Hoffman, Lewin, and Doty 1977*a*, *b*; van Paradijs 1978), as well as individual spectra of unusually long bursts from two sources (Swank *et al.* 1977; Hoffman *et al.* 1978), suggested that all these sources were radiating as blackbodies with radii consistent with neutron stars, which cooled as the bursts progressed. Van Paradijs (1978) showed that the near-uniformity in burst spectra, combined with the assumption that the peak luminosity of X-ray bursts is a standard candle, leads to a consistent picture of burst sources, all with apparent emission-region radii within ~20% of 6.5 km. He further showed (van Paradijs 1979) that correcting the fitted temperatures and deduced radii for the effect of gravitational redshift (up to ~40% if the emission region is located on the surface of a neutron star) leads to upper limits on the mass of neutron stars on whose surfaces bursts occur. Critical to these conclusions is the blackbody nature of burst spectra.

In this *Letter* we present the results of an analysis of data from a type I X-ray burst from MXB 1728−34 observed by three large-area instruments on *HEAO 1*. These measurements cover the energy range from 2 to 150 keV and provide for the first time the capability of resolving significant intensity changes on a time scale of tens of milliseconds and spectral changes on a time scale of tenths of seconds. The counting statistics and energy resolution allow a meaningful comparison between blackbody models and models using a partly scattering atmosphere, which would result in a lower emissivity and hence different apparent radii. We do

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not apply any redshift corrections to the data in this paper, so all temperatures, radii, luminosities, etc., are "apparent" quantities as measured at the Earth, not as they are at the origin of the burst.

II. OBSERVATIONS

MXB 1728−34 is known to burst at intervals of ~3–8 hours (Hoffman *et al.* 1976). During the present observation, it was possible to point *HEAO 1* up to only 3 hours at a time. To maximize the chances of observing a burst during the four pointing opportunities, the source was monitored by the *SAS 3* X-ray observatory in order to predict the best 3 hour period for the *HEAO* observations. One burst occurred just 2 minutes after the chosen pointing interval, one was missed because of Earth occultation, and one occurred while *HEAO 1* was turned off in the South Atlantic Anomaly. The fourth burst predicted by the *SAS 3* observers occurred at $18^h41^m19^s$ UT on 1978 March 10 and was the only one observed by both *SAS 3* and *HEAO 1*.

Three *HEAO 1* instruments were used in the observation of this burst. One module of the A-1 array with an area of 1800 cm^2 was used to provide the high time resolution data (5 ms). This module was operated in the 5–17 keV range set by high time resolution mode discriminators. Detailed spectral information was provided by the A-2 and A-4 instruments. The A-2 measurements were made with a 750 cm^2 argon proportional counter covering the 2–20 keV range ("medium energy detector" or "MED") and with two 840 cm^2 xenon proportional counters extending over the 2–60 keV range ("high energy detector" or "HED"). The A-4 measurements were made by two phoswich scintillation counters having a total area of 200 cm^2 and a detector efficiency $>25\%$ over the energy range 13–180 keV. For a spectrum resembling that of the burst observed from MXB 1728−34 (see below) the median photon energy (equal counts above and below) of the various energy bands are A-1 ~8 keV; A-2 ~4 keV (MED) and ~12 keV (HED), and A-4 ~15 keV.

III. RESULTS

a) *Temporal Features*

Figures 1*a*, *b*, and *c* display the overall structure of the burst in three overlapping energy intervals. It is typical of the structure of type I X-ray bursts (Hoffman, Marshall, and Lewin 1978). The initial rise is nearly simultaneous at all energies, but the burst reaches maximum slightly later at higher energies. The maximum of the burst is broader at high energies than at low energies. The decay is faster at high energies. At lower energies, there is a broad subburst prior to the decay. Such multiple peaks are observed in some, but not all, type I bursts.

The rise of the burst has been studied in detail in the 5–17 keV range using A-1 data. The first few seconds of the burst are displayed with a resolution of 10 ms in Figure 2. The data are well fitted by the functional form $f(t) \propto 1 - e^{-t/\tau}$, where $\tau \sim 150$ ms. This functional form reflects the approach to saturation which the burst displays during its rise.

