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TITLE: 3-10 keV AND 0.1- TO 2-MeV OBSERVATIONS OF FOUR GAMMA-RAY BURSTS

AUTHOR(S): J. G. LAROS, W. D. EVANS, E. E. FENIMORE, R. W. KLEBESADEL,
S. SHULMAN, and G. FRITZ

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

3-10 keV AND 0.1- to 2-MeV OBSERVATIONS OF FOUR GAMMA-RAY BURSTS

J. G. Laros, W. D. Evans, E. E. Fenimore, R. W. Klebesadel
Los Alamos National Laboratory, Los Alamos, NM 87545

S. Shulman* and G. Fritz
NRL, (need city and state)

ABSTRACT

Four catalogued γ -ray bursts that occurred between 79/3/7 and 79/7/31 have been observed over the 3-10 keV range by a joint NRL/Los Alamos experiment on the Air Force P78-1 satellite. The bursts were also well observed by members of the interplanetary network. In this paper we present hardness ratios, X-ray/ γ -ray luminosity ratios, and time histories. The most significant results presented herein can be summarized as follows: (1) Gamma-ray bursters can emit fairly strongly at X-ray energies near the time of the γ burst with $L_x/L_\gamma \sim .02$ ($L_x \sim 10^{37}$ ergs s⁻¹, 3-10 keV, assuming a distance of 1 kpc). (2) The centroid of the X-ray emission generally lags the γ -ray centroid, but there is also evidence for one or more types of X-ray precursor activity.³ The γ -ray hardness ratios were not highly variable for these particular events. However, there is some evidence that the γ -ray spectra softened near the ends of the bursts when the X-ray/ γ -ray ratios were high. (4) The X-ray/ γ -ray power law number index during times of the strongest γ -ray emission ranged from 0.8 to ~ 1.1 for the four bursts. (5) The X-ray tail of GB790307 probably can be modeled as the cooling of hot plasma generated during the γ -ray burst. Simple versions of this model can be used to estimate various source parameters. These estimates imply a distance of a few hundred to a few thousand pc. (6) Gamma-ray bursters probably do not produce events similar to "classical" X-ray bursts independently of the γ -ray emission.

1. INTRODUCTION

Our current incomplete understanding of γ -ray bursters is due in large part to a lack of observations at other than γ -ray and very hard X-ray wavelengths during the outbursts. The optical data base consists of possibly three archival events).^{1,2} The few X-ray observations below ~ 10 keV³⁻⁸ are either actually of down-scattered γ -rays or are compromised by poor time resolution, calibration uncertainties, long data gaps, or inadequate characterization of the bursts at γ -ray energies. In this paper we present new 3-10 keV observations along with 0.1-2 MeV observations of four gamma-ray bursts that occurred in 1979 on March 7, March 25, May 4, and July 31. Although the X-ray observing conditions were not ideal due to changing background rates and incomplete temporal coverage, these

*Also Sachs-Freeman Associates

new low energy observations have fewer limitations than were inherent in the previous work. Thus, the data presented here significantly increase our knowledge of the behavior of γ -ray bursters outside the γ -ray regime, and therefore should play a key role in the eventual determination of the correct γ -ray burst model.

II. INSTRUMENTATION

The X-ray observations were performed by the NRL/Los Alamos "XMON" experiment on the USAF P78-1 satellite which was launched into a 600 km near-polar orbit on Feb. 24, 1979. The OSO-type satellite consists of a sun-pointing "sail" and a "wheel" that spins with a 5.5 ± 0.1 s period. XMON is a wheel experiment consisting of two crossed-field-of-view proportional counters. Each 100 cm^2 detector has a $3^\circ \times 30^\circ$ FWHM aperture centered 50° from the spacecraft spin axis, which is inclined 6° to the equatorial plane and precesses with a one year period. This geometry results in $\sim 25\%$ sky coverage integrated over a spacecraft spin period, and $\sim 90\%$ coverage in the course of a year. At no time can solar X-rays directly enter the detector apertures, but a minor penalty for this arrangement is a lack of coverage near the celestial poles. A source observation consists of a "snapshot" each spacecraft rotation. This results in a selection effect in favor of sources that emit strongly for longer than ~ 5 s.