The combined data from A-1 and A-2, plotted with

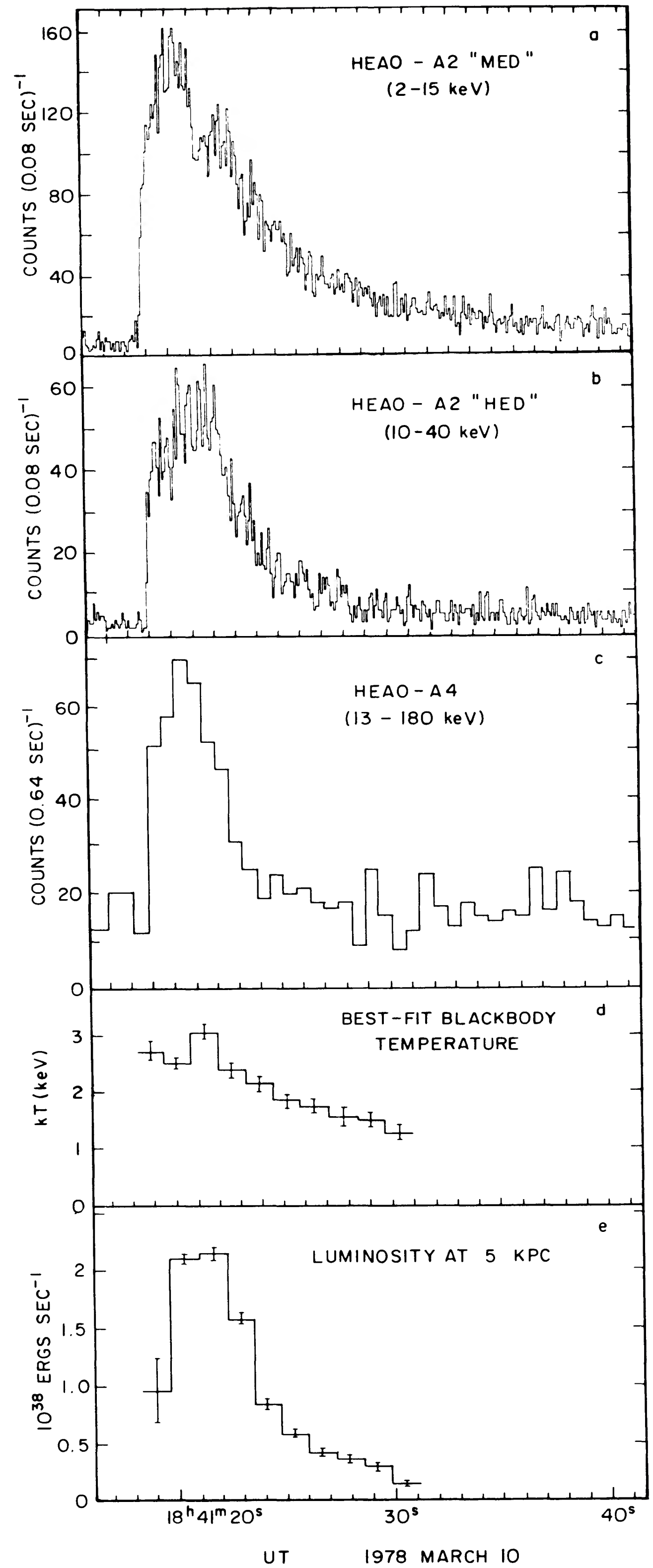

FIG. 1.—(*a*)–(*c*) Light curves of the X-ray burst from MXB 1728−34 observed by the *HEAO* A-2 MED, HED, and A-4 instruments. Energy ranges given are for detector efficiency $>25\%$. (*d*) Spectral-fit determinations of the blackbody temperature for the burst in successive 1.28 s bins. (*e*) Evolution of the burst luminosity in 1.28 s bins, assuming spherically symmetric source emission at 5 kpc.

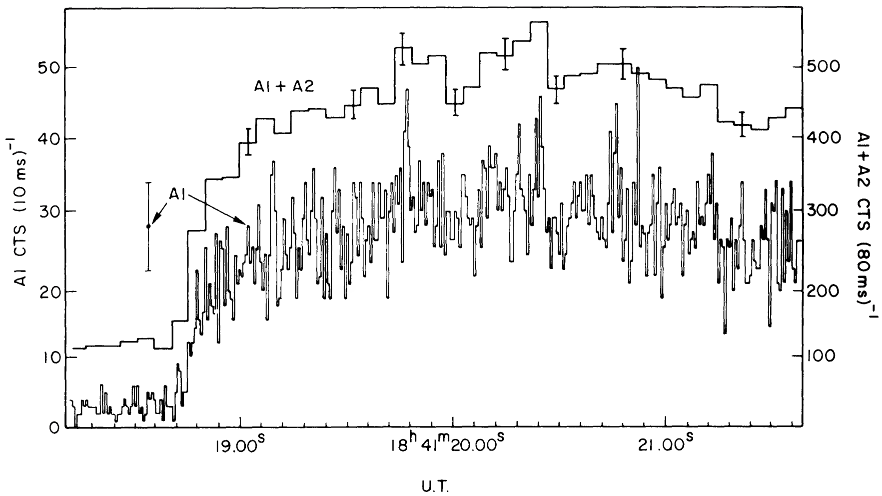

FIG. 2.—*Lower curve,* high time resolution (10 ms) light curve from the *HEAO* A-1 detector during the first part of the burst from MXB 1728−34. *Upper curve,* combined data from the A-1 (5–17 keV) and A-2 MED (2–15 keV) detectors, in 80 ms bins.

a resolution of 80 ms, are shown in Figure 2 above the 10 ms resolution A-1 data. Two features ~250–300 ms wide are apparent in the 80 ms data, at 19.8 s and 20.3 s, and a broader feature is centered at ~20.8 s. The peaks of these three features are ~0.5 s apart. We have searched for but not found any evidence for a persistent modulation at this period in the remaining portion of the burst. As a test of the significance of this structure, polynomials up to quartic order had only a 5% probability of satisfactorily fitting the combined 80 ms data in this interval. The two features near 19.8 s and 20.3 s were included in the data that were fitted but are nonetheless ~3 σ above the fitted curves.

There are also significant intensity variations with a time scale of tens of milliseconds. The ~30 ms spike at 19.8 s, for example, is ~3.5 σ above the adjacent average rate. These narrow spikes are correlated with the hundreds of milliseconds-wide features discussed above. Bins in the 10 ms data with rates exceeding the local 100 ms average by $\geq 2\ \sigma$ contribute ~30% of the flux in the broad, enhanced features in the 80 ms data.

b) Spectral Evolution

The spectrum of the burst was monitored by the three A-2 proportional counters in nine 1.28 s intervals following the rise. These counters provide 12 independent, although partially overlapping, energy channels. Spectral fits were made separately to the data from these nine segments for blackbody, thermal bremsstrahlung, and Boltzmann models. Allowance was made in bremsstrahlung models for a moderate optical depth to Compton scattering using the series developed by Chapline and Stevens (1975), generalized to incorporate the Gaunt factor. In the energy and temperature regimes involved here, the fitted temperatures were insensitive to assumed elemental abundances. The blackbody model fitted the data best, although the values of reduced χ^2 were as large as 2 per degree of freedom for segments 3, 6, and 7. Fits to a set of bremsstrahlung models either thin, moderately thick, or so thick to Compton scattering ($\tau_{\text{Compton}} \sim 15$) as to be in the regime approximated by a Boltzmann distribution were not acceptable (<0.1% confidence level). In comparison, the blackbody model was acceptable at the 5% level when all intervals were considered together. The overall χ^2 was calculated by adding the individual χ^2 values of each interval, allowing the spectral parameters to change from interval to interval as the burst evolved to give the best fit in each interval.

We cannot in a physically meaningful way isolate an optical depth parameter in a blackbody model and allow it to decrease slowly from infinity to approximate different shades of gray. "Gray body" spectral models require solutions of radiative transfer and must consider both free-free absorption and scattering. A model described by Swank, Eardley, and Serlemitsos (1979), which will be presented in detail in a separate paper, can fit these data as well as, but not better than, a blackbody model. Their model has $\tau_{\text{Compton}} \sim 8$. This model has only three explicit free parameters, temperature, absorption, and normalization, the same as the blackbody model. However, the model itself implicitly has the Compton scattering and free-free opacity as parameters, even though they are not explicitly variable. The best-fit temperatures for this model are roughly one-third higher than for the blackbody model.

The best-fit values of kT in the blackbody model are plotted in Figure 1*d* on the same time scale as the light curves. The blackbody energy flux during each segment was calculated using the best-fit spectral values for intensity and temperature. The total source luminosity as the burst progresses, assuming spherical symmetry and a source distance of 5 kpc (van Paradijs 1978), is shown in Figure 1*e*. The fits gave an average absorbing column density of $(2.3 \pm 0.4) \times 10^{22}$ cm^{-2} of hydrogen. This is consistent with the value of $(1.8 \pm 0.2) \times 10^{22}$ cm^{-2} that the A-2 data give for the steady component from MXB 1728−34, which is best fitted by a thermal bremsstrahlung model.