The proportional counters are constructed in two layers, with charged particle rejection derived by noting coincidences between the layers and between adjacent anode wires in the front layer. The nominal 3-10 keV energy range of the instrument is determined at the low end primarily by the .010 inch Be entrance window, and at the upper end by a level-discriminator and the 4.6 mg cm^{-2} thickness of the Ar/CO₂ counter gas. Inflight energy calibration is provided by Fe-55 radioactive sources that are periodically rotated into the detector fields-of-view by command.

The XMON scientific data stream is normally comprised of 64 ms accumulations covering the 3-6 and 6-10 keV ranges for the two counters. Additionally, there exists a special "fast" data mode used $\sim 7\%$ of the time, whereby 32 ms resolution is obtained at the expense of the 6-10 keV channels. Certain housekeeping data are telemetered with 2 s resolution. One of the housekeeping channels - namely, the >10 keV rate - is of some scientific value for the γ burst observations.

The γ -ray observations presented in this paper were carried out by the Pioneer Venus Orbiter Gamma-Ray Burst Detector (PVO), which has been described previously.⁹

III. OBSERVATIONS

Concurrent XMON data and PVO data covering March through December of 1979 are in hand at Los Alamos. During this period there occurred 45 γ bursts for which locations have been derived.¹⁰ This particular data set is especially amenable to XMON analysis

because: (1) the known locations enable one almost immediately to eliminate from further consideration ~85% of the events, which are either earth-blocked or otherwise out of the XMON field of view. (2) The catalogued locations can be compared with independently derived XMON locations to convincingly establish the association of observed XMON bursts with the γ burster. (3) Since many of the catalogued events were observed only by interplanetary spacecraft, a location is needed to temporally align the X-ray and γ -ray data records. For these reasons, the X-ray results presented herein are derived from an examination of XMON data only at times of γ -ray bursts having known locations. (A search involving the remainder of the γ burst data base is underway.)

Of the 45 localized bursts, it was determined that eight were probably in the XMON field-of-view during a time period when XMON data were available. Four of these events were positively detected, and the results are summarized in Table I and presented in detail below. Upper limits for the other four bursts cannot be stated quantitatively due to changing background rates combined with uncertainties in source location (hence exposure) and X-ray time history. Qualitatively, these limits are in the $10^{36} - 10^{37}$ ergs s^{-1} range, assuming a distance of 1 kpc. In the interest of brevity we will proceed directly to descriptions of the observed events, leaving the discussion of two important observational matters - namely, our methods of dealing with the changing background rate of a polar-orbiting experiment and the response of our detectors to >10 keV photons - to a future paper.

(a) GB790307

Due to its high fluence, this burst was detected by at least eight γ -ray instruments. At those energies the event is characterized by a long and irregular time history and a lack of fast structure.¹¹ The location of this event was near the center of the XMON field-of-view, and the burst fortuitously occurred during a time period when the XMON background counting rate was especially stable. None of the other detections were carried out under such favorable circumstances. Figure 1a shows superimposed X-ray and Pioneer Venus Orbiter (PVO) γ -ray time histories. Each X-ray point is the sum of two ~0.1 s "snapshots" taken by the two XMON

TABLE I

Gamma-Ray burst Fluences

Burst	>30 keV γ -rays (ergs cm^{-2})	3-10 keV X-rays (ergs cm^{-2})
790307	3.2×10^{-4}	3.1×10^{-6}
790325	8.7×10^{-5}	3.0×10^{-6}
790504	1.3×10^{-5}	2.6×10^{-7}
790731	9.5×10^{-5}	2.5×10^{-6}

Figure 1. (a) X-ray and γ -ray Overall Time Histories of GB 790307. The γ -ray data points (filled circles) are XMON "snapshots" obtained once per spacecraft rotation. The energy range is 3-10 keV. The γ -ray data (histogram) are from the Pioneer Venus Orbiter >100 keV real-time data record. (b) Detailed PVO γ -ray time history (histogram), γ -ray hardness ratio (error bars), and unnormalized X-ray data (filled circles). The hardness ratio uses channel edges at 0.1, 0.2, and 2.0 MeV.