The total energy emitted during the burst was $(4.4 \pm 0.1) \times 10^{-7}$ ergs cm^{-2}, corresponding to $(1.3 \pm 0.03) \times 10^{39}$ ergs at a distance of 5 kpc (van Paradijs 1978). The peak intensity was $(7.1 \pm 0.2) \times 10^{-8}$ ergs cm^{-2} s^{-1} or $(2.1 \pm 0.1) \times 10^{38}$ ergs s^{-1} at 5 kpc.

c) *Integrated Burst Spectrum*

High spectral resolution data were obtained with an integration time of 41 s from the A-2 experiment. The onset of the burst occurred 20 s after the beginning of an integration period. These data from A-2, together with the high energy A-4 data, are plotted in Figure 3 for the first 21 s of the burst. The detector response function has been unfolded. There is no evidence of significant spectral features in the data from any of the detectors. These high spectral resolution data do *not* represent a single burst spectrum with a specific temperature and intensity, since they were accumulated over a time during which the burst spectrum was changing rapidly. A set of evolving burst spectra can be used, however, to generate spectral data which would be collected during the first $\sim$20 s after the burst onset, which can then be compared to the actual data. The solid line in Figure 3 is the time-integrated burst spectrum given by the sum of the individual best-fit blackbody spectra for each of the 1.28 s segments in figure 1*d*. The total reduced χ^2 for the three A-2 detectors was 1.25 for 128 degrees of freedom for this set of blackbody fits, the best of any of the simple evolving models we have tried. For comparison, evolving Boltzmann and thin thermal bremsstrahlung models gave 1.4 and 3.0, respectively, with the same number of degrees of freedom.

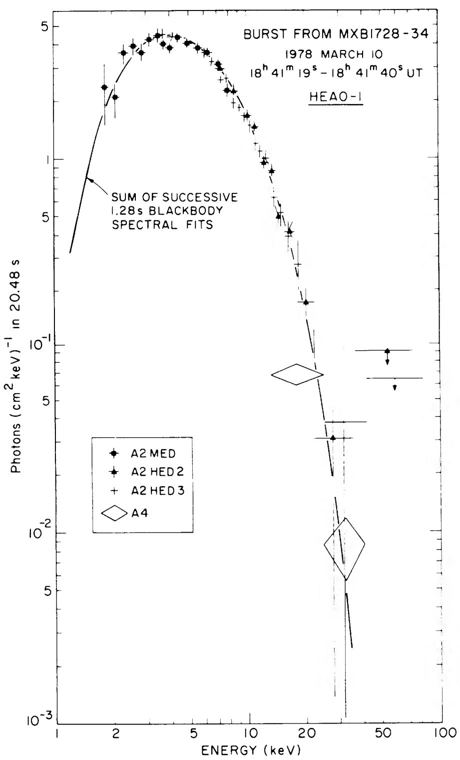

FIG. 3.—High spectral resolution data for the entire first 20 s of the burst from MXB 1728−34 from the *HEAO* A-2 MED and HED detectors and from the *HEAO* A-4 hard X-ray detectors. The solid line is the overall burst spectrum that would be given by the sum of individual fitted spectra for each of the segments in Fig. 1*d* (see text).

The upper limits in the two highest A-4 energy channels, 40–85 keV and 85–180 keV, are consistent with a continuation of the rapidly falling blackbody spectrum observed at lower energies. The 99% confidence upper limit for the total X-ray flux from 85 to 180 keV during the burst is 2.6×10^{-8} ergs cm^{-2}, or $\sim$6% of the total observed X-ray flux at energies $<$25 keV.

IV. DISCUSSION

The rise to burst maximum takes several tenths of a second. This is consistent with predictions from the nuclear flash model for type I bursts (Joss 1978). The burst maximum exhibits significant structure on time scales of tens and hundreds of milliseconds, with the shorter time-scale spikes contributing $\sim$30% of the flux in the broader features. A detailed analysis of the short-time-scale behavior is being pursued by the NRL group using A-1 data.

The overall spectral characteristics of the burst are well described as blackbody emission, but there are difficulties with a simple interpretation early in the burst. As seen in Figure 1*e*, the luminosities observed in the second and third 1.28 s segments are nearly identical; however, Figure 1*d* shows that the blackbody temperatures for these intervals differ markedly. This is inconsistent with emission from a blackbody of constant area. We note that the third segment, in which the high temperature was measured, coincides with a dip in the low energy light curve (Fig. 1*a*). This could imply an increase in absorption, but our data favor a higher temperature and a lower radius. Using a superposition of seven bursts observed by *SAS 3*, Hoffman, Lewin, and Doty (1977*a*) found evidence for a small increase in temperature between 3 and 7 s after burst onset.