proportional counters at times differing by 0.12 s. The obvious features of the X-ray emission are its intensity, long duration, and time lag relative to the γ -rays. Less obvious, but also reasonably certain (chance probability 5×10^{-4}) is that the X-rays "turned on" ~ 10 s before the γ -ray onset. (This is not a detection threshold effect, because the X-ray and γ -ray sensitivities were comparable.) Another possible feature (chance probability per bin of 1.2×10^{-3}) is a short, isolated X-ray precursor ~ 25 s before the start of the γ 's. This particular data point is the only one to show possible variability ($\sim 90\%$ confidence) on time scales as short as the 0.12 s separation of the observations by the two proportional counters.

The X-ray observation of GB790307 was of sufficient sensitivity to allow a meaningful, though rudimentary spectral analysis. Figure 1b shows the detailed γ -ray time history (histogram), the γ -ray hardness ratio (error bars) and the 3-10 keV data (filled circles). The hardness ratio uses channel edges at 0.1, 0.2 and 2 MeV, and for display purposes is defined in such a way that at zero source strength the sensitivity to spectral change becomes zero, but the error bars remain finite. It can be seen that the γ -ray spectrum shows little variability, except possibly for a softening trend during times of high X-ray/ γ -ray ratio. Table II displays additional GB790307 spectral information divided into time blocks based on the γ -ray emission, but not more finely subdivided due to statistical considerations. The quantity α_x is the X-ray power law index based solely on the XMON (6-10)/(3-6) keV hardness ratio; α_{xy} is derived from the 3-10 keV XMON data and the PVO 200-500 keV channel; α_y is calculated from the > 200 keV PVO γ -ray spectral data. For statistical reasons, we used PVO accumulations ~ 2 s wide centered on the X-ray points, provided that the overall PVO rate was

TABLE II

GB790307 Spectral Indices

X-ray	α_x	α_{xy}	α_y
Data points*			
1 + 2 (pre- γ)	0.1 ± 1.1	>1.6	--
1 + 2 + p (pre- γ)	0.55 ± 0.95	>1.6	--
3 + 4 + 5 (strong- γ)	0.45 ± 0.42	0.8 ± 0.1	1.7 ± 0.1
6 + 7 + 8 (weak- γ)	0.43 ± 0.34	1.1 ± 0.1	1.9 ± 0.2
9 through 14 (post- γ)	1.5 ± 0.64	>1.6	--

*X-ray data point 1 appears in Fig. 1a at $T_0 + 83$ s. Point 7 is the highest X-ray point. The possible X-ray precursor is labelled "p".

well behaved during the entire 2 s. The Konus data,¹⁰ though extending to lower energies, cannot be used to determine α_{xy} or α_y because the spectral accumulation time intervals generally are not specified in the various Mazets *et al.* publications. Table II shows that during the time of strong γ emission, the X-ray spectrum is hard and lies near a smooth extrapolation of the γ -ray spectrum, assuming a gradual slope change. A more pronounced slope change is evident in the spectrum taken during the weak- γ time period. Evidence for X-ray spectral variability is marginal, but a softening does appear to have occurred ($>90\%$ confidence) during the post- γ phase of this event.

(b) GB790325

The X-ray observation of this γ -ray burst was compromised by a changing background rate and by a relatively lower - 0.5 on the detector response function - exposure to the source. Figure 2a shows the X-ray and γ -ray time histories of GB790325. Like GB790307, the burst is long and irregular, but it contained one well defined peak with faster structure (see Fig. 2b). The X-rays appear to bracket, and possibly slightly lag the γ 's, but due to counting statistics the location of the X-ray centroid is uncertain. Again, we see evidence (chance probability per bin $\leq 1.4 \times 10^{-3}$) for an isolated precursor, this time ~ 60 s before the γ -ray onset. A possibly unique feature of GB790325 is the very high X-ray point near the end of the γ -ray burst. Relative to the γ 's, the point is a factor of 4 higher than the highest X-ray point seen during GB790307, and could be described as an X-ray "burst" that occurred independently of any important variations in the γ -ray emission. It does coincide with a broad minor peak in the γ -ray time history (the arrow in Fig. 2b), but that peak appears undistinguished.