After about 4 s, however, the luminosity and temperature decline smoothly, and a cooling blackbody model gives a good description of the burst. During the decay the flux is proportional to T^4. The weighted average of seven determinations of the apparent radius of an isotropic blackbody emitter is $(12 \pm 0.4) \times d_{10}$ km, where d is the distance to the source in tens of kiloparsecs. Van Paradijs (1978) has shown that the radii determined from blackbody spectral fits for ten type I burst sources are nearly the same if the peak luminosity in a burst is a "standard candle." If the maximum luminosity of this burst is $\sim 1.8 \times 10^{38}$ ergs s^{-1}, which is the Eddington limit of a 1.4 $M_{\odot}$ object, then the distance to the source is 4.6 ± 0.1 kpc, and the apparent radius of the emitting region is 5.6 ± 0.2 km.

Two notes of caution are necessary concerning these results. The peak flux of 1.7×10^{-7} ergs cm^{-2} s^{-1} reported by Hoffman, Lewin, and Doty (1977*a*) for several bursts from MXB 1728−34 is twice the value observed here. The corresponding radius and distance of MXB 1728−34 derived by van Paradijs (1978) from *SAS 3* data are 6.5 ± 0.4 km and 4.2 ± 0.2 kpc. These values differ from the present values by more than the statistical uncertainty inherent in the data. Thus, while X-ray bursts as a class may reasonably be characterized as "standard candles," it must be recognized that individual bursts fluctuate about the average.

The determination of a radius from these data assumes totally thick blackbody emission. A "gray body" at a higher temperature with a larger size could produce the same luminosity with a similar, although not identical, spectrum. Our results have excluded thermal bremsstrahlung and Boltzmann spectra with optical depths due to Compton scattering as high as $\tau \sim 15$. This is the same result earlier found by Hoffman, Lewin, and Doty (1977*a*).

The work of Swank, Eardley, and Serlemitsos (1979) mentioned above shows, however, that a scattering model ($\tau_{cs} \sim 8$) with a free-free opacity ($\tau_{ff} \lesssim 8$) fits these data as well as a blackbody model. The radius of the emission region in this model is about twice that in the blackbody model. Decreasing the free-free opacity below this value yields predominantly Compton-dominated models, which we have shown give poorer fits to the data. Models with increased free-free opacity will approach the blackbody case ($\tau_{ff} = \infty$) and will thus fit the data as well as this model or the blackbody model, with best-fit temperature and radii converging to the blackbody values as the free-free opacity increases. We know of no models giving acceptable fits to the data which would give emission-region radii much in excess of twice the blackbody radius. This result is important in light of the constraints van Paradijs (1979) is able to place on neutron star masses when he applies gravitational redshift corrections to spectral fits of bursts and assumes blackbody radii. The relativistic corrections decrease for larger radii, and the upper limits on the mass are relaxed.

The fits of the A-2 data to both the burst and nonburst emission from MXB 1728−34 are consistent with an average absorption column density of $\sim 2 \times 10^{22}$ cm^{-2}. This corresponds to 8 ± 1 mag of optical extinction (Gorenstein 1975; Ryter, Cesarsky, and Audouze 1975). For a distance to the source of ~ 5 kpc, this gives an absorption of ~ 1.6 mag kpc^{-1}, which is a reasonable value. With this extinction, a globular cluster would have been detected by Liller (1977) and by Glass (1978). However, a blue stellar counterpart only slightly fainter than that of 4U 1735−44, with $M_v \sim 3$ (McClintock, Canizares, and Backman 1978), would probably have escaped detection at 7200 Å and certainly at 2.2 μm. We suspect that MXB 1728−34 is an object similar to MXB 1735−44.

The hard X-ray flux observed during this burst can be compared to the hard X-ray flux observed during gamma-ray bursts. Wheaton *et al.* (1973) and Metzger *et al.* (1974) have analyzed two gamma-ray bursts at energies from <10 keV to >1 MeV. Below 100 keV, the gamma-ray burst spectra are well described by a power law with a photon number exponent of ~ 1.4 and a normalization of a few photons cm^{-2} s^{-1} keV^{-1} at 10 keV. This gives several tens of times more flux in the 25–40 keV region than in this X-ray burst and hundreds of times more in the 40–85 keV region. Thus, in the hard X-ray spectral region, this X-ray burst has both a softer spectrum and an energy density two orders of magnitude smaller at the Earth than the γ-ray bursts. It is clearly a different phenomenon.

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