Due to poor counting statistics we can say little about the X-ray spectrum of GB790325, other than that it is not obviously different from the GB790307 spectrum, even during the X-ray spike. Except during that spike $\alpha_{xy} \approx 0.9$, so the two events are also very similar in this respect. During the high X-ray point, we obtain $\alpha_{xy} \geq 1.4$.

(c) GB790504

This event, at $\sim 1.3 \times 10^{-5}$ ergs cm^{-2} was the weakest (and shortest) of the four γ -ray bursts observed at X-ray energies. The event was initially detected only by the Konus experiment, but subsequent examination of the PVO and ISEE-3 real-time data records (as opposed to triggered responses) also revealed the event. The X-ray fluence was similarly low, as can be seen from Fig. 3. This was the only event of the four that showed no evidence for X-ray activity either significantly before or after the γ -ray burst. However, if this event had an isolated precursor comparable to those possibly associated with GB790307 and GB790325, it would not have been detected. Due to poor statistics, X-ray spectral information

Figure 2. Similar to Fig. 1, but for GB790325. In (b) instead of showing the X-ray data points we have drawn an arrow at the position of the highest X-ray point.

Figure 3. Same as Fig. 1(a), but for GB 790504. Statistical considerations preclude showing a γ -ray hardness ratio.

is essentially nonexistent. Comparing GB790307 and GB790504 X-ray/ γ -ray ratios, we obtain $\alpha_{X\gamma} \approx 0.8$ for this event also.

(d) GB790731

This burst was also long and irregular, appearing to be a weaker version of GB790307. The X-ray observation was severely compromised due to a combination of unfavorable circumstances: The background rate was rapidly varying, the exposure to the source was only 0.35 of maximum, proximity to the Crab Nebula rendered half of the data unusable, and no 6-10 keV data were obtained due to the instrument being in the "fast" telemetry mode. Even so, it is clear from Fig. 4a that the X-rays lag the γ 's, and that there is a precursor candidate (chance probability per bin $\leq 7 \times 10^{-3}$) ~ 35 s

Figure 4. Similar to Fig. 1, but for GB 790731. The γ -ray data are from the UCB/Los Alamos experiment on ISEE-3. The hardness ratio uses channel edges at 72, 136, and 328 keV. The X-ray rate is actually a 3-6 keV rate normalized to the 3-10 keV band according to the average X-ray hardness ratio observed for GB790307.

before the γ -ray turn-on. Due to a fortuitous source location, we were able to search for this precursor at energies above ~ 5 keV in the data record from the UCB/Los Alamos ISEE-3 experiment. Frustratingly, we failed to confirm the XMON precursor, but instead observed two additional unconfirmed sharp precursor candidates within ~ 5 seconds of the one for which we were searching. It is possible that some sort of flickering is occurring. Although the statistics are poor, this γ -ray burster appears to have been a strong X-ray emitter in the latter half of the γ -ray event. Relative to the γ 's, the late X-ray emission is at least as intense - and may be several times as intense - as that from GB790307. Also, the γ -ray spectrum appears to have gradually softened. Unfortunately, quantitative information about α_{xy} during the strong- γ period cannot be reliably extracted from these data.

IV. DISCUSSION

The observations presented herein reveal γ -ray burster emission characteristics which affect existing models and which must be addressed in future modeling efforts. As discussed below, these characteristics involve the interplay of temporal and spectral information. Our discussion will emphasize the GB790307 observation, since those data are the most definitive.

The X-ray and γ -ray time histories for three of the events do not track one another closely, nor do they seem trivially interrelated, such as by a temperature change. Support for this statement stems from the GB790325 X-ray "burst" and from the complicated evolution of the GB790307 spectral indices and X-ray/ γ -ray luminosity ratio. However, the post- γ phase of GB790307 does seem compatible with simple cooling (i.e., no further energy input) on time scales of tens of seconds. Under this assumption, it is feasible, using only simple concepts, to explore a range of possibilities for the emitting region. At one end of this range is the notion - supported by the apparently soft post- γ X-ray spectrum - of a large, optically thin "fireball" that was generated during the energetic part of the event. At the other extreme is the idea - motivated by but not necessarily limited to, thermonuclear burning models (e.g., Ref. 12) and also compatible with the observations - of a residual blackbody-emitting hot spot on the surface of a neutron star. In the following paragraphs we present scenarios for GB 790307 based on the two different sets of assumptions. Computational details will appear in a future longer paper. We wish to stress that we are not attempting to determine whether or not particular models are compatible with the X-ray data. In our view, all of the models are still evolving rapidly enough to make such a determination impossible.

According to the "fireball" scenario, an energy supply (e.g., nuclear burning, neutron star reconfiguring, asteroid impact, etc.) becomes available over a time period comparable to the duration of the resulting γ -ray emission. Some of this energy is converted into X- and γ -rays, with efficiencies depending on the configuration of the source region. The observed intensities depend on the

efficiencies and the source orientation, all of which can change to time scales that are short compared to the energy deposition time scale. Thus, rapid and complex variability will often be observed. Initially, the energy deposition region is small, but internal pressures overcome the confining forces and cause an expansion, resulting after several seconds in a volume of hot, thinning plasma. The long duration of the X-ray tail indicates that the expansion does not proceed freely. Our calculations show that shortly after the energy source turns off (or decouples) the plasma cloud (assuming solar abundances) has a density of $2 \times 10^{13} \text{ cm}^{-3}$, a radius of 2.4 lt. sec., and a mass of 3×10^{-11} solar masses. The inferred average expansion velocity during the energy deposition period is $\sim 0.06 \text{ c}$. The calculated fireball luminosity of $8 \times 10^{36} \text{ ergs s}^{-1}$ implies a distance of 1.3 kpc. The integrated γ -ray energy is $6 \times 10^{40} \text{ ergs}$. All of these numbers are rather sensitive to the assumed optical depth to electron scattering, in this case unity. If we allow any optical depth between 0.3 and 3 (consistent with the spectral information and reasonable expansion velocities) the distance estimate ranges from $\sim 250 \text{ pc}$ to 7 kpc. The estimate scales linearly with the assumed average atomic number of the plasma.

The "hot spot" scenario begins similarly, but assumes a confining force strong enough to prevent the formation of a fireball. Based on the X-ray data and the thermonuclear burning model, it is reasonable to assume a 2 keV blackbody source having a surface of $\sim 1 \text{ km}^2$. This model obtains a cooling time $\gtrsim 50 \text{ s}$ (also compatible with the data) determined by conduction within the neutron star. Under this set of assumptions, the observed X-ray flux implies a "hot spot" luminosity of $2 \times 10^{35} \text{ ergs s}^{-1}$ and a distance of 220 pc. The integrated γ -ray luminosity is $2 \times 10^{39} \text{ ergs}$. In contrast to the fireball model, the distance estimate is within about a factor of three of being an upper limit.

These scenarios, though apparently self-consistent and somewhat useful as distance and energy indicators, say unsatisfyingly little about the key questions - namely, "What is the energy source?" and "What is the γ -ray production mechanism?" Conceivably, some insight regarding the first question can be obtained from the X-ray precursors possibly associated with 3 of the 4 events. If they are real, they might imply a "trigger" 10 's of seconds or more before the γ -ray onset, with energy transport at two different velocities or to two separate emission regions. In either case, the implication is an energy source at some distance from the site of energy deposition. It would be natural to invoke diffusion as the transport mechanism because the transport and energy deposition times seem to be approximately equal. Clearly, X-ray measurements with higher sensitivity and more complete temporal coverage are needed, as are theoretical calculations of the spectral shapes expected for realistic emission mechanisms.

A final point is that prior to this study, the entire XMON data base had been searched for "classical" X-ray bursts, and no convincing high-Galactic-latitude events were seen. The four γ bursts described in this paper escaped detection primarily because a "global" search cannot be as sensitive as one undertaken only at

discrete points in time, particularly for a satellite in a polar orbit. Also, GB790307 was missed because of its long duration relative to the events being searched for. Nonetheless, it can be inferred from this negative result that γ -ray bursters probably do not often produce X-ray bursts (5-30 s duration, intensity ≥ 0.5 Crab Nebulas) independent of the γ -ray emission.

V. ACKNOWLEDGMENTS

